The presentation and interpretation of arrow symbolism in biology diagrams at secondary-level

By

Lynn du Plessis
BSc, UED (University of Natal)

Submitted in fulfilment of the academic requirements for the degree of Doctor of Philosophy in Biochemistry in the School of Biochemistry, Genetics, Microbiology and Plant Pathology
University of KwaZulu-Natal,
Pietermaritzburg.

December 2006

PREFACE

The research described in this dissertation was carried out in the Science Education Research Group (SERG), Discipline of Biochemistry, School of Biochemistry, Genetics, Microbiology and Plant Pathology, University of KwaZulu-Natal, (Pietermaritzburg Campus), from October 2000 to December 2006 under the supervision of Professor Trevor R. Anderson.

These studies represent original work by the author and have not otherwise been submitted in any other form for any degree or diploma to any other University. Where use has been made of the work of others, it has been duly acknowledged in the text.

Lynn du Plessis (Candidate)

Prof. Trevor R. Anderson (Supervisor)

December 2006

I dedicate this dissertation to my family, Aubrey, Wayne and Leigh du Plessis for their never-ending love, support and belief in me, to my mother, Meryl Frankish for her unfailing love, patience and concern, and to the memory of my father, Trevor Frankish. He would have been so proud.

ABSTRACT

The literature contains conflicting ideas about the effectiveness of diagrams, and their constituent symbolism as teaching and learning tools. In addition, only limited research has been specifically conducted on the presentation and interpretation of arrow symbolism used in biology diagrams, let alone on the nature, source and remediation of student difficulties caused by arrows. On the basis of this limited research and 30 years of experience of teaching biology at secondary-level, the author suspected that students might have difficulties interpreting arrow symbolism in diagrams used as explanatory tools and decided to thoroughly investigate this issue. The hypothesis, '*Secondary-level students have difficulty with the use of arrow symbolism in biology diagrams*' was formulated and the following broad research questions defined to address the hypothesis:

1. *How much of a problem is arrow symbolism in diagrams?*
2. *How effectively is arrow symbolism used in diagrams to promote the communication of intended ideas?*
3. *To what extent does the design of arrow symbolism in diagrams influence students' interpretation and difficulties?*
4. *How can the emerging empirical data and ideas from literature be combined to illustrate the process of interpretation of arrow symbolism?*
5. *What measures can be suggested for improving the presentation and interpretation of arrow symbolism in biology diagrams at secondary-level?*

To address Research question 1, a content analysis of all arrow symbolism in seven popular secondary-level biology textbooks was undertaken. This revealed a wide diversity of arrow styles, spatial organisations, purposes and meanings that could be confusing to students. These results suggested the need for an evaluation of the effectiveness of arrow symbolism (Research question 2). As there was no definitive set of guidelines available for specifically evaluating arrows, general guidelines from the literature on diagrams were used to develop a set of 10 criteria, to evaluate the syntactic, semantic and pragmatic dimensions of arrow symbolism, which were validated by selected educators, students and a graphic design expert. Application of the criteria (which constituted expert opinion) to the arrow symbolism used in 614 realistic, stylised and abstract diagram types, revealed a relatively high incidence (30%) of inappropriately presented arrow designs that could mislead students. To establish whether this problem could be the cause of student difficulties, and to thereby address Research question 3, a stylised and an abstract diagram were selected and evaluated according to the criteria. The results of the evaluation were compared to the responses given by 174 students to a range of written and interview probes and student-modified diagrams. In this way, student performance was correlated with expert opinion. The results confirmed that students experience a wide range of difficulties (26 categories) when interpreting arrow symbolism, with some (12 categories) being attributable to inappropriately presented arrow symbolism and others (14 categories) to student-related processing skills and strategies at both surface- and deeper-levels of reasoning. To address question 4, the emerging empirical data from the evaluation and student studies was combined with a wide range of literature, to inform the development of a 3-level, non-tiered model of the process of interpretation of arrow symbolism in diagrams. As this model emphasised the importance of both arrow presentation in diagrams and arrow interpretation by students, it could be used as an effective explanatory tool as well as a predictive tool to identify sources of difficulty with the use of arrow symbolism. This model was, in turn, used to inform the compilation of a range of guidelines for improving the presentation and interpretation of arrow symbolism, and so target Research question 5. These, and other guidelines grounded in the data and relevant literature, were suggested for all role players, including students, educators, textbook writers, graphic artists and researchers, to use as remedial tools. Future research should focus on the implementation of these guidelines and studying their effectiveness for improving the presentation and interpretation of diagrams with arrow and other types of symbolism.

ACKNOWLEDGEMENTS

When I graduated from 'Varsity many, many years ago, I promised myself that I would return to study further. Little did I realise that it would take nearly 30 years to accomplish that dream. I returned somewhat naïve, very rusty and with very little idea of 'what I had let myself in for'. On the other hand, I was enthusiastic to sample academia and determined to make the most of this opportunity. However, I could never have accomplished my dream on my own. I am indebted to many people for their considerable encouragement and guidance - the completion of this dissertation is in large measure due to them.

Acknowledgement must firstly go to my supervisor Prof. Trevor Anderson, for affording me the opportunity. Thank you for your considerable support and nurturing through the long and sometimes tortuous learning curve to get Cupid off the ground! Thank you for revealing the broad and interrelated nature of Science Education, for encouraging me to think about issues, to consider the merits of arguments and to ponder new ideas. Through your guidance, efforts and patience, my dream has (eventually) become a reality! Thank you so much.

Acknowledgement is also extended to Prof. Diane Grayson for her input in the first year or so of the project. I appreciated your ideas and constructive criticism. I also owe a debt of gratitude to Prof. Colleen Downs for reading the rough draft of the dissertation and for giving her expert and discerning comment. Thank you.

I also acknowledge with gratitude the funding I received from the National Research Foundation (NRF) and University Research Fund (URF).

To ALL my fellow researchers I extend my thanks for the academic stimulation shared with you during SERG meetings. You have all contributed in some measure to the maintenance of my enthusiasm and the development of my ideas. I would like to extend particular thanks to Sheelagh Halstead for her most appreciated support and encouragement, to Anne Line for hours of proofreading and to Konrad Schönborn, my role model, who set the standard!

My thanks are also extended to Mr. David Wilkinson of St Anne's Diocesan College for supporting me in my endeavours and for allowing me to conduct research at the school. In this regard, I also thank my school colleagues for 'lending' me their classes and for their input in evaluating diagrams and probes and moderating propositional statements. The students of St. Anne's also need a special mention for their co-operation and willingness to participate in the written probes and interviews. Thank you too, to Mr Brett Armstrong for evaluating diagrams and passing comment on the set of criteria developed during the course of the research. There are many others who have contributed in other ways – I thank you all. I have appreciated every act of kindness and every ounce of support.

There were many times when I had to put myself before my family. I thank them, Aubrey, Leigh, Wayne and Mom, for their indulgence and patience. I often had to choose between enjoying your company and working on my dissertation and wished I could cut myself in two! It was only because of your individual strengths that I was able to pursue my studies. I am so grateful to you all for your understanding.

Without my daughter, Leigh, I would never have mastered the intricacies of computers and reference searches, both on and off-line. I not only appreciate the considerable time you spent 'showing me the ropes' (sometimes several times over) and for your technical help, but also for being my 'sounding-board' during our many discussions about the various aspects of my research. Without your input and perceptive comments, I could never have reached this point in my studies.

To my husband, Aubrey, I thank you for continually believing in me and encouraging me to believe in myself. You have unceasingly demonstrated the depth of your love in the myriad sacrifices you have made so willingly to give me the time to devote to 'my project' and by uncritically sharing both the good and hard times along the way. Your persistent faith in my ability has kept me focused and for this reason, this dissertation is as much yours as mine!

CONTENTS

LIST OF CONTENTS

3. Du Plessis, L., Anderson, T. R. & Grayson, D. J. (2003). Student difficulties with the use of arrow symbolism in biological diagrams, In J. Lewis, A. Magro & L. Simmonneax (Eds.), *Biology Education for the Real World, Proceedings of the IVth ERIDOB Conference*, Toulouse, France, pp. 89 – 103, Ecole nationale de formation agronomique, Toulouse-Auzeville.

LIST OF TABLES

LIST OF FIGURES

SOURCES OF DIAGRAMS USED IN THIS DISSERTATION

Ashwell, A., Clitheroe, F., Dilley, L., Doidge, M., Marsden, S. & Mtombeni, G. (1999a). *Focus on Biology Grade 11*, Maskew Miller Longman (Pty) Ltd., South Africa.

Ashwell, A., Clitheroe, F., Dilley, L., Doidge, M., Marsden, S & Mtombeni, G. (1999b). *Focus on Biology Grade 12*, Maskew Miller Longman (Pty) Ltd., South Africa.

Ayerst, P. W., Green-Thompson, A. L., Pellew, V. W. & Thienel, A. in collaboration with van Rensburg, N. P. J., van Rensburg, C. A. J. & Roux, J. S. (2000a). *Discovering Biology Grade 11* (10th ed.), Shuter and Shooter (Pty) Ltd., Pietermaritzburg, South Africa.

Ayerst, P. W., Green-Thompson, A. L., Pellew, V. W. & Thienel, A. in collaboration with van Rensburg, N. P .J., van Rensburg, C. A. J. & Roux, J. S. (2000b). *Discovering Biology Grade 12* (4th ed.), Shuter and Shooter (Pty) Ltd., Pietermaritzburg, South Africa.

Degenaar, J. P., Scholtz, D. A., Thomas, A. M. L. & Kuhn, M. S. F. (1999). *Active Biology Standard 9* (2nd ed.), Kagiso Publishers, Pretoria, South Africa.

Degenaar, J. P., Scholtz, D. A., Thomas, A. M. L. & Kuhn, M. S. F. (2000). *Active Biology Standard 10* (7th ed.), Kagiso Publishers, Pretoria, South Africa.

Independent Examinations Board, South Africa. (1994). *Senior Certificate examination paper*.

Roberts, M., Reiss, M. & Monger, R. (1993). *Biology Principles and Processes*. Thomas Nelson and Sons, Ltd, United Kingdom.

Wright, D. (1989). *Human Biology*. Oxford: Heinemann Educational, Great Britain, p. 55.

ABBREVIATIONS

C: Scientific content (propositional knowledge) represented in the diagram

C/M: Integration of scientific content represented by the diagram and cues from the mode of presentation of arrow symbolism in the diagram (such as conventions of spatial organisations or arrow styles). This process should result in an Image Base.

D-L: Deeper-levels of reasoning during interpretation of arrow symbolism

Difficulty codes: See Tables 5.2 and 5.4

E: Educator

F: Frame of reference of the student (including G, K and T)

G: Graphical schemata (prior knowledge and understanding of design principles used to create the diagram)

G-E: Graphic expert

K: Conceptual schemata (prior conceptual knowledge)

P: Purpose of, including the relationships specified by, the arrow symbolism in the diagram

P/C: Integration of the purpose of arrow symbolism with the explicitly presented scientific content represented in the diagram to attribute meaning to the symbolism. In this way a Mental Base will be achieved resulting in better understanding of the scientific content of the diagram.

M: Mode of presentation (including spatial organisation and style) of the arrow symbolism in the diagram.

M/P: Integration of cues from the modes of presentation of arrow symbolism with the purpose of the arrow symbolism. This process should result in a Visual Base.

Q: Question

S: Student (1, 2 etc refer to the number of the quotation used in the discussion of a particular point, not to the number of the student. Where reference is made to particular students, the students initials are used, such as in Table 6.4)

S-L: Surface-level reasoning (the perceptual stages of interpreting a diagram)

T: Cognitive schemata (Reasoning ability (skills and strategies) during interpretation of the diagram).

GLOSSARY

Abstract diagrams: Word diagrams such as flow charts. Elements are usually represented as symbols and processes and relationships by connecting lines or arrows. Groups of elements may be placed within boxes (Wheeler & Hill, 1990). See Diagram types: Abstract, for a more detailed description.

Algorithm: A step-by-step procedure, which, if followed precisely will produce the intended result (Nickerson, 1994).

Alternative conception: An ' idea which is neither conflicting nor clearly compatible with scientific conceptions but which has its own value and is therefore not necessarily wrong' (Abimbola & Baba, 1996. Also used by Duit & Treagust, 1995).

Analogical representations: Such mental models preserve information intrinsically, are tied to a sensory modality, and play a crucial role in many tasks (McNamara, 1994).

Axis: 'This is a linear layout of a diagram, which may be imposed on a diagram in an attempt to simplify the appearance of a spatial arrangement or provide a focus; or it may emerge as an essential and integral part of it' (Garland, 1979).

Beliefs, values, attitudes

Beliefs: What is assumed to be true.

Values: What one believes to be important, good or valuable.

Attitudes: Manifestation of beliefs and values (Stern & Robinson, 1994).

Bottom-up processing: Processing from local details to global configurations (local to global processing). Such processing is data driven and uses grouping to 'elaborate' the data in the retinal image.

Boundary: A discontinuity or partition separating portions of the diagram (Mathewson, 2005). See also explicit and implicit boundaries.

Captions: Captions can be words, numbers, symbols, arrowheads, pictures etc. to identify or qualify elements, clusters or connectives.

Categories:

Superordinate category – a general or most inclusive category.

Subcategory – more specific categories appearing below superordinate category (Roth & Frisby, 1986).

Chunking: This is a perceptual skill of coding whole chunks (clusters of several elements) or spatially segregated groups of information (Egan & Schwartz, 1979).

Clarity: The components of the diagram should have meaning for the reader (Thompson, 1994).

Cognitive skill: Competency (Paquette *et al.*, 2006) or mastery of certain abilities (Taconis *et al.*, 2001) used in an activity or series of activities. Paquette *et al.* (2006) include memorisation, transposition, analysis, synthesis, evaluation and self-control in their definition of cognitive skills.

Cognitive strategies: Cognitive strategies are specific methods of applying procedural knowledge when using and reasoning with information for a particular task, including concentrating on the task, deducing, sorting out relevant from irrelevant information, determining a purpose, and so on. They are not subject specific, but rather to do with general ways of thinking (White & Gunstone, 1993). See also Working memory.

Cognitive schemata: Procedural knowledge required to use and reason with information including interpretation of visual materials and problem-solving.

Conceptual schemata: Prior domain-specific knowledge.

Combinational treatment: A subjective evaluation undertaken after an evaluation using a set of pre-determined criteria in order to decide on the overall suitability of the picture (Bell, 2001).

Complexity: Level of difficulty attributed to a diagram based on several factors including the number of perceptual units in a diagram.

Compositional display: A display composed of interlinked diagrams.

Concept: A concept is 'anything that can be recognised; that is, can be attributed to an identity.' (Holley & Danserau, 1984). Concepts or conceptual categories are mental representations of objects, entities or events, stored in memory (Roth & Frisby, 1986).

Concept map: Key features of concept maps are their spatial or graphic properties. They make use of labelled nodes to represent concepts. Lines and arcs represent relationships between pairs of concepts (e.g. Novak, 1996).

Conceptions: 'Conceptions are the individual's idiosyncratic mental representations, whereas concepts are something firmly defined or widely accepted. Conceptions stem from and are deeply rooted in daily experiences because they have proved to be helpful and valuable in the individual's daily experience.' (Duit & Treagust, 1995).

Conceptual change: 'A person changes his conceptions by capturing new conceptions, restructuring existing conceptions, or exchanging existing conceptions for new conceptions' (Hewson, 1996).

Connectives: Arrows representing links of various kinds between nodes /ensembles (Waller, 1981).

Constructivism: Each learner constructs knowledge in a unique way, based on a variety of inputs. In other words, people are actively involved (in accordance with the ideas of Bruner, 1986) in organising and reorganising knowledge in order to construct new knowledge (and therefore their own meaning) based on prior knowledge and ideas that they already hold (Jonassen & Hawk, 1984; Driver & Bell, 1986; Johnson & Gott, 1996) and influenced by the social context in which learning takes place (Driver, 1989; von Glasersfeld, 1992).

Content: 'The meaning or significance of a poem, painting or other work of art {including diagrams], as distinguished from its style or form' (Collins Dictionary, 2003).

Context: The condition and circumstances that are relevant to an event, fact etc. (Collins Dictionary, 2003). In this dissertation, context is defined as both the content and purpose of the diagram.

Continuity effect: See Principle of Continuity: Arrows arranged sequentially to imply a continuous line or process.

Cue-value: Significance of arrow symbolism for guiding interpretation of the purpose or scientific content of the diagram.

Cues: Information (usually implicit) or hints (Collins Dictionary, 2003) provided by features of the diagram or ideas in text that may suggest or act as a directive in order to foster understanding. See also explicit and implicit cues.

Decoding: Reorganization of information, including integration, leading to interpretation (Reed, 1988).

Deeper-level reasoning: During this second stage of information processing, the information in short and long-term memory is integrated (Kosslyn, 1989) and if successful, culminates in an understanding of the scientific content represented in the diagram (Winn, 1993). It is dependent on, and regulated by, all three categories of schemata: conceptual schemata including prior knowledge of the subject (Johnson-Laird, 1983; Gillespie, 1993; Winn, 1993; Mayer *et al.*, 1995; Taconis *et* *al.*, 2001); graphical schemata to understand the context of the task; and cognitive schemata that influence the process of integration (Kosslyn, 1985). According to Winn (1993), this is a conscious stage of reasoning as the reader is, according to Reed (1988), aware of the image.

Design elements: Any lines, dots or areas including arrows, colours and textures used to convey a message (Fleming, 1967).

Diagram: A diagram provides information visually that is available elsewhere in non-visual form and includes charts, graphs of maths functions or data, maps, plans, engineering drawings, block diagrams etc. Like writings a diagram depends on socially agreed on intentions, usage and conventions. Unlike writings, a diagram presents its information by means of relatively non-arbitrary visual forms. 'Diagrams are visual aids to thinking and provide external supports for the complex psychological activity that Arnheim (1971) so aptly labelled visual thinking' (Ittelson, 1996).

Diagram types:

Abstract: Abstract diagrams are non-representational (Lowe, 1986a) and depict non-spatial arrangements as two-dimensional spatial organisations (Lowe, 1993b), often depicting a limited number of possible features (Perini, 2005). The elements are usually represented as symbols or as words often enclosed in box-type shapes (frames), with connecting lines or arrows to represent relationships (Hill, 1988; Wheeler & Hill, 1990) such as structural, conceptual and temporal (time sequence) relationships (Kress & van Leeuwen, 1996). Such relationships may be represented in various spatial organisations such as networks and chains, as in the case of a metabolic map or pathway of consecutively linked biochemical reactions.

Stylised: Stylised diagrams are highly specialised representational diagrams (Henderson, 1999), often presented using spatial properties (Cheng *et al.*, 2001) according to certain rules, as two-dimensional line drawings (Larkin & Simon, 1987). The information in them is in a concentrated form with key features, such as distortion of proportion, sometimes deliberately or inadvertently exaggerated (Lowe, 1993b; Wheeler & Hill, 1990) or illustrating part (rather than the whole) of an object. Additional information, lines and symbolism, including arrows, may be incorporated to emphasise particular relationships (Geva, 1983; Schollum, 1983; Hill, 1988; Hardin, 1993 and 1995; Lowe, 1993b; Henderson, 1999). For example, the anatomy of the heart may be shown in section, and in a simplified or plan format, to illustrate its internal chamber structure. Arrows may be added to explain the path of blood flow through the chambers. In their explicative role, stylised and abstract diagrams rely on functional elements to enhance aspects of structure or function and to emphasise relationships between features displayed in the diagram. To accomplish their specific focus, symbolism such as arrows is used (Geva, 1983; Schollum, 1983; Hill, 1988; Hardin, 1993; Lowe, 1993b; Henderson, 1999).

Realistic: Realistic displays, such as authentic drawings of animals and plants, are isomorphic to their representation (Stenning & Lemon, 2001). In other words, they are life-like and proportional representations of the whole organism, describing its superficial structure, without deeper levels of content organisation. No sectioning is shown and no additional lines except label lines are included on the display. They usually have an attentional role.

Discriminability: The ability to see a feature distinct from its background (a feature that is too small or does not contrast enough with the background will not be seen) (Kosslyn, 1989).

Dual coding theory: The verbal (text) and non-verbal (imaginal or visual) representations are interpreted separately but complement each other by being linked by means of referential connections into a network of associations (Paivio, 1986 and 1991; Clark & Paivio, 1991) potentially allowing imaging to words and naming to pictures.

Dual channel theory: This theory, known as the cognitive theory of multimedia learning (Mayer, 2003) is an elaboration of the dual coding theory. See Chapter 3 for explanation.

Emergent properties: Properties of diagrams that arise when parts of the symbol, or group of symbols, are attended to simultaneously (Bennett & Flach, 1992). An emergent property may 'appear as a consequence of large shifts in magnitude' (Mathewson, 2005, page 543).

Emphasis: One component of a diagram stands out from the rest, in contrast to harmony (Thompson, 1994).

Encoding to internal representation: The transfer of information from short-term memory to long term by comparing against previously stored and categorized information.

Encoding in external representations: Scientific information 'at levels of abstraction beyond 'hands-on' experience' is expressed using symbolic codes (Mathewson, 2005, page 547).

Expert: A person who has a good understanding of the concepts of a domain and is therefore able to see patterns that are meaningful and are recognised as potential cues to relationships (Goldman, 2003).

Explicit boundaries: Outer, clearly identifiable boundaries or overall pattern of the diagram

Explicit cue: Information that is clearly stated. Explicit cues include propositional guidelines (captions, labels, annotations and text), easily recognisable spatial arrangements and arrow styles.

Expression model: An external representation of a mental model.

External cognition: A focus on cognitive processing while interacting with graphical representations (Scaife & Rogers, 1996).

External representation (ER): A visual representation e.g. diagram.

Extraneous cognitive load: This 'corresponds to the mental effort imposed by the way information is presented externally' (Bodemer *et al.*, 2004).

Extrinsically: Operating from without, not linked to a body.

Figure-ground differentiation: Visibility of arrows distinct from the background and other features of the diagram (e.g. Rock & Palmer, 1990).

Flow charts /Flow diagrams: "Flowcharts are graphical representations of procedural knowledge or algorithms, composed of actions and decisions that trigger a series of actions in a dynamic rather than a static way." (Paquette *et al.*, 2006). In other words, flow charts or flow diagrams are usually sequential, with a directional element and are used to show a process (Maribe, 1997).

Flow diagrams: see Flow charts

Frame of reference: The background of a person including his /her schemata, culture, beliefs, values and attitudes.

Frequency effect: the number of arrows in a group to imply syntactic emphasis.

Gestalt principles: Principles describing organisational phenomena that therefore influence the way that objects are perceived. See also Principles.

Generalisability: applicable to all situations (e.g. diagrams).

Generative theory: This theory explains the connections between visual and verbal representations and advocates incorporating annotations (captions and labels) into the illustration (Mayer *et al.*, 1995).

Germane cognitive load: This 'is a result of mental activities that are directly relevant to learning' (Bodemer *et al.*, 2004).

Gestalt: (German for form or shape). The Gestalt principles describe the perceptions of components of diagrams around which vision is organised. These include the Principles of continuity, figural closure, grouping, orientation, proximity and similarity (Mathewson, 2005, page 547).

Goals of search: Cues (e.g. propositional guidelines) provided on or with the diagram to guide the reader to search for relevant information and symbolism when interpreting the diagram.

Graphic devices: lines, arrows or other marks used in a diagram in order to convey the intention of the diagram (Beck, 1984).

Graphical literacy: This is the ability to interpret charts, maps, graphics and other pictorial presentations (Gillespie, 1993).

Graphical schemata: Prior domain-general knowledge about the meaning and purpose of symbolism and the techniques used for presenting information in a visual form. Such schemata facilitate understanding of graphic representations (Gillespie, 1993) and hierarchical structures (Lowe, 1994a and 1994b) and the limitations of design principles (Lowe, 1993b). Knowledge about symbolism (T. R. Anderson, pers comm.) and the use of visual characteristics (Lowe, 1993a) and patterns (Lowe, 1999).

Harmony: All parts of the diagram should relate and complement each other to portray a unified message (Thompson, 1994).

Hierarchy: This is a way of organising information into super- and sub-ordinate categories. It shows the relationships between categories in the domain. Information is thereby classified (Roth & Frisby, 1986). Sequence and ranking are presented (Garland, 1979).

Illustration: Any configuration of lines, dots or area or any combination of them that resembles events or objects, perceived or conceived. It therefore includes number line, geometric figures, structural chemical formulae, curves, graphs and time lines (Fleming, 1967).

Image base: The image base (Mayer *et al.*, 1995) refers to the recognisable structural groups or patterns resulting in a perceptual image (Kosslyn, 1987) that are formed by the reader when searching the diagram (Larkin & Simon, 1987). Images are detected, selected and matched against each other.

Images: Images are mental representations of sensory (often visual) perceptions (White & Gunstone, 1993).

Implicit boundaries: Implied boundaries, not demarcated by a line around a perceptual unit.

Implicit cue: Information in which the significance or meaning is implied rather than being explicitly stated. Implicit cues may be embedded in arrow styles, spatial arrangements and relationships, requiring deeper-levels of reasoning to understand the message.

Information: Any form of written text, graphics, audible or tactile message (Taconis *et al.*, 2001).

Interpret : expond (set forth in detail) the meaning of ....; make out the meaning of; bring out the meaning of, render, by artistic representation or performance; explain, understand, in specified manner ....(Oxford Dictionary, 2002).

Interview: 'An interview about an instance or an event is a conversation that an expert has with one student, focussed by initial questions about situations represented in a series of line diagrams, to check the student's ability to recognise the presence of a concept or the student's interpretation of a natural phenomenon or social occurrence.' (White & Gunstone, 1993, Chapter 4).

Instructional strategy: This refers to the way in which a teacher uses any means or behaviours to create a learning environment that fosters the desired outcomes (Hofstein & Walberg, 1995).

Intrinsically: Inherently, part of the basic nature (Collins Dictionary, 2003) .

Intrinsic cognitive load: This 'is determined by the complexity of the application domain as well as by the learner's prior knowledge' (Bodemer *et al.*, 2004).

Juxtaposition: Adjacency of information.

Knowledge: New knowledge is produced through a series of cognitive activities undertaken to process elements of information by combining external information and prior knowledge (Taconis *et al.*, 2001).

Procedural knowledge – Skills, cognitive operations and knowledge of how to do things (McNamara, 1994).

Declarative knowledge – knowledge that can be visualised or verbalised, in other words, declared in some manner (McNamara, 1994).

Metacognitive knowledge – knowledge about thought processes in general and includes knowledge on how to monitor, control, and evaluate one's performance on cognitively demanding tasks." (Nickerson, 1994).

Learning: 'A person changes his conceptions by capturing new conceptions, restructuring existing conceptions, or exchanging existing conceptions for new conceptions (i.e. a process of conceptual change).' (Hewson, 1996). Learning should result in a knowledge base with new content and a better mastery of cognitive activities (Taconis *et al.*, 2001). It is meaningful if the new information can be related to something already known (i.e. in the existing cognitive structure) (Jonassen & Hawk, 1984).

Discovery learning requires the learner to reorganise incoming information with prior learning (Jonassen & Hawk, 1984).

Learning level: Learning level encompasses a student's age, school grade and the knowledge expected of students at that level.

Long-term memory: Relatively permanent internal representations (mental models) (Frisby, 1986; Kosslyn, 1989; Johnstone, 1993; Winn, 1993; Schnotz & Bannert, 2003).

Magnitude: 'The dimensions, extent, scale, or size of objects or events (Mathewson, 2005, page 543).

Meaning: Understanding gained from integrating information from external sources with prior knowledge.

Mental base: During deeper-level reasoning the reader recognises the significance of the style and spatial organisation of the arrows in the context of the diagram and integrates these cues with the supporting data in the diagram (extra-integration) as well as with previous knowledge (intra-integration) (Buzan, 1991). In this way the abstracted information is reconstructed and meaning in the context of the diagram, or a Mental base, is achieved.

Mental model (Internal representation): Representation of information in long-term memory.

Memory: Working memory includes all the information being held in the various short-term memory structures plus the information that is activated in the various long-term memory structures. In addition, it includes the 'control processes" ...that

activate information in long-term memory and maintain short term-memory (Kosslyn, 1994).
Long term memory has relatively enduring representations.
Short term memory has relatively temporary representations and is constructed as an intermediate stage in the processing of sensory input during perceptual processing (Roth, 1986).

Misconception: Is an idea, caused by scientific instruction that is in conflict with scientific conceptions (Abimbola & Baba, 1996). Misconceptions can be attributed to unsound scientific conceptions resulting either from poor science instruction (Barman *et al.*, 1995; Duit & Treagust, 1995) or arising from ineffective information processing (Fisher, 1985).

Modality: Forms of expressions that are used for displaying information (Reimann, 2003).

Modes of presentation: presentation of arrow symbolism including spatial organisations (layouts) and styles and the conventions used in each. See Modality.

Models: 'A model is a simplified representation of a phenomenon which concentrates attention on specific aspects of it thus facilitating scientific enquiry.' (Ingham, 1991). A model is a representation of a scientific phenomenon with a predictive power (Gobert & Discenna, 1997). A model is 'an idea or theoretical construct that has been developed to organise and account for the available evidence in the field' – they are mental inventions. Models ' contain a set of interacting components that re-enact or replicate existing (or postulated) complex structures and associated processes (systems)' (Mathewson, 2005, page 547). Models 'make predictions about new observations and experiments' and 'serve as conjectures, explanations, didactic devices and communication vehicles' Mathewson, 2005, page 533). A diagram may be used to represent them (Hill, 1988).

Multimedia: This refers to the combination of different types of technical resources, used to present information in a variety of ways, such as visual and verbal methods, using words and pictures to stimulate a range of senses (Mayer *et al.,* 1996; Schnotz & Lowe, 2003). A multimedia instructional message is a message consisting of words and pictures designed to facilitate meaningful learning (Mayer, 2003).

Network: A network is a system of connected points to show relationship between the points. It does not show the dimensional relationship and can therefore have many shapes (Garland, 1979).

Participants or referents: The two elements connected by an arrow to form a unit of communication.

Partition: Break down, divide or separate (e.g. the diagram) in order to facilitate interpretation (Winn, 1993).

Pattern perception: How groups of lines are organised into identifiable patterns, how they are recognised, remembered etc. (Ittelson, 1996).

Perceive: 'to become aware of (something) through the senses, especially the sight; recognise or observe' (Collins Dictionary, 2003).

Perception: Perception has several meanings in science education literature. For example, Frisby (1986), Roth (1986), Fleming (1987) and Moore (1994) used the word perception to include collecting information (for example, from diagrams) through senses, recognising, selecting and organising the information in short term memory, as well as linking the information through cognitive processing with information in long-term memory (referred to in this dissertation as the reader's frame of reference). In other words, these researchers equated the process of perception with the whole process of interpretation, ultimately resulting in understanding.

Although, their explanations of the steps in the process of interpretation are not disregarded, in this dissertation perception is defined according to Kosslyn's (1989) visual information processing theory and the views of Ittelson (1996) and other Gestalt protagonists. They describe perception as a process of observation. This stance is supported by the definition of the word 'perceive' in Collins Dictionary (2003), namely: 'to become aware of [something] through the senses, especially the sight; recognise or observe'. In this report therefore the process of perception equates with the stages of observation, including the sensory stage of search (including detection) as well as the stages of pattern recognition, selection of data and the organisation of that data into patterns that may be influenced by previous knowledge and experience. As a result, relatively temporary representations of the syntactic dimension of the diagram are constructed in short term memory (Roth, 1986). The author therefore supports the explanation of Winn (1993) that perception is an unconscious process governed by the design features of the diagram, many of which are expressed using the Gestalt principles. Thus the stage of perception is restricted to interpretation of the surface or syntactic features of the diagram. Hence, the term 'surface-level reasoning' is used.

Perceptual precedence: The area to which the reader first pays attention because of the way the features of the diagram are presented. Salient (prominently presented) features are usually accessed first.

Perceptual units: Units of information 'that cannot be reduced to smaller subunits and retain their identity and role' (adapted from Mathewson's, 2005 definition of units).

Plan: A plan is defined by as a hierarchical process that controls the order in which a sequence of operations is to be performed.

Polysemy: Arrows presented in different styles but cueing for the same purpose (Pinto *et al.*, 2000).

Pragmatic factors: Factors that are influenced by the reader's frame of reference (see Kosslyn, 1989).

Presentation (of arrows): This includes the design features of arrows, including their pointing direction and placement in relation to each other and to other features of the diagram (spatial organisation).

PRINCIPLES: There is a range of perceptual (graphic or design) principles based on the Gestalt principles and Principle of Pragnanz. They are described and referred to by various researchers (e.g. Goldsmith, 1987; Kosslyn, 1989; Bennett & Flach, 1992; Thompson, 1994; MacEachren, 1995; Kress and van Leeuwen, 1996). The principles referred to in this dissertation include the principles of:

a. Acceptability: Refers to the compatibility of the style of presentation and spatial organisation of the elements of the diagram with the purpose or focus of the diagram.
b. Apprehension: The structure and content of the external representation should be readily and accurately perceived and comprehended (Tversky & Morrison, 2002).
c. Between-Mapping: A semantics principle referring to the effectiveness of arrows for communicating meaning in their position between referents.
d. Congruity: Refers to the compatibility of the appearance (or style) of connectors (e.g. arrows) with meaning. 'The structure and content of the external representation should correspond to the desired structure and content of the internal representation' (Tversky & Morrison, 2002).
e. Continuity: Refers to a row of symbols presented as a continuous line.

f. Finite Capacity: A diagram should have a limited number of elements to ensure that it is not beyond the short-term memory of the reader.
g. Harmony: All parts of the diagram should relate and complement each other to portray a unified message (Thompson, 1994).
h. Perceptual apprehension: Refers to the ability of the perceiver to detect one feature (in this instance, arrows) from other features such as lines, colours and regions.
i. Perceptual organisation: This principle refers to the way that the reader perceives (or perceptually arranges) symbols or other features of the diagram to form visual groups or patterns. This principle underpins and explains the Gestalt principles.
j. Pragnanz: This principle proposes that perception is as 'good' as the design of the diagram allows. 'Good' refers to the simplicity, regularity and symmetry of the design.
k. Proximity: Symbols such as arrows near to each other tend to be grouped to form discrete units of focus.
l. Purpose-compatibility: Arrow style should be relevant to the purpose of the diagram.
m. Similarity: Similar features will tend to be grouped together, and objects perceived as different, will be separated.
n. Simplicity: The diagram should be simple, portray one concept, and use only the information needed to interpret it.
o. Within-Mapping Principle: Refers to the placement of arrows between referents to reflect relationships between the referents.

Processing:

Bottom-up processing: Processing from local details to global configurations (local to global processing). Such processing is data driven and uses grouping to 'elaborate' the data in the retinal image.

Top-down processing: Processing from global configuration to local detail (global to local processing). Such processing is concept driven and uses stored knowledge of the properties of configurations (Roth & Frisby, 1986).

Properties: Perceptual property: Features of diagram that are visual are called perceptual features (Roth & Frisby, 1986).

Propositions: 'A proposition is the smallest unit of knowledge that can stand as an assertion; the smallest unit that can be true or false.' (McNamara, 1994). Propositions are facts, opinions or beliefs encoded as meaning (White & Gunstone, 1993). A structural description is a set of propositions about a pattern from which the actual pattern (or an object) may be reconstructed (Roth & Frisby, 1986). A propositional representation: a "mental sentence" that clearly explains the meaning of an assertion (Kosslyn, 1994).

Propositional guidelines: Textual information such as caption, labels and annotations provided on, with or near the diagram to guide the reader's search for cues.

Propositional statements: Knowledge statements (used to provide possible 'answers' to questions or probes).

Proximity effect: Arrows grouped close together tend to form a unit. See Principle of Proximity.

Purpose of diagram: The intention of the diagram, specifically the functional aspects (opposed to content) of the diagram.

Reciprocity of cues: The ways in which features of the diagram influence each other (Beck, 1984).

Referents or participants: the two elements connected by an arrow to form a unit of communication.

Realistic displays /diagrams: Life-like and proportional representations of the whole organism. See Diagram types: Realistic for a more detailed description.

Relative discriminability: The visibility of a symbol or feature of a diagram because of its size in relation to other surrounding objects (Smith, 1979).

Representation: Something that stands for something else. A model of the thing it represents, whether an external representation e.g. maps, graphs, charts, diagrams, pictures, tables, organograms, displays, models, symbols and (text) etc. – used to explain and communicate, or an internal representation or mental model developed from mental operations and cognitive processes (Roth, 1986). 'A representational picture is any marking in which the real world content is spontaneously recognized by the uneducated eye' (Ittelson, 1996).

Salience: Describes visual prominence or how well a feature stands out relative to other features.

Schema(ta): Schemata, or patterns of association between elements of knowledge, represent information stored in memory structures schemata. Schemata therefore represent what an individual knows and forms the basis for integrating new information, filtering through these schemata (Gillespie, 1993). Schemata have been variously explained: 'A cognitive construct that organises information according to the manner in which it will be dealt.' 'A schema is a unit in human memory representing a functional package of knowledge' that functions 'as an active device of recognition' (Taconis *et al.*, 2001). A schema is a knowledge structure that captures regularities of objects and events (McNamara, 1994). 'Schemas reduce cognitive load by permitting us to ignore most of the information impinging on our senses' (Sweller & Chandler, 1994, page 187).

Semantic factors: Factors that allow interpretation of meaning. Relating to the meaning of words (Collins Dictionary, 2003).

Semi-guided probe: Some guidance was provided to the student by focussing attention on specific requirements, certain features or particular regions of, in this case, diagrams, but still allowing free-response answers.

Semiotic shift: A shift in emphasis from using text to using diagrams.

Short-term memory: This is a transitory state or intermediate phase in which a perceptual image is matched to information activated from long term memory (Roth, 1986; Paivio, 1991; Mayer & Anderson, 1992; Mayer *et al.*, 1995; Mayer, 2003).

Similarity effect: See Principle of Similarity: Arrows presented in similar style tend to be interpreted as a unit.

Simplicity: A diagram should deal with one concept and only provide the essential information needed for the reader to understand that concept (Thompson, 1994).

Situational dynamics: The interactions between units of information in a diagram to imply changes over a period of time. For example, the design of a static diagram may imply sequence over a period of time, similar to an animated diagram or series of diagrams.

Skills: Ability requiring expertise.

Strategy: An overall plan.

Spatial ability: 'Spatial ability is the ability to visualize, imagine, perceive, retain, recognize, reason or reproduce representations of objects in their correct proportions when they are depicted on paper, rotated in space, translated, juxtapositioned, projected, sectioned, reassembled, inverted, re-oriented and verbally described' (Rochford *et al.*, 1989).

Spatial contiguity: Textual and visual information should be presented together to assist integration and reduce visual search and minimise the split-attention effect (Mayer, 1997 and 2003).

Spatial frequency: Distance of arrows in a spatial organisation from each other.

Spatial organisation: The way in which the arrows are arranged to form patterns; the layout of the diagram (Gropper, 1970). Formats include:

Discrete format: Individual arrows linking two elements together e.g. as pointers or to communicate information.

Collective format: Grouped (two or more arrows per functional unit) arrows in various patterns or layouts

Combinational format: discrete and collective formats in one diagram.

Strategies:

a. Focussing strategies: Tests the relevance of a feature for interpreting the concept (Roth & Frisby, 1986).
b. Scanning strategies: Hypothetical rules are formulated consistent with the first positive piece of information (Roth & Frisby, 1986).
c. Learning strategies are activities that support successful learning, including 'behaviours and thoughts that learners engage in during learning and that are intended to influence the learner's encoding process.' 'Learning strategies are a schematic structure combining a sequence of specific learning activities that will be executed by the learner to gain new knowledge.' There are 'four main components: selection, acquisition, construction and integration' (Lewalter, 2003).
d. Elaboration strategies are 'learning techniques such as building connections between new information and prior knowledge or experiences'. These are 'crucial for deeper comprehension' (Lewalter, 2003).
e. Control strategies are 'learning techniques that aim at the planning or regulation of the further steps in learning' and 'refer to the control of the actual level of comprehension' (Lewalter, 2003).
f. Problem solving strategies are planned sequences of activities leading to a goal, the solution of the problem (Taconis *et al.*, 2001).

Stylised diagram: Manipulated representations often in the form of line drawings. See Diagram types: Stylised, for a more detailed description.

Surface-level reasoning: This level of processing describes the stages of perception and recognition of the surface or syntactic features of the diagram.

Symbolic representations: Such mental representations preserve information extrinsically, are abstract and amodal and form the principal basis of inference (McNamara, 1994).

Symmetry: Regular proportions used in the creation of patterns (Mathewson, 2005).

Synonymy: Arrows presented in similar style but cueing for different purposes (Pinto *et al.*, 2000).

Syntactic factors: The perceptual and physical attributes of a representation (e.g. diagram).

Syntactic emphasis: Presentation of features of the diagram in a prominent way in order to draw the reader's attention to them.

Think-aloud protocols (during interviews): The interviewee expresses his /her thinking verbally so that the interviewer can understand how the interviewee is interacting with the materials (Lewalter, 2003).

Thompson's guidelines of harmony: Thompson (1994) presented suggestions to promote diagram design. All parts of the diagram should relate and complement each other to portray a unified message.

Top-down processing: Processing from global configuration to local detail (global to local processing). Such processing is concept driven and uses stored knowledge of the properties of configurations (Roth & Frisby, 1986).

Unconscious: Without thought or awareness, automatic (Roth, 1986).

Understanding: Ability to apply what is learned to solve new problems (Mayer *et al.*, 1996), or 'the ability to categorize, to appreciate relationships between concepts, and to recognise implied ideas' (Reid, 1984). Understanding includes an awareness of the basic ideas and concepts and the ability to use that knowledge in new situations (Duit & Treagust, 1995).

Unintended (or unexpected) emergent properties: patterns that are perceived by the reader that were not intended by the designer. Unintended emergent properties usually emerge in inappropriately designed diagrams.

Units: 'The components of systems that cannot be reduced to smaller subunits and retain their identity and role (Mathewson, 2005, page 546).

Unit binding: The process by which the reader combines features perceived to belong together into a unit of information called a perceptual unit.

Unity: Components of a diagram placed so that they are read as a whole (Thompson, 1994).

Visual apprehension: Perception of the syntactic features of the diagram. See Perception (Kosslyn, 1989).

Verbal elements: Any configurations that resemble alphabetical or numerical symbols including punctuation marks and arbitrary scientific notation systems (Fleming, 1967).

Visual base: A Visual base (Mayer *et al.*, 1995) is formed when spatial skills are used to organise related arrows with their referents into functional groups. As a consequence of this organisation, surface level processing occurs resulting in a literal interpretation.

Visual communication: Using visual symbols to express ideas and convey meaning (Seels, 1994).

Visual literacy: Information processing skills and strategies (Fleming, 1979) and therefore competency in mental operations. Ferk & Vrtacnik (2003) cite Christopherson (1997) who defines a visually literate person as one who can interpret, understand and appreciate the meaning of visual messages, understand and use the principles of visual design, produce visual messages and use visual thinking to solve problems. The diagram user should therefore have the required cognitive, graphical and conceptual schemata. According to Seels (1994) visual literacy encompasses visual thinking, visual learning and visual communication, all of which have an internal focus.

Visual processing: Refers to 'perception and processing of external representations or of mental images. Processing proceeds according to the spatial characteristics of the information. Patterns and associations are formed using design features including colour, size, shape, and pattern (van Dusen *et al.*, 1999).

Visual thinking: 'Manipulating symbols representing elements of the internal and external environment by using imagery' (Seels, 1994).

Visual learning: Acquiring and constructing knowledge as a result of interaction with visual phenomena (Seels, 1994).

Visualisation: Hortin (1994) described visualisation as a process for thinking. See Visual literacy.

Working memory: According to Baddeley (1992), working memory is a conscious part of the brain that can process the image information (Johnstone, 2000) against information activated from long-term memory structures. Working memory includes the 'control processes' (Kosslyn, 1994) such as the rehearsal, coding, decision-making and retrieval strategies (Reed, 1988) that activate information in long-term memory and maintain short term-memory. Working memory will organise, contrast, compare, evaluate alternative choices (for problem solving), work on and integrate the information transferred from the perceptual stage of information processing (Reed, 1988; Winn, 1993; Kirschner, 2002), including visio-spatial interpretation (Kirschner, 2002). By activating both long and short term memory, a dynamic relationship (Kosslyn, 1994; Johnstone, 2000; Kirschner, 2002) is set up between them, allowing image maintenance during the process of reasoning (Kosslyn, 1994). These processes together constitute the cognitive strategies required during the process of deeper-level reasoning.

CHAPTER 1

INTRODUCTION: THE CONTEXT AND AIMS OF THE STUDY

Most schools use science textbooks as a source of visual displays (namely realistic displays and stylised and abstract diagrams) for the teaching and learning of sciences including biology. Realistic displays are life-like and proportional representations; stylised diagrams are highly specialised representational diagrams (Henderson, 1999); and abstract diagrams are non-representational diagrams (Lowe, 1986a) that depict non-spatial information as two-dimensional spatial organisations (Lowe, 1993b). Each has an important role to play in the teaching and learning of science including biology. In general terms, realistic representations show mainly (or only) structure, while stylised diagrams show structure, function or both. Abstract diagrams enhance aspects of structure or function as well as emphasise relationships between elements of the diagram.

Unlike realistic displays, which have been used for centuries to teach and learn biology, the introduction of stylised and abstract diagrams into biology textbooks is relatively recent. From about 1960, researchers have noted an increasing use of stylised and abstract diagram types in the scientific and technical fields (e.g. Lowe, 1994a) and in schools (e.g. Lowe, 1991), particularly for the teaching of school science subjects (e.g. Lowe, 1986; 1988a and 1987a; Chandler & Sweller, 1991; Hegarty, 1992). Furthermore, many biological models, such as the structure of DNA and the Krebs cycle, are now presented in the visual rather than the linguistic form (Perini, 2005). In fact, teaching and learning of biology now relies heavily on a range of diagram types to describe structural features, explain functions and elucidate processes occurring in organisms.

In order to accomplish their specific functions and communicate scientific and technical concepts, stylised and abstract diagrams often use distinct spatial arrangements (e.g. flow diagrams) and a diversity of visual presentation devices and techniques. Such presentation devices include a multitude of signs and symbols, including arrows, some of which have been discussed by various researchers (e.g. Lowe, 1986; 1988c and 1993b; Hill, 1988; Henderson, 1999; Jiminez-Valladares & Perales-Palacios, 2001; Ametller & Pinto, 2002). In fact, an overview of research literature (See Literature Review, Chapter 2) conducted in several domains including philosophy, art, linguistics, perceptual psychology, imagery theory and communication research (as suggested by Moore, 1994), as well as from cognitive science, psychology of learning and educational research (as suggested by Schnotz, 1993), shows extensive research in the field of visual literacy, particularly from the mid-1980's. Research findings are however, two-fold. On the one hand they show that stylised and abstract science diagrams can be facilitative and improve student understanding of scientific concepts (e.g. Mayer & Gallini, 1990; Winn *et al.,* 1991; Phillips & Quinn, 1993; Moore *et al.*, 1993; Mayer *et al.*, 1995; Sterner, 1998). On the other hand, however, there are warnings that the design of diagrams may be confusing (e.g. Lowe, 1986; Hunter *et al.*, 1987; Henderson, 1999) and may be a source of difficulties for students (e.g. Hill, 1988; Henderson, 1999; Hull, 2003).

Various articles, mostly in the fields of physics and chemistry, have been written on students' difficulties with arrow symbolism specifically. Some difficulties were attributed to the design of arrows (e.g. Henderson, 1999; Jiminez-Valdares & Perales-Palacios, 2001; Amettler & Pinto, 2002), while other research indicated that students might have difficulty processing arrow symbolism (e.g. Schollum, 1983; Lowe, 1986). However, despite their significance as specifiers of purpose and relationships and their integral role in directing meaning, there appears to be no rigorous study reported on the evaluation of the design of arrows used in diagrams, and on students' difficulties with the interpretation of arrows in scientific diagrams per se, let alone in biology diagrams used for teaching and learning at secondary-level.

Despite the significant use of arrows in diagrams it would appear, therefore, that the role of arrow symbolism in diagrams has been neglected. This dearth of research on the use of arrow symbolism in biology textbook diagrams could suggest that no such research is necessary. However, from my 30 years of experience of teaching biology to secondary-level students, I suspected that many students had problems interpreting arrows used for various purposes in diagrams. Moreover, the extent, source/s and nature of the difficulties experienced by these students were not clear. This convinced me that research into difficulties with arrow symbolism was not only indicated, but possibly long overdue. I therefore contend that there is a strong case for more extensive and in-depth research into issues pertaining to the use of arrow symbolism in biology diagrams at secondary-level.

To this end I hypothesised that: *Secondary-level students have difficulty with the use of arrow symbolism in biology diagrams.* To address this hypothesis and find out whether students have difficulty with the use of arrow symbolism in biology diagrams, several broad research questions were defined.

RESEARCH QUESTIONS

The following research questions were defined to find out whether students have difficulty with the use of arrow symbolism and, if so, what are the possible sources of difficulty. In line with the title of this thesis, the research questions are therefore designed to investigate both the appropriateness of arrow presentation in diagrams and student interpretations of arrow symbolism.

1. *How much of a problem is arrow symbolism in diagrams?*

2. *How effectively is arrow symbolism used in diagrams to promote the communication of intended ideas?*

3. *To what extent does the design of arrow symbolism in diagrams influence students' interpretation and difficulties?*

4. *How can the emerging empirical data and ideas from literature be combined to illustrate the process of interpretation of arrow symbolism?*

5. *What measures can be suggested for improving the use (presentation and interpretation) of arrow symbolism in biology diagrams?*

These five questions became the objectives of the investigation, as defined by the hypothesis, and the focus of the research protocol outlined in Figure 1.1 (page 4) and briefly discussed below. Each of the five research questions is addressed using specific methods best suited to the nature of information being investigated. The selected theoretical and methodological research frameworks used in this study are fully discussed in Chapter 3. Furthermore, to address each of these broad research questions, additional sub-questions are defined. These are detailed in the relevant chapters.

Research Question 1, '*How much of a problem is the use of arrow symbolism in biology diagrams?*' is addressed by first considering how arrow symbolism was used in biology textbook diagrams. To find out this information, a content analysis of all of the diagrams in several biology textbooks was conducted. The findings are reported in Chapter 4.

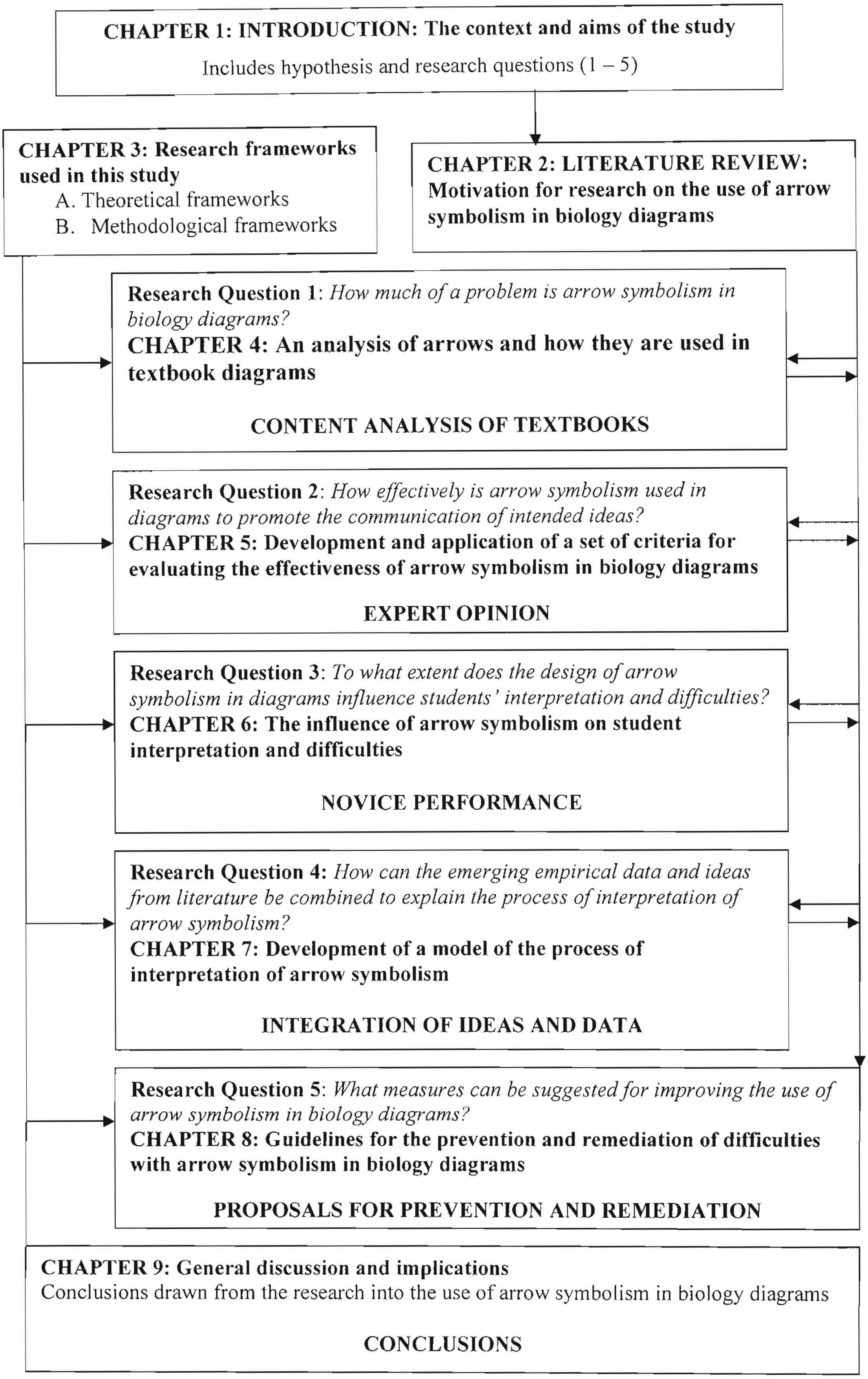


Figure 1.1 An outline of the research protocol for the investigation into the use of arrow symbolism in biology diagrams at secondary-level.

To fully investigate and evaluate the effectiveness of arrow design, as required by Research Question 2: '*How effectively is arrow symbolism used in diagrams to promote the communication of intended ideas?*' the author considered the broad parameters of the syntactic, semantic and pragmatic aspects of arrow symbolism used in diagrams (following the example of researchers such as Frisby (1986) and Kosslyn (1989)). To accomplish this, a set of criteria was developed based on ideas in the literature and from various categories of diagram users. These criteria were then used to evaluate a range of diagram types. This information, reported in Chapter 5, forms an experts' opinion of arrow presentation in diagrams.

In Chapter 6, Research Question 3: '*To what extent does the design of arrow symbolism in diagrams influence students' interpretation and difficulties?*' is addressed to obtain a novice (or student) perspective. This involved investigating student interpretations of arrow symbolism in order to ascertain the influence of arrow presentation during the process of interpretation of diagrams. Probing of students' processing skills and strategies would also provide information about the nature of difficulties experienced during the interpretation of arrows.

Not only does the author propose to investigate for difficulties, but also to synthesise the emerging data to explain the process of interpretation of arrow symbolism and highlight the possible sources of difficulty. To this end, the empirical data obtained from the content analysis of textbook diagrams (Chapter 4), experts' opinions about arrow symbolism (Chapter 5) and students' interpretations of arrow symbolism in diagrams informed the development of a visual model to show how students process arrow symbolism used in diagrams. Chapter 7 therefore addresses the Research Question 4: '*How can the emerging empirical data and ideas from literature be combined to illustrate the process of interpretation of arrow symbolism?*'

In furthering this research, I also offer guidelines in chapter 8 for the prevention and remediation of difficulties. Suggestions are also made for the dissemination of the information to all role players involved in the design and use of arrow symbolism. The implications of this research, and therefore some suggestions toward Research Question 5: '*What measures can be suggested for improving the use of arrow symbolism in biology diagrams?*' are addressed.

Since not all fields pertaining to the focus of this research, and sometimes not even researchers within the same field, have defined terminology used to describe the processing of diagrammatic information in the same way, it was considered crucial that I present a comprehensive Glossary of terms (See page xxiii). This, hopefully, will effectively and fully familiarise the reader with the considerable amount of jargon used in the various fields. In particular the reader should note that, for the purposes of this thesis, 'perception' has been defined as a process of observation (in accordance with the views of Kosslyn (1989) and Ittelson (1996) as motivated in the Glossary), including the stages of search (including detection), pattern recognition, selection of data and the organisation of that data into patterns resulting in relatively temporary representations of the syntactic dimension of the diagram constructed in short term memory (Roth, 1986). Thus the stage of perception is restricted to interpretation of the surface or syntactic features of the diagram. Based on this definition, the author divided the processes used during interpretation into the two broad categories of surface-level (S-L) processing of the perceptual features of the diagram, and deeper-level (D-L) reasoning which includes the integrative stages of information processing (Chi *et al.*, 1981).

To keep the argument focused, the various probes (questions requiring written or verbal responses) for Chapter 6 have been included as appendices (pages 233 - 251) rather than in the body of the text. To fully appreciate the diverse nature of this investigation into the presentation and interpretation of arrow symbolism in biology diagrams at secondary-level, much cross-referencing of information will be required of the reader.

CHAPTER 2

LITERATURE REVIEW: MOTIVATION FOR RESEARCH ON THE USE OF ARROW SYMBOLISM IN BIOLOGY DIAGRAMS

Using ideas from the literature (e.g. Hortin, 1994; Messaris, 1994; Stern & Robinson, 1994; Ittelson, 1996), and from Anderson, T. R. (pers. comm., 2003), visualization was defined as the process of interpretation of an external representation (ER) such as a diagram, within the reader's frame of reference (or existing schemata) to form an internal representation (or mental model), which may or may not in turn be expressed in some external form. According to this definition, therefore, a holistic investigation of diagrams demands that both the presentation of the diagram and of the diagram features such as arrow symbolism (e.g. Hardin, 1995; MacEachren, 1995; Kress & van Leeuwen, 1996), is considered, as well as how students interpret diagrams (e.g. Lowe, 1987b; 1991 and 1993a; Winn, 1993; Scaife & Rogers, 1996; Blackwell & Engelhardt, 2002; Mayer, 2003) and express them (e.g. Lowe, 1987a; 1993a) within the parameters of their mental models. In other words, realisation of the potential of a diagram depends on both the quality of the design and on the users' schemata (Dwyer, 1970; Lowe, 1988a; 1991 and 1993c; Ittelson, 1996).

Based on this definition, a study of diagrams should consider both the presentation of diagrams (including the symbolism used in them) and the interpretation of the diagram (including the features of the diagram) by the reader. In the context of this study, to find out whether students do in fact have difficulties with the use of arrow symbolism, it is necessary to evaluate the effectiveness of arrow presentation and study how the design (mode of presentation) influences secondary-level students' interpretation of arrow symbolism used in biology diagrams. To frame the review of literature the following series of questions was posed:

a. What evidence is presented in the literature about the use of diagrams and particularly of arrow symbolism in diagrams? (addressed in Section 2.1, page 8)
b. What guidelines are given in the literature for the design of diagrams and of the symbolism used in diagrams to effectively promote communication of the intended ideas? (addressed in Section 2.2, page 11)
c. Does the design of diagrams and of arrow symbolism used in diagrams influence student interpretation and cause difficulties? (addressed in Section 2.3, page 12)

d. To what extent has research focused on the use of arrow symbolism and particularly on arrow symbolism used in biology diagrams at school level? (addressed in Section 2.4, page 17)

e. Based on the review of literature, is it important to research the use of arrow symbolism in biology diagrams at secondary-level? (addressed in Section 2.5, page 18)

2.1 The use of diagrams and arrow symbolism in biology diagrams

The increasing use of diagrams as communication tools

Until the mid 20th century, most books, including textbooks, tended to employ realistic drawings (defined in the Glossary) that do not rely on symbolism for communication. Subsequently, with a more functional approach to teaching (where the application of knowledge became more important than the acquisition of facts) and the introduction of programmed instruction and response-orientated learning (Gropper, 1970), the layout of information (spatial organisations) became more significant in order to reflect the relationships between the elements of the stimulus materials. From the mid-1960's explanatory tools such as stylised and abstract diagrams (see Glossary), therefore, became increasingly more important in instructional materials and learning resources. Despite interest in diagram research being sparked by Gropper's (1963) article: 'Why is a picture worth a thousand words?', Holliday *et al.* noted in 1977 (Holliday *et al.*, 1977) that diagram research was still in its infancy. In fact, according to Guri-Rozenblit (1988a), right up until the mid-1980's most research on visuals dealt with pictures with few studies conducted on the effectiveness of stylised and abstract diagrams. However, the greater use of stylised and abstract diagrams, including in science subjects at school level, inevitably led to a surge of interest in the use of these types of diagrams over the next three decades (e.g. Krampen, 1965; Fleming, 1967; 1977; 1979 and 1987; Holliday, 1976; Duchastel, 1978; Levie & Lentz, 1982; Geva, 1983; Sless, 1984; Lowe, 1988a; 1991; 1993c; 1994a; 1994b; 1996 and 1997; Evans *et al.*, 1987; Mayer & Gallini, 1990; Bennett & Flach, 1992; Mayer & Anderson, 1992; Hardin, 1993; Levin & Mayer, 1993; Winn, 1993; Fredette, 1994; Sewell, 1994; Mayer *et al.*, 1995; Kress & van Leeuwen, 1996; Mayer *et al.*, 1996; Henderson, 1999; Pinto *et al.*, 2000; Ametller & Pinto, 2002; Pinto & Ametller, 2002; Roth, 2002). According to Lowe (1991), Kress & van Leeuwen (1996), Pinto *et al.* (2000) and other researchers, this shift toward the use of explanatory diagrams accelerated in the 1990's as a result of the rapid advances in technology that allowed vast amounts of increasingly complex information to be generated. Tversky & Morrison (2002) also suggested that the proliferation of diagrams could be attributed to the increasing need for communication between people who do not share the same spoken language. In fact, Fisher *et al.* (2000) claimed that the success of the information and communication age could be attributed to the use of diagrams.

This greater dependence on stylised and abstract diagrams would in itself suggest that it is important to understand graphic principles guiding the construction and interpretation of diagrams. Such knowledge would ensure that explanatory diagrams used as instructional materials were educationally sound.

The use of symbolism, including arrow symbolism, in stylised and abstract diagrams

Stylised and abstract diagrams use particular spatial arrangements (e.g. flow diagrams) and a diversity of visual presentation devices and techniques, some of which are described by Wheeler & Hill (1990), Lowe (1993b) and Henderson (1999), including symbolism, to communicate scientific and technical concepts (e.g. Evans *et al.*, 1987; Eltinge & Roberts, 1993; Gillespie, 1993; MacEachren, 1995). In fact, as early as 1965 Krampen (page 3) wrote: 'Thus in graphic communication, the application of signs and symbols has become increasingly important'. Arrows are one category of the multitude of signs and symbolism used in stylised and abstract diagrams to convey particular ideas. Many researchers have discussed their impact on interpretation of diagrams (e.g. Fletcher, 1971; Reid & Miller, 1980; Waller, 1981; Winn & Holliday, 1981; Dutkiewicz, 1982; Schollum, 1983; Lowe, 1986; 1988c and 1993b; Hunter *et al.*, 1987; Hill, 1988; Phillips & Quin, 1993; Lemke, 1998; Henderson, 1999; Jiminez-Valladares & Perales-Palacios, 2001; Ametller & Pinto, 2002; Perini, 2005). From this literature, it is clear that the intention of arrow symbolism is not always clearly understood. This suggests that the use of arrows in diagrams, including their design or mode of presentation (both style and spatial organisation of arrows) and interpretation, should be investigated.

Warnings about the design of stylised and abstract diagrams including of arrow symbolism

In 1965 Krampen (page 3) made a plea for effective communication with diagrams by stating: 'Effective graphic communication should leave no room for different interpretations. Its function is to communicate a message in the most direct way.' Subsequently Lowe (1988c and 1993b) reinforced these sentiments by emphasising that conventions and symbols are introduced to help clarify subject matter. Despite these and other similar views by various researchers, there are many cautionary notes in the literature about the inappropriate and possibly confusing design of stylised and abstract diagrams (e.g. Alesandrini, 1984; Joshua, 1984; Lowe, 1986; 1993a and 1993b; Hunter *et al.*, 1987; Henderson, 1999; Hull, 2003). Hunter *et al.* (1987, page 118) summed up this view by stating: Diagrams 'may be ambiguous, incomplete, or imprecise, or they may be depicted at an inappropriate level of abstraction'. In fact, various researchers have shown that information in stylised and abstract diagrams may be extensively manipulated (Wheeler & Hill, 1990; Henderson, 1999), over-simplified (Lowe, 1986 and 1993b; Henderson, 1999) and transformed (Lowe, 1987a; 1988a; 1988c and 1993b) for various effects, including for two dimensional and sectional viewing (Lowe, 1988a; 1991 and 1993b; Sanders, 1995), and therefore may bear little resemblance to the information portrayed (Lowe, 1997).

Several researchers (e.g. Fleming, 1987; Hill, 1988; Kosslyn, 1989; Mayer & Gallini, 1990; Reid, 1990a; Wheeler & Hill, 1990; Winn, 1993; Lowe, 1996) have warned that the construction of diagrams, and of the arrow symbolism specifically (e.g. Schollum, 1983; Hardin, 1993 and 1995; Kress & van Leeuwen, 1996; Henderson, 1999), must be instructively effective and relevant to the representation of the information or content and relevant to the task. A shortfall in any one or more of these areas of design may imply an unintentional meaning and result in students showing difficulties with the interpretation of diagrams (e.g. Hill, 1988; Hull *et al.*, 2002; Schönborn *et al.*, 2002a; Hull, 2003; Schönborn & Anderson, 2003 and 2004, Schönborn, 2005). Indeed, Hill (1988) suggested that a number of diagrams used in school textbooks might even mislead naïve readers. It is therefore imperative that diagrams and the symbolism, including arrows, used in them is appropriately presented (Kindfield, 1993/1994; Schnotz & Bannert, 2003) as poor design may transmit wrong ideas (Pinto & Ametller, 2002) and lay the foundation for misconceptions.

From this information about the use of diagrams and of arrow symbolism, it was concluded that it is important to evaluate the design of diagrams, and their constituent arrow symbolism, before they are used as teaching and learning tools. For evaluations to be effective and comprehensive, a set of detailed guidelines is required. Further literature was therefore reviewed for guidelines on the design of diagrams and for arrow symbolism specifically.

2.2 Guidelines for the design of diagrams and arrow symbolism

Suggestions about spatial organisations of diagrams

The Gestalt Principles (see Glossary), noted by many researchers (e.g. Goldsmith, 1987; Kosslyn, 1989; MacEachren, 1995; Kress & van Leeuwen, 1996), describe how certain spatial organisations (or groupings) determine how objects are perceived. Included in these principles are the conditions required for adequate figure-ground differentiation (e.g. Rock & Palmer, 1990). From these principles, other laws, principles and guidelines for diagram design developed, such as the Principle of Pragnanz (see Glossary). There are several sets of broad guidelines in the literature for constructing diagrams in general (e.g. Gropper, 1970; Szlichcinski, 1979; Beck, 1984; Fleming, 1987; Lowe, 1988a; Lowe, 1991 and 1993b; Winn & Solomon, 1993; Scaife & Rogers, 1996), some of which stress the impact of design on the meaning of the diagram (e.g. Winn, 1993).

Although few of the above mentioned guidelines are specific to arrow symbolism, their value may, by implication, be important especially as arrows are inextricably bound with their referents (see Glossary) in the context of the diagram (Szlichcinski, 1979; Blackwell & Engelhardt, 2002) and therefore form part of the overall design. For example, guidelines such as the Principles of Perceptual Organisation (e.g. Kosslyn, 1989; see Glossary) are applicable to the use of arrow symbolism, as arrows are often arranged in groupings or patterns for particular purposes and meanings.

Suggestions about styles and spatial organisations of arrows specifically

The literature also contains various suggestions about the suitability of various arrow styles and spatial organisations for the type of information being communicated (e.g. Geva, 1983; Hardin, 1993 and 1995; Kress & van Leeuwen, 1996), although again not for biology diagrams specifically. For example, Kress & van Leeuwen (1996) give examples of the intentions of some variations in style, including that a change in arrow head size suggests more or less prominence; that an arrow head placed in the middle of the line diminishes the strong sense of impacting usually suggested by arrow symbolism, and that bolder arrows amplify their intended effect. However, such suggestions are given piece-meal and there appears to be no comprehensive set of guidelines or criteria for the design of style and spatial organisation or of evaluation of arrow symbolism specifically, let alone a set of conventions governing arrow presentation. Therefore, to fully investigate the design of both the syntactic and semantic aspects (both are important according to Brody (1984), Frisby (1986), Goldsmith (1987), Kosslyn (1989), Lowe (1988a; 1993c) and Ittelson (1996)) of arrow style and spatial organisation in diagrams the author needed to develop a set of guidelines or criteria based on the principles mentioned above and other relevant literature.

Such a set of criteria would constitute the expert view of arrow design and provide ideas on how experts may interpret arrow symbolism in diagrams. However, it cannot be assumed that student perceptions will be the same as experts. In fact, there is evidence to show that students' perceptions may differ from those of designers (Wheeler & Hill, 1990), educators (Henderson, 1999) and each other (Mayer, 1993). As this study aims to investigate arrow symbolism in biology textbooks at secondary-level (Grades 11 and 12), the investigations should be directed at students who are usually novices at using diagrams. To find out how students cope with the interpretation of diagrams and arrow symbolism used in diagrams, the author searched the literature for research findings about the influence of diagram design on student interpretation and difficulties.

2.3 The influence of diagram design and arrow symbolism on student interpretation and difficulties

On-going and extensive research on diagrams over the last two or more decades has provided a wealth of evidence, both positive and negative, about the influence of diagrams in teaching and learning.

Findings suggesting that diagrams are facilitative

Extensive research has shown that diagrams can improve student motivation and understanding of concepts (their proponents include Rigney & Lutz, 1976; Duchastel, 1978; Szlichcinski, 1979; Winn & Holliday, 1981; Levie & Lentz, 1982; Brody, 1984; Reid, 1984 and 1990a; Kirby & Cantwell, 1985; Hunter *et al.*, 1987; Fleming, 1987; Larkin & Simon, 1987; Constable *et al.*, 1988; Mayer & Gallini, 1990; Winn *et al.*, 1991; Gillespie, 1993; Levin & Mayer, 1993; Moore *et al.*, 1993; Winn & Solomon, 1993; Mayer *et al.*, 1995; Sterner, 1998; Lewalter, 2003; Mayer, 2003; Schnotz & Bannert, 2003). In addition, diagrams help students to integrate new knowledge into existing knowledge structures (Schnotz, 1993); facilitate recall and retention of information (Guri-Rozenblit, 1988a and 1988b; Levin &

Mayer, 1993; Lewalter, 2003); and foster processes involved with thinking and problem-solving (Mayer, 1989; Mayer & Gallini, 1990; Winn *et al.*, 1991; Kindfield, 1993/1994). Furthermore, Perini (2005) proposed that the visual format of diagrams used to explain hypotheses can make complex information comprehensible and can contribute to the explanatory role.

Many of the above facilitative effects were attributed to particular design features of diagrams, including of arrow symbolism. For example, highlighting important ideas and relevant information using various techniques (including using arrows) and removing extraneous information, focuses students' attention (Mayer, 1989; Winn *et al.*, 1991; Kindfield, 1993/1994), reduces load on working memory (Chandler & Sweller, 1991) and makes diagrams easier to search than text (Larkin & Simon, 1987). Spatial layouts, often incorporating arrows as links, show relations between concepts and between the objects that they illustrate (Winn & Holliday, 1981; Larkin & Simon, 1987; Winn, 1991; Winn *et al.*, 1991; Kindfield, 1993/1994) allowing clarity and organisation of materials (Gropper, 1970; Jonassen & Hawk, 1984). Much research has also pointed to the advantages of presenting diagrams and text (in the form of labels, annotations or accompanying paragraphs) contiguously (e.g. Royer & Cable, 1976; Holliday *et al.*, 1977; Dean & Kulhavy, 1981; Levie & Lentz, 1982; Geva, 1983; Mayer *et al.*, 1995; Mayer & Anderson, 1992; Lewalter, 2003; Mayer, 2003; Schnotz & Bannert, 2003), according to the dual coding theory (Paivio, 1986; Clark & Paivio, 1991) and elaborations of that theory (Mayer, 1997 and 2003). Text would, no doubt, help the reader to understand the meaning of the symbolism and arrows used in the diagram.

Particular forms of diagrams, some of which use arrow symbolism, have also been mentioned as helpful aids to teaching and learning. For example, Kammann (1975), Rasco *et al.* (1975) and Phillips & Quinn (1993) noted the facilitative effects of flow charts. Furthermore, Cullen (1990), Wallace & Mintzes (1990), Novak (1990), Pendley *et al.* (1994), Plotnick (1997), Pinto & Howard (1997), Peuckert & Fischler (1999) and others promoted concept mapping, a modified form of flow chart construction that uses linking lines or sometimes arrows.

This wealth of literature either influenced or supported the concept of the picture superiority effect (PSE; see Glossary) explained by Reid (1984 and 1990a) and advocated by many other researchers. Based on this information, it would seem that design features of diagrams do aid interpretation. However not all authors confirm the use of diagrams unconditionally.

Findings suggesting that students may have difficulties interpreting diagrams

It may be assumed that the more extensive use of diagrams has exposed students to a range of visual presentation techniques, including arrow symbolism and different types of diagrams. However, it cannot be assumed that familiarity necessarily equates with visual literacy. Indeed, there have been indications that diagrams may not fulfil their intended role in all instances and therefore may not be as facilitative as the discussion so far suggests. In fact, Levin & Mayer (1993) went as far as claiming that graphics did not live up to their potential. Furthermore, some researchers (e.g. Constable *et al.*, 1988; Lowe, 1991; Kindfield, 1993/1994; Mayer, 1993; Mayer *et al.*, 1995) have proposed that diagrams, especially cognitively demanding abstract diagrams, show no obvious instructional purpose and might serve little more than an attentional role. Reid *et al.* (1983) suggested that diagrams might enhance recognition, but not comprehension, while Glenberg & Langston (1992) argued that diagrams might only sometimes facilitate motivation and retention of information by the student. Many researchers (e.g. Holliday *et al.*, 1977; Reid & Beveridge, 1986 and 1990; Winn & Sutherland, 1989; Reid, 1990b; Levin & Mayer, 1993; Lowe, 1993a; 1994 and 1996) found that the advantage of diagrams depended on the ability of the student, favouring the more able. In fact, Lowe (1987b), Hortin (1994) and others have cautioned that visual literacy demands more than just 'reading' the diagram as students need to make decisions about its broad context and purpose, based on the meaning of the various elements in the diagram, and on the relationships between them (Hill, 1988; Wheeler & Hill, 1990). As arrows often cue relationships in diagrams, inadequate understanding of the intention of arrows could therefore be a source of this difficulty.

Although not explicitly expressed, most of the above literature sources imply that difficulties with interpretation of diagrams may depend on the students' conceptual, cognitive and graphical schemata. To adequately interpret diagrams, students should have prior knowledge of the context of the diagram (e.g. Dwyer, 1970; Lohse *et al.*, 1991) in order to anticipate and search for information (Lowe, 1996) and have the required level of cognitive ability for the task (Lowe, 1986 and 1991), including being able to cope with various conventions used for different purposes (Henderson, 1999). In addition, students should have a sound knowledge and understanding of graphical (design) principles (e.g. Lohse *et al.*, 1991; Lowe, 1999 and

2003) including previous experience with various types of visual resources (Barlex & Carre, 1985). Although it would appear from the literature that all three schemata can together, or separately, influence interpretation of the diagram, the way students interpret design features of diagrams or symbolism is of particular significance to this study.

Possible influences of design features of diagrams on interpretation

Our current understanding of the way graphic design affects interpretation of diagrams has been profoundly influenced by the ideas of many researchers (e.g. Fleming, 1987; Goldsmith, 1987; Kosslyn, 1989; Lowe, 1989 and 1997; Bennett & Flach, 1992; Hardin, 1993 and 1995; Thompson, 1994; MacEachren, 1995). For example, salient features (see salience in Glossary) influence the reader's attention (Barlex & Carré, 1985; Winn, 1993) during the stage of visual apprehension (Kosslyn, 1989). Groups of symbols or parts of diagrams may be attended to simultaneously (Winn *et al.*, 1991; Bennett & Flach, 1992) to form entities as described by the Principles of Perceptual Organisation (e.g. Kosslyn, 1989; MacEachren, 1995; Kress & van Leeuwen, 1996). Such configurations occur as people first seek out forms that are most convenient to find or discern (Roth & Frisby, 1986; Winn, 1993) and, during the process of unit binding or chunking (Egan & Schwartz, 1979; Lowe, 1989), mentally assemble the separate parts of a pattern by matching them to patterns in memory (Finke, 1990). In this way cohesive units of information or perceptual units are formed (Szlichcinski, 1979; Winn, 1993; Songer & Mintzes, 1994; Stern & Robinson, 1994; Henderson, 1999). For example in Figure 2.1 below, the four lines in Diagram A are accessed together forming the familiar, single unit, 'square' shape, whereas the four separated lines (Diagram B), grouped in an unfamiliar pattern, are seen as unrelated and tend to draw the eye outward.

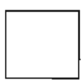
A.  B. 

Figure 2.1 Diagrams to illustrate grouping of information to form perceptual units.

The same Principle of Perceptual Organisation (Kosslyn, 1989) underpins several sub-categories of perceptual grouping. For example, interpretation of chain and network (e.g. hierarchical) spatial organisations such as a row of arrows: (→ → → →) as a continuous line, complies with the Principle of Continuity (Kosslyn, 1989). Similar features (e.g. shape, colour, size, function, quantity, direction) will, according to the Principle of Similarity, tend to be grouped together and objects, or arrows, perceived as different, will be separated

(Fleming, 1987). For example: !!!OOO, although a single group, is seen as 2 units. The Principle of Proximity (Kosslyn, 1989; Winn *et al.*, 1991; Stern & Robinson, 1994) states that marks (such as arrows) near each other tend to be grouped to form discrete units of focus within the diagram. For example, XXX XXX is perceived as two groups and: XX XX XX, as three groups. The parts that are grouped are usually physically close and configure to make recognisable shapes (such as a triangle), or other identifiable unit.

The patterns that are perceived, termed the emergent properties (see Glossary), therefore depend on the way that the features of the diagram are arranged. Therefore, the properties of diagrams (such as those listed by Winn, 1993) have an influence on the way the information in them is processed. Diagrams using poorly designed patterns of arrows may create unexpected or unintended emergent patterns (Roth & Frisby, 1986; Finke, 1990; Winn, 1993) that could negatively influence the interpretation of the diagram. Thus to ensure the intentions of diagrams are clear to the students, presentations of arrow symbolism should be consistent with these principles. This information again indicates that symbolism presented in diagrams should be evaluated before the diagram is used for teaching or learning to ensure that the diagrams are in fact, consistent with these principles and therefore perceptually sound. Moreover, as not all students have the same schemata, and certainly not the same level of sophistication of schemata as experts, student interpretations of the symbolism should be investigated to ensure that what is perceived is what is intended. In this way, potential difficulties specifically relating to the presentation and interpretation of arrow symbolism may be detected.

Findings suggesting that students have difficulty with arrow symbolism specifically

The literature contains relatively few reports on student difficulties with interpretation of arrow symbolism specifically. Some evidence links particular designs of arrow symbolism to possible difficulties. For example, Szlichcinski (1979) suggested that students might have difficulty interpreting arrows if the positioning and dimensions of arrows showing movement were inaccurate. Dutkiewicz (1982) expressed concern that a single arrow shown in a formula may incorrectly imply uni-directional reactions. Jiminez-Valladares & Perales-Palacios (2001) described student difficulties with the design of arrows used as vectors. Several authors also noted that confusion could result when similarly styled arrows are used for different purposes (termed synonymy) or differently styled arrows for the same purpose (polysemy) (e.g. Henderson, 1999; Pinto *et al.*, 2000; Ametller & Pinto, 2002). However, other research referred to the processing of arrow symbolism in diagrams. For example, Schollum (1983), in addition to noting some of the above difficulties, reported that students equate arrows with movement. Barman & Mayer (1994) and Barman *et al.* (1995) studied and reported on difficulties with the use of arrows in food chains and webs. Lowe (1986) noted that novices might not process arrows effectively. Such information indicates that it is important to consider not only presentation, but also interpretation of arrow symbolism in diagrams.

2.4 The use of arrow symbolism in biology diagrams at school level

Some research has shown that students may experience difficulties with diagrams used in schools to teach science (e.g. Winn & Holliday, 1981; Schollum, 1983; Hegarty, 1992; Henderson, 1999; Ametller & Pinto, 2002), including biology (e.g. Sanders, 1995; Sanders & Khanyane, 2002; Perini, 2005). However, Reid & Miller (1980) suggest that designers seldom appear to consider the readability of diagrams, especially the effectiveness of stylised diagrams, although Eltinge & Roberts (1993) and Ametller & Pinto (2002) claim that they feature prominently in textbooks for various purposes. In fact, reports on the analysis of textbooks consistently either ignore, or communicate a cursory and superficial analysis of, the presentation and readability of diagrams as evidenced in the analyses of Gould (1977), Johnston (1985) and Abimbolo & Baba (1996). Holliday (1990) and Leonard & Penick (1993) list diagrams as an important consideration when evaluating textbooks, but do not draw attention to the use of symbolism in the diagrams, let alone to the use of arrows. Research into diagrams used in resource materials at school level is therefore strongly indicated.

Many researchers including Winn (1993), Hortin (1994) and Ametller & Pinto (2002) suggest that the trend toward the greater use of stylised and abstract diagrams in textbooks demands a high level of visual literacy if diagrams are to be interpreted as intended. This in turn suggests that visual literacy should form an integral part of students' education (Reid & Miller, 1980; Lowe, 2000; Roth, 2002). However, in the opinion of Lowe (1988a), Chauvet *et al.* (1999) and Pinto *et al.* (2000), educators are not very aware of difficulties that students may have with interpretation of diagrams, let alone with the use of arrows specifically. If this is the case, research could provide descriptions of difficulties substantiated by empirical data. Educators as well as students could then be instructed about diagram issues followed, if necessary, by customized remediation.

In conclusion, despite a wide diversity of research into the field of visual literacy, few studies appear to have used a multi-faceted approach to investigate diagrams, and certainly not of arrow symbolism used in diagrams. Notable exceptions include the investigations undertaken by the Science Teacher Training in an Information Society (STTIS) consortium (Pinto *et al.*, 2000). Although they did describe the diagrams used in their particular study, they did not, or did not report on, evaluations of diagram design according to pre-determined and defined criteria based on experts' opinions. Evaluations of the diagram could therefore be considered subjective. Although the findings of some of their and other studies revealed difficulties with interpretation of diagrams using arrow symbolism as a design feature, the author did not encounter any studies specifically on the design of arrow symbolism in biology diagrams at school level. This strongly suggests the need for a comprehensive study on the following issues:

1. Evaluating diagrams (and arrow symbolism) for potential problems using pre-determined criteria;
2. Investigating how students interpret diagrams and arrow symbolism, including describing difficulties and substantiating difficulties with empirical data;
3. Explicitly linking students' difficulties to design features (including arrow symbolism).

2.5 Importance of further research into the use of arrow symbolism in biology diagrams at secondary-level

The above extensive review of the literature has revealed that:

1. There is ample evidence for the fact that the use of stylised and abstract diagrams (some of which use arrow symbolism) as instructional tools has increased dramatically over the last few decades. Reports have provided much evidence supporting the use of diagrams, but there are also warnings that they do not always live up to expectations. From this, it can be concluded that diagram design should be evaluated to ascertain possible sources of difficulties.

2. The establishment of guidelines for the design of diagrams and constituent symbolism is essential to effectively promote the communication of the intended ideas. However, there is no comprehensive and inclusive set of criteria for the evaluation of arrow symbolism specifically. Such a set of criteria should be developed to objectively evaluate arrow symbolism used in diagrams.

3. Although diagrams have proved facilitative in certain circumstances, students may have difficulty interpreting them, including arrow symbolism used in them. Relatively few studies show how arrow symbolism affects interpretation. Fewer still refer to arrows used in biology diagrams. In fact, there appears to be no research using comprehensive methods on the use of arrow symbolism in biology diagrams at school level. Thus, clearly, the effect of arrow design on student interpretation should be further investigated.

4. A study of arrow symbolism in biology diagrams at school level is not only indicated by the currently available literature, but also strongly advised.

2.6 CONCLUSIONS

Stylised and abstract diagrams that use arrow symbolism have become increasing important in the teaching and learning of science subjects at school level in recent times. As arrows specify relationships in diagrams, satisfactory interpretation of arrows used in diagrams is integral to understanding the intention of diagrams. Studies on the use of arrows in diagrams have been reported in the literature. However, there appears to be no comprehensive and rigorous study reported on the evaluation of the design of arrows used in diagrams, and on difficulties with the use of arrows in biology diagrams used for teaching and learning at secondary-level, the focus of the present study. Thus based on this literature review, as well as on the author's own teaching experience, the author contends that there is a strong case for more extensive and in-depth research into a wide range of issues pertaining to the use of arrow symbolism in biology diagrams at secondary-level. The study should therefore be pursued to find out whether secondary-level students have difficulty with the use of arrow symbolism in biology diagrams. Studies aimed at further strengthening this case for research on biology diagrams specifically is presented in Chapter 4.

CHAPTER 3
RESEARCH FRAMEWORKS USED IN THIS STUDY

Winberg (1997) describes a research paradigm as 'the collective set of attitudes, values, beliefs, procedures and techniques that create a framework of understanding through which theoretical explanations are formed.' The research paradigm therefore provides for both the theoretical frameworks (explained in Section 3.1, page 20) that underpin the study and show the standpoint of the researcher in relation to the study (Sanders, 1993), and the methodological frameworks or methods (explained in Section 3.2, page 25) used to investigate the research questions presented in Chapter 1 (page 1), namely:

1. *How much of a problem is arrow symbolism in diagrams?*
2. *How effectively is arrow symbolism used in diagrams to promote the communication of intended ideas?*
3. *To what extent does the design of arrow symbolism in diagrams influence students' interpretation and difficulties?*
4. *How can the emerging empirical data and ideas from literature be combined to illustrate the process of interpretation of arrow symbolism?*
5. *What measures can be suggested for improving the use of arrow symbolism in biology diagrams?*

3.1 THEORETICAL FRAMEWORK

Our investigation into the use of arrow symbolism in biology diagrams was framed by Schönborn's (2005) model of the factors required for interpretation of diagrams and grounded in the theory of constructivism.

3.1.1 Model of factors affecting interpretation of diagrams (Schönborn *et al.*, 2002b; Schönborn, 2005)

To be comprehensive, the investigation needed to consider all of the factors that may interact during interpretation of arrows in diagrams. The model of factors affecting interpretation of diagrams developed by Schönborn and Anderson (Schönborn, 2005) was therefore used as the main reference for this study. This model suggests three major factors affecting ability to interpret a diagram, namely:

a. Students' conceptual or prior knowledge of the concepts (C factor) of relevance to the external representation (ER),

b. Students' reasoning ability for interpreting the diagram (R factor),

c. The mode of representation or nature of the diagram (M factor).

Schönborn and Anderson (Schönborn, 2005) explain that during the process of interpretation, none of these factors is exclusive. For example, to make sense of the diagram students need to simultaneously access, select, retrieve and use information about the mode of representation (Interactive factor R-M) using their conceptual knowledge (R-C) to interpret the content represented in the diagram (C-M). Therefore to successfully interpret the diagram the student needs to integrate the various cues and therefore engage all of these factors (C-R-M) - hence the interactive nature of the model developed by Schönborn and Anderson (Schönborn, 2005) depicts as a Venn Diagram. This model suggests that the same factors will be applicable to any external representation and therefore also to the interpretation of arrow symbolism used in diagrams, the focus of this study.

Application of the model (Schönborn, 2005) to this study

The primary objectives of this research were to investigate the following:

The effectiveness of the various modes of presentation of arrow symbolism in diagrams (M factor), addressed by Research Questions 1 and 2 (defined in Chapter 1, 3 and detailed above);

The influence of arrow design on the way that students use arrows in diagrams (R factor), addressed by Research Question 3;

A method, such as a model, of combining the empirical data on the presentation (M factor) and interpretation (R factor) of arrow symbolism within each student's prior knowledge (C), to illustrate the process of interpretation (including C-M, R-C and R-M factors) as applicable to arrow symbolism, addressed by Research question 4; and

What measures /guidelines can be introduced, in terms of all three factors (C-R-M), to promote effective use of arrow symbolism, addressed by Research Question 5.

Therefore this study not only incorporated the M, R and C factors suggested by Schönborn and Anderson, but was also framed by the interactive model of these factors (Schönborn, 2005).

Table 3.1 (page 22) shows how the various interacting factors of this model (Schönborn, 2005) informed the research questions and consequently each stage of the investigation (Chapters 4 – 6). As it framed my thinking, it also informed the development of the model presented in Chapter 7 to explain the process of interpretation of arrows and guidelines for improving arrow use (Chapter 8).

Table 3.1 The influence of the model of interactive factors (Schönborn, 2005) on the investigations in terms of the stated research questions (Chapter 1).

Research question	Chapter	Context of influence	Area of investigation influenced by the interactive factors for interpretation of diagrams (Schönborn, 2005)
1	4	Diversity of symbolism	Content analysis of diagrams for diversity of mode of presentation (M factor)
2	5	Development of criteria	To evaluate the modes of presentation of arrow symbolism (M factor)
3	6	Probing student interpretations	Probing of students' interpretations of arrow symbolism used in biology diagrams (R factor) to find out about student difficulties
4	7	Development of model	Levels to represent the mode of presentation (M), reasoning strategies of the students (R) and prior knowledge of students (C) were included in the model of the process of interpretation of arrow symbolism.
5	8	Development of guidelines for improving arrow use	Guidelines were suggested for the M, R and C factors.

3.1.2 The theory of Constructivism and its application to this study

Constructivist ideas, originating from the ideas of Ausubel (1968) and Bruner (1960 and 1986), have been used, and elaborated on, by numerous researchers (e.g. von Glasersfeld, 1992; 1993 and 1995; Pfundt & Duit, 1994; Driver *et al.*, 1994; Duit & Treagust, 1995 and 2003; Garnett *et al.*, 1995; Johnson & Gott, 1996; Treagust *et al.*, 1996) to form the most commonly held current views on constructivist learning theory. Basically, the constructivist theory proposes that knowledge about the world is a human construction, where learners create their own meaning from the information available to them. This means that people (and in a school context, students) do not receive information passively, transferred as an identical copy from the information source or educator. Rather, people are actively involved (in accordance with the ideas of Bruner, 1986) in organising and reorganising knowledge in order to construct new knowledge (and therefore their own meaning) based on prior knowledge and ideas that they already hold (Jonassen & Hawk, 1984; Driver & Bell, 1986; Johnson & Gott, 1996) and influenced by the social context in which learning takes place (Driver, 1989; von

Glasersfeld, 1992). In other words, a person's prior knowledge and experiences (schemata - see Glossary) can be viewed as a filter through which new information must pass (Anderson *et al.*, 2000). During assimilation, new elements of information are linked with, and integrated into, existing schemata during the various stages of information processing (McNamara, 1994; Treagust *et al.*, 2002). In this way, schemata are reorganised (White & Gunstone, 1993; van Dusen *et al.*, 1999; Ward & Wandersee, 2002) and continually adjusted (Hegarty, 1992; McNamara, 1994; Johnson & Gott, 1996; Treagust *et al.*, 1996). Each person therefore not only constructs knowledge, but also constructs their own personal (unique) knowledge units or schemata according to how they recognise and will use the information (Yager, 1991; von Glasersfeld, 1992; Gillespie, 1993; McNamara, 1994; Duit *et al.*, 1996; Grayson, 1996; Anderson *et al.*, 2000; Kirschner, 2002).

It could be assumed that this process would result in the person becoming more expert in their field of study. However, empirical evidence from recent research on student difficulties shows that there is a vast range of widely accepted student ideas (Johnson & Gott, 1996) that make sense to students (Fisher, 1985; Ben-Zvi & Hofstein, 1996; Anderson *et al.*, 2000), but do not necessarily support accepted scientific views. Such alternative frameworks or misconceptions (Treagust, 1988; Duit & Treagust, 1995), have also been termed minitheories (Claxton, 1993), children's science (Gilbert *et al.*, 1982), preconceptions (Navon, 1977), mixed conceptions, private conceptions, naïve theories (Ogborn, 1993), mistakes, errors, misunderstandings, misleading ideas, misinterpretation of facts (Treagust, 1988) or loose sets of incoherent ideas (Kuiper, 1994). Whether these arise from poor science instruction as Barman *et al.* (1995) and Duit & Treagust (1995) suggest, or from ineffective information processing as Fisher (1985) proposes, they tend to interfere with the learning of new information, including of accepted scientific ideas.

According to constructivist theory, a person's prior knowledge and experience, including conceptual and cognitive schemata (Petre & Green, 1993; Lowe, 1996 and 1999) will influence his /her ability to interpret 'new' information and therefore determine their level of expertise. In Table 3.2, differences in the cognitive, conceptual and graphical schemata of experts and novices and their possible effects on the ability of the reader to interpret diagrams are summarised. For example, experts may be able to organise complex domain-specific information, whereas novices have difficulty doing this (e.g. Kozma, 2003). This information indicates that the same outcomes should not be expected from experts and novices.

Table 3.2 Summary of the differences in the cognitive, conceptual and graphical schemata of experts and novices and the possible effects on interpretation of diagrams.

Schema	Status	Possible effects of schemata on the interpretation of diagrams
Cognitive schemata	Experts	Organise huge amounts of complex and sophisticated domain-specific information into chunks for storage (Egan & Schwartz, 1979; Winn, 1993; Kozma, 2003). Knowledge well-organised often in abstract relational terms (Guri-Rozenblit, 1988a).
		Chunks of information can be processed as single units in a controlled way (Kirschner, 2002), reducing cognitive load (Chandler & Sweller, 1991).
		Chunking facilitates encoding and subsequent search (Winn, 1993).
		Tasks are performed in a structured and often automated manner using continual checks to ensure satisfactory progress during the activity (e.g. Pinker, 1990; Lowe, 1996; Taconis *et al.*, 2001). Processing appears to be unconscious - a term used by Roth (1986).
		Glaser (1992) suggests that as the component skills become automatic, conscious processing is enhanced, thereby promoting overall performance.
		Elaboration strategies (Lewalter, 2003) make connections between the new information and prior knowledge and experiences i.e. experts reason with (Kozma, 2003) and integrate (Glaser, 1992) information. Prior domain-specific knowledge essential for effective interpretation (Lowe, 1994b and 1996)
		Organise information perceptually into patterns that are meaningful to the context of the diagram (Goldman, 2003).
		Apply knowledge, use appropriate procedures and employ effective problem solving strategies (Glaser, 1992).
		Process diagrams in terms of high-level abstract relations and generalisations (Lowe, 1993a).
	Novices	Difficulty co-ordinating information in multiple representations (Kozma, 2003) and spatial distributions (Pinto *et al.*, 2000).
		Difficulty with relationships between verbal and graphical information (Pinto & Ametller, 2002).
		Difficulty associating the representation with the physical object it represents (Pinto *et al.*, 2000; Kozma, 2003).
		Tend to deal with superficial features of the diagram (Lowe, 1988b and 1994b) and miss cues to relationships and meaning (Lowe, 1988a and 1999).
		Fragmented approach to extracting information (Lowe, 1999). Captions may be ignored (Pinto & Ametller, 2002).
		Interpret relationships at an every-day level (Lowe, 1999).
Conceptual schemata	Experts	Use cognitive skills in conjunction with their superior knowledge (e.g. Lowe, 1996; Taconis *et al.*, 2001).
		Well-integrated knowledge (Glaser, 1992) with more (Guri-Rozenblit, 1988a) and distinctive links between concepts (Lowe, 1993a)
		Knowledge differently structured and tending to be more stable (Lowe, 1993a; 1994b).
		Hierarchical arrangement of information in memory (Egan & Schwartz, 1979) facilitates appreciation of higher order relationships (Lowe, 1994b).
		Recall of knowledge is superior (Lowe, 1993a).
		Stability in recall tasks (Lowe, 1993a)
		Knowledge cues readers to anticipate and search for information (Lowe, 1999).
	Novices	Do not appreciate the cause-and-effect relationships appropriate to the context of the diagram (Lowe, 1988a and 1999).
		Surface-level explanations result, expressed in concrete, not abstract terminology (Sandmann *et al.*, 2002) or in everyday knowledge (Lowe, 1999).
Graphical schemata	Experts	Understand graphic presentations (Gillespie, 1993), hierarchical structures (Lowe, 1994a and b) and limitations of design principles (Lowe, 1993b).
		Easy access to meaningful patterns and principles reduces search time and therefore increases capacity of short-term memory (e.g. Johnson, 2000a and 2000b).
		Chunking facilitates pattern recognition (Frisby, 1986; Lowe, 1989).
		Spatial organisations can help organise information and act as memory prompts (Fisher *et al.*, 2000).
	Novices	Use visual characteristics (Lowe, 1993a), patterns (Lowe, 1999), including left /right direction of reading (Lowe, 1997), shape (Pinto & Ametller, 2002) and other salient features (Lowe, 2003 and 2004) instead of scientific concepts to group information into perceptual units.
		Focus on local rather than global features (Pinto & Ametller, 2002; Lowe, 2004).
		Emphasis on descriptive rather than explanatory statements (Winn, 1993; Lowe, 1988b and 1994b) using salient or proximal cues (Lowe, 1999).

It is clear from Table 3.2 that the differences in knowledge and skills between experts and novices will have a profound effect on their respective abilities to interpret diagrams and, therefore, any constituent symbolism including arrows. This is in sharp contrast to comments from Phillips & Quin (1993) that readers do not have to rely on experience or do not need prior practice to interpret arrows used in flowcharts.

Thus in conclusion, the classification of knowledge and skills in Table 3.2 framed my thinking in this investigation particularly with respect to novices' interpretation of arrow symbolism (studied in Chapter 6) versus experts' intended meaning of such symbolism (studied in Chapter 5). Furthermore, constructivism framed the overall thinking in that students' (and experts') unique prior knowledge was considered when evaluating their interpretation of diagrams and constituent arrow symbolism (Chapter 6). Furthermore, a level to represent the students' frames of reference was also included in the model developed to explain the process of interpretation of arrow symbolism, explained in Chapter 7.

Thus in summary, the investigation into students' use of arrow symbolism was grounded in the theoretical ideas of the model developed by Schönborn and Anderson (Schönborn, 2005) and of constructivism. However, specific methods were used to carry out the investigation. A discussion of these methods follows.

3.2 THE METHODOLOGICAL FRAMEWORK

In outlining the methodological framework adopted for the study, the choice of instruments selected for the research design are justified, and the limitations, validity and reliability of the methods used, are considered. Specific details of the various research protocols are discussed in the respective chapters. To optimise the quality of the research, it was grounded in established methods of other researchers in the field.

3.2.1 Research paradigms

I followed a pragmatic and therefore flexible research design, which allowed the type of information required for each particular area of the study to dictate the methods used. As a result, I used multiple methods that drew on both the quantitative and qualitative paradigms, as suggested by Jacobs *et al.* (1999).

Quantitative paradigm

A quantitative paradigm was adopted for the aspects of the investigation where the data could be decontextualised, counted and summarised in numbers (McMillan & Schumacher, 1993). This approach suited the analysis of data collected during content analysis of diagrams and arrow symbolism presented in textbooks (discussed in Chapter 5) as the data could be aggregated, summarised, tabulated and compared (Gall *et al.*, 1996; Jacobs *et al.*, 1999; Bell, 2001). This in turn, facilitated the making of predictions about the material (Staver & Lumpe, 1993). As a relatively large sample of students was used to assess student interpretations of arrow symbolism, the incidence of difficulties emerging from probes (discussed in Chapter 6) was also quantified. However, as this study was limited and students were not randomly selected (the study focussed on all Grade 11 and 12 students in a single, girls-only school), it was considered inappropriate to apply statistical analysis to generalise the incidences to wider populations, as this would have inferred that all schools were similar (Rogan, J., 2005, pers. comm.).

Qualitative paradigm

Gall *et al.* (1996, page 25) list the requirements for a qualitative approach – a method considered pertinent for investigating the complex and unpredictable nature of human responses to probes such as those administered in Chapter 6. A qualitative approach allowed the author to select one phenomenon, in this case arrow symbolism and investigate it in depth by means of relatively small case studies (Phelps, 1994), such as with interviews (reported on in Chapter 6). According to McMillan & Schumacher (1993) the qualitative paradigm acknowledges the subjectivity of the researcher, although to support the validity and reliability of investigations, precautions should be taken to minimise the level of subjectivity wherever possible. Qualitative methods also underpin the principles of naturalistic research (Lincoln & Guba, 1985; Cohen *et al.*, 2000; see Section 3.2.2.2, page 30) and allow for the discovery of new ideas and unanticipated occurrences. As the emerging data in a qualitative investigation is usually expressed in words (McMillan & Schumacher, 1993), description of new ideas and difficulties, supported by quotations selected from the responses to written and interview probes, is facilitated.

Qualitative methods were therefore appropriate to investigate and analyse students' responses to written and interview probes and describe the emerging difficulties. The results of these investigations are discussed in Chapter 6.

3.2.2 The research design

McMillan & Schumacher (1993) describe a research design as a systematic procedure developed to guide an investigation and gather and analyse data in order to find answers to research questions. The research design therefore demands a carefully laid out plan or procedure correlated with the series of research questions. The scope of this investigation therefore required a variety of methods including content analysis (used in Chapters 4 and 5), the development, implementation and analysis of written and interview probes, including use of the 4-level framework of Grayson *et al.* (2001) as discussed in Chapter 6, as well as an iterative process for developing a model of ideas (Chapter 7).

3.2.2.1 The method of content analysis (used in Chapters 4 and 5)

According to Cohen *et al.* (2000), content analysis is a method used to derive quantitative (or numerical forms of) data from qualitative sources of information, including from the content and character of visual resources (Bell, 2001; Collier, 2001). As this method allows comparisons to be drawn between materials, it is suitable to gain understanding about the topic in a wider context. Cohen *et al.* (2000) and Bell (2001) suggest that content analysis should begin with precise hypotheses, expectations or questions about well-defined variables. However, content analysis is a subjective process, relying on the researcher's personal judgement of the materials being analysed. The process therefore also requires checks to reduce subjectivity in order to ensure inter-rater reliability (Cohen *et al.*, 2000).

Application of content analysis to this study

The method of content analysis was used to survey the occurrence and diversity of arrow modes of presentation (Chapter 4) and to evaluate the presentation of arrow symbolism in a selection of textbooks (Chapter 5). The steps taken and the reasons for the steps are summarised in Table 3.3, page 28. To achieve inter-rater reliability, the investigations were based on well-established, systematic observational procedures outlined by Bell (2001) and Collier (2001) that would ensure repeatability and, according to Sanger & Greenbowe (1999), keep attention focussed on the purposes of the research.

Table 3.3 Applications of content analysis to this dissertation.

Steps taken	Reasons for steps	References
Method of content analysis selected	To derive quantitative (or numerical forms of) data from qualitative sources of information i.e. diagrams.	Sanger & Greenbowe, 1999; Cohen *et al.*, 2000; Bell, 2001; Collier, 2001
Convenience survey conducted	To ascertain textbooks widely used in KZN schools.	Cohen *et al.*, 2000
Survey of the occurrence and diversity of arrow modes of presentation (Chapter 4)		
Variables for investigation defined as summarised below:	To investigate broad and independent categories to provide an overall visual record, as well as in more focused subcategories to facilitate comparison.	Cohen *et al.*, 2000; Bell, 2001
1. Complete census of 3218 diagrams in 7 selected textbooks	To find out the occurrence of arrow symbolism in the selected textbooks.	Rogan, 2005
2. Categorisation of 3218 diagrams in the 7 selected textbooks into the sub-categories of: realistic, stylised, and abstract diagram types	To find out the occurrence of different types of diagrams in the selected textbooks.	Alesandrini, 1984; Lowe, 1986, 1993d; Larkin & Simon, 1987; Hill, 1988; Wheeler & Hill 1990; Lohse *et al.*, 1991; Kress & van Leeuwen, 1996; Henderson, 1999; Cheng *et al.*, 2001; Stenning & Lemon, 2001; Blackwell & Engelhardt, 2002
3. Analysis for arrow symbolism in each of the diagram types	To find out the occurrence of arrow symbolism in different types of diagrams.	
4. Analysis of the structural and functional aspects of arrow symbolism in diagrams	To find out about the diversity of arrow symbolism in the sub-categories of: style, spatial organisation, purpose, and meaning.	Lowe, 1993b; Kress & van Leeuwen, 1996
Repetition of evaluations	To check on reliability of analyses.	
Evaluation of the presentation of arrow symbolism in a selection of textbooks (Chapter 5).		
Synthesis of literature on graphic design principles	To determine graphic principles relevant to arrow symbolism.	See Chapter 5
Variables for investigation defined: A set of criteria for evaluating arrow symbolism was developed (as discussed in Chapter 5)	To evaluate arrow symbolism precisely and methodically. Facilitate repetition. Allow evaluation of sub-categories of information. Allow an overall evaluation.	van Leeuwen & Jewitt, 2001
Categorisation and coding of criteria	For easy use of the set of criteria.	de Berg & Treagust, 1993; Eltinge & Roberts, 1993
Evaluation of 50 diagrams using criteria	To hone and validate criteria.	
Development of sets of propositional statements	For benchmarking: against which to compare evaluations of other users.	Glenberg & Langston, 1992; White & Gunstone, 1993; McNamara, 1994
Compare evaluations of certain diagrams to those of students, educators and a graphic designer.	To validate criteria. To check on inter-rater reliability and reduce subjectivity.	Abimbolo & Baba, 1996; Ametller & Pinto, 2002; Cohen *et al.*, 2000
Application of criteria to 614 diagrams	To determine the generalisability of the study.	Staver & Lumpe, 1993
Re-evaluation a few days later	To check on reliability of the evaluation process.	Cohen *et al.*, 2000; Bell, 2001

I adopted Bell's suggestion (Bell, 2001) of analysing pictorial information in broad and independent categories to provide an overall visual record, as well as analysing information in more focused subcategories to facilitate comparison. For example, in Chapter 4, I investigated the occurrence of arrow symbolism in the textbooks as a whole, as well as in the sub-categories of realistic, stylised and abstract diagram types. To find out about the diversity of arrow symbolism, sub-categories of style, spatial organisation, purpose and meaning were created. In Chapter 5, a series of discrete criteria (or sub-categories) were selected to guide the evaluation of arrow symbolism in diagrams.

These criteria were then refined into a more discriminating, inclusive, reliable and comprehensive classification or set of criteria, which was then coded as suggested by de Berg & Treagust (1993) and Eltinge & Roberts (1993). These criteria for evaluating arrow symbolism are presented in Chapter 5, Table 5.1 (page 95). Although these criteria (or sub-categories) fulfilled the requirements of a very precise and methodical evaluation tool that facilitated repetition as recommended by van Leeuwen & Jewitt (2001), they allowed little space for the researcher to use own initiative. To compensate for this, Collier (2001) suggests returning to the complete visual record to search for the significance of the findings in order that the information from the detailed analyses is placed into context. I therefore included an additional criterion, Criterion 9, in the set of criteria (Chapter 5, Table 5.1, page 95) to allow for an overall evaluation.

To promote the generalisability of the study, a relatively large sample of seven recently published or newly revised editions of textbooks, widely used in KwaZulu-Natal, South Africa was selected. The selection process was guided by the results of a convenience survey (Cohen *et al.*, 2000) conducted (see Chapter 4, Section 4.3.1, page 57) by the author with independent and government teachers in KwaZulu-Natal schools in July 2000. (It should be noted that the data, in this case the popularity of textbooks, obtained from a convenience sample, cannot be generalized to a wider population.) Every diagram on every page of the seven textbooks (614 in total) was examined, firstly to ascertain the diversity of arrow modes of presentation (reported in Chapter 4), and at least once during the development and application of the set of criteria for evaluating arrow symbolism in diagrams (discussed in Chapter 5). Cohen *et al.* (2000) and Bell (2001) consider such a method of re-evaluation with a time interval between evaluations a necessary step for checking the constancy of the evaluator assessments. Furthermore, cross-reliability was attempted by comparing evaluations of certain diagrams to those of students, educators and a graphic designer (as explained in Chapter 5).

Using these methods, I am confident that the analyses were reliable and meaningful enough to develop an excellent understanding of how arrows are presented in biology textbook diagrams, both for this study and for application by other users of diagrams.

3.2.2.2 The method of probing for student difficulties (used in Chapter 6)

To ascertain how the presentation of arrow symbolism might influence interpretation, it was necessary to probe students' interpretations of arrows in diagrams. This was done using a naturalistic enquiry approach to develop and implement a series of probes.

Application of the principles of naturalistic enquiry to the development of probes

The naturalistic approach, described by Lincoln & Guba (1985), Winberg (1997) and Cohen *et al.* (2000), was considered suitable for this study for several reasons:

a. The study focused on an issue, the use of arrow symbolism in biology diagrams in order to understand possible sources of student difficulties, with the ultimate aim of developing remedial tools. The research thus critically addressed a real world situation of textbook diagrams used by students in an educational context.

b. Investigations into student interpretations of arrow symbolism were context-bound and descriptive in nature.

c. The researcher, as evaluator and analyst, played a key role in the process of enquiry into arrow symbolism. Some degree of subjectivity during research was therefore unavoidable. Firstly, the researcher brought his /her own values and beliefs to the research. Secondly, according to the constructivist ideas on which this study is grounded, human subjectivity is an important aspect of knowledge creation, and thirdly, researchers need to engage closely with their subjects in order to gain meaningful insights. The control of subjectivity was therefore an important consideration during the investigation.

d. The data was analysed inductively by identifying pattern of responses, ascribing meaning to the data and drawing inferences from it (Cohen *et al.*, 2000). In this way, successive investigations were more focussed and relevant to the task in hand and allowed the author to gain progressive insight into the nature of the presentations and of the difficulties during the process of interpretation of arrow symbolism.

e. To complete the naturalistic method of enquiry, the author reported the meaning and intention of the data from the students' point of view, using quotes from interviews and probes to substantiate their understanding.

f. The author acknowledges that the student ideas and difficulties might be unique to the particular population used in the investigation and therefore the difficulties, and incidence of difficulties, might not be generalisable to society at large. Further investigations could be undertaken to establish such generalisability.

Development and administration of probes

To form the focus of the probes, the author first selected and evaluated suitable examples of a stylised diagram (Chapter 6, Figure 6.2, page 121) and an abstract diagram (Chapter 6, Figure 6.3, page 121). Then, from the various methods suggested by Lowe (1993c) for investigating students' responses during interpretation, and for discerning the process of understanding and mental model formation, I elected to use a range of diagnostic tools or probes (thereby also satisfying the requirement of triangulation) to ascertain student difficulties with the presentation and interpretation of arrow symbolism in biology diagrams. These methods included written and interview probes. In addition, students were also encouraged to modify the diagrams used in the probes by drawing their ideas on the diagram.

The written probes (pencil and paper testing methods) enabled investigation of groups of up to 70 students economically and over short periods of time - an important consideration suggested by Cohen *et al.*, 2000. On the other hand, although interviews are more costly and time consuming, requiring 45 - 60 minutes per interview as well as time for transcription, they allowed deep probing of specific ideas. Furthermore, modification of the diagrams during the interview protocol allowed a deeper understanding of the way students perceived and reasoned with the diagrams. Using these methods, I sought to understand the mental models of individual students.

Table 3.4 Summary of the process used to probe students' interpretation of arrow symbolism in biology diagrams.

Steps followed	Reasons for steps	References and referees
Types of probes		
Use a range of diagnostic tools	To adequately discern the process of understanding and mental model formation. Inductive analysis was used to inform successive probes, thus allowing elaboration of difficulties suspected from previous responses but still allowing further, unanticipated difficulties to be exposed.	Lowe, 1993c and 2003; Phelps, 1994; McMillan & Schumacher, 1993; Bisanz *et al.*, 1994; Grayson *et al.*, 2001
1. Pencil and paper testing method (written probes)	To enable investigation of groups of up to 60 students economically and over short periods of time.	Haslam & Treagust, 1987; Treagust, 1988; Tamir, 1989; Duit *et al.*, 1996
a. Semi-guided probing	To focus students' attention on specific requirements, certain features or particular regions of the diagrams, as Figures 6.2 and 6.3 were considered to be of a medium level of complexity. Broad, free-response probing to investigate suspected difficulties and allow unanticipated difficulties to emerge.	Tamir, 1989; Anderson *et al.*, 2000; Grayson *et al.*, 2001; Stylianidou *et al.*, 2002
b. Multiple-choice type with justification of choice	To focus more specifically on the outcomes of the semi-guided probes. The free-response justification helps to remove the guess factor. The researcher can clarify students' reasoning behind the choice of answer, particularly if the distractor is selected.	Haslam & Treagust, 1987; Treagust, 1988; Tamir, 1989; Lazarowitz & Penso, 1992; Barman *et al.*, 1995; Odom & Barrow, 1995
2. Interview procedures using think-aloud protocols (where the interviewee expresses thinking verbally)	Although interviews are more costly and time consuming, requiring 45 - 60 minutes per interview as well as time for transcription, they allowed deep probing of specific ideas. Interviews are flexible, have no limit to what may be revealed, can be combined with other probes, can be open (interviewee is invited to explain a broad concept) or specific (the interviewer asks direct questions), can move from general to specific with ease and can be used to probe any form of knowledge. They allow greater depth, clear up misunderstandings, encourage co-operation and rapport and allow a truer assessment of what the respondent believes, still allowing unexpected or unanticipated answers to emerge. To record cognitive and metacognitive processing during interviews.	Posner & Gertzog, 1982; Lincoln & Guba, 1985; Bowen, 1994; Krishnan & Howe, 1994; Odom & Barrow, 1995; Duit *et al.*, 1996; Nakleh & Krajick, 1996; Cohen *et al.*, 2000, White & Gunstone, 1993; Lewalter, 2003; Schönborn, 2005
3. Modification of diagrams during the interview protocol	To allow a deeper understanding of the way students perceived and reasoned with diagrams.	Schönborn, 2005
Choice of diagrams		
Selection of suitable examples of a stylised (Chapter 6, Figure 6.2, page 121) and an abstract diagram (Chapter 6, Figure 6.3, page 121)	To cater for a range of arrow symbolism (as described in Chapter 6, Section 6.3.1, page 119)	Wright, 1989; Independent Examination Board
Evaluation of diagrams	To find out whether arrow symbolism is used effectively in the diagram.	Criteria discussed in Chapter 5, Figure 5.1
Format of probes		

Leading questions were avoided	To allow the researcher to understand how the student was addressing the diagram.	
Questions were carefully sequenced	To limit the influence of one question on the responses of later questions.	
Questions focused on interpretation of relationships	Probing for perceptual strategies can result in a fragmented approach to investigations.	Lowe, 1997; 1999; Fisher *et al.*, 2000
Figure 6.2 was labelled	To ensure that students did not need to rely on memorisation and knowledge of terminology and to foster interpretation. The combination of verbal and graphical modes fostered interpretation.	Mayer *et al.*, 1995; van Dusen *et al.*, 1999. Paivio, 1986; Clark & Paivio, 1991; Mayer, 2003
Proposed format for interview was detailed	To guide interview from free-response, through guided to specific questioning and to ensure thorough coverage of the topic according to existing difficulties. This provided comprehensive coverage of the topic and particularly of the difficulties already exposed from previous probes. Data collection was systematic and similar for each student, thereby enhancing comparability.	Cohen *et al.*, 2000; Schönborn, 2005.
Preparation of propositional statements	To guide the analysis of probes and thereby reduce subjectivity.	Glenberg & Langston, 1992; White & Gunstone, 1993; McNamara, 1994
Content and face validation		
1. Of probes	To check probes for format, length, sequencing of questions, language level and appropriateness for the investigation.	Prof. Anderson, Prof. Grayson, three educator colleagues
2. Of propositional statements	To check for accuracy of knowledge, for the inclusion of all relevant data and for appropriateness of expression.	Prof. Anderson, Prof. Grayson, three educator colleagues
Sampling strategy		
Sample population	Limited to a readily accessible sample population of Grade 11 and 12 students from one girls-only school, but drawn from the classes of four different educators over a period of three successive years.	de Berg & Treagust, 1993; Staver & Lumpe, 1993
Different student populations used for each probe set	To guard against students applying strategies learnt during the probing process to subsequent investigations.	
Administration of probes		
Post-instruction	To ensure an appropriate degree of prior conceptual understanding and cognitive development, but within 20 days of instruction or revision to reduce the effects of learning decay.	Barman *et al.*, 1995
Pilot studies: on written probes on interviews	 To determine whether students are able to answer the probes effectively. To determine the suitability of the interviewing technique.	Prof. Anderson, Prof. Grayson
Written and verbal instructions for written probes	To ensure students understood what they were required to do.	
Training session before interviews	To explain think-aloud procedures and modification of drawings.	

Audio-taping of all interviews	For full recording for later transcription.	Duit *et al.*, 1996; Cohen *et al.*, 2000
Video-taping of some interviews	To record the actions of the student during the think-aloud protocols.	Jacob *et al.*, 1999
Transcription of interview recordings	To be able to pass through data repeatedly, to compare with data collected from other instruments, to ensure a thorough search for a range of difficulties, and to allow objectivity.	Johnson & Gott, 1996
Analysis of probes		
1. Qualitative analysis of: written responses interview transcripts diagram modifications video observations written observations	To explore the data obtained from the various probes by comparing student responses to the propositional statements and to responses given to questions probing similar information as described below.	Lincoln & Guba, 1985; McMillan & Schumacher, 1993; Gall *et al.*, 1996; Johnson & Gott, 1996
Interview transcripts compared to audio-, videotapes & notes	To prevent the transcription becoming de-contextualised and possibly subjective.	Cohen *et al.*, 2000
Verification of emerging data	For validation.	Prof. Anderson, Prof. Grayson
Difficulties identified and categorised	To verify emerging difficulties with difficulties from previous probes already described. To understand the nature of the difficulties and group similar difficulties.	Lincoln & Guba, 1985; Treagust, 1988; Duit *et al.*, 1996
Classification against 4-level framework	To guide the process of progressively gaining greater insight into the nature of each difficulty and classify the difficulties according to the amount of insight the researcher has about the nature of the difficulty.	Grayson *et al.*, 2001
2. Quantitative analysis of: written responses	To show incidence of difficulties.	
Validation of data		
Validation of samples of the analyses by supervisor, co-supervisor, three educators	To check the adequacy and objectivity of the analyses.	Lincoln & Guba, 1985; McMillan & Schumacher, 1993; Sanders & Mokuku, 1993; White & Gunstone, 1993; Johnson & Gott, 1996; Gall *et al.*, 1996; Anderson & Arsenault, 1998; Cohen *et al.*, 2000
Triangulation using a multi-methods approach	To validate data by using different methods and comparing the relevant data to converge on a more accurate description of the emerging data.	Lincoln & Guba, 1985; McMillan & Schumacher, 1993; Gall *et al.*, 1996; Johnson & Gott, 1996; Anderson & Arsenault, 1998; Bell, 1999; Cohen *et al.*, 2000
Reliability checked	Replicability should remain stable over time, over groups of respondents and over equivalent instruments.	White & Gunstone, 1993; Bell, 1999; Cohen *et al.*, 2000

In the following sections, I describe the instruments selected, the sampling strategies used, the development and implementation of the selected instruments and the methods of analysis of the findings. The process used for this part of the study is summarised in Table 3.4, page 32. Examples of the probes are provided in Appendix 1 (page 233).

Design and administration of probes

The design of the probe is crucial for the type of information required (Lowe, 1993c), in this instance how presentation of arrow symbolism affects student interpretations (reported in Chapter 6). I therefore consulted the ideas and suggestions of various researchers (e.g. White & Gunstone, 1992; Amir & Tamir, 1994; Cohen *et al.*, 2000; Duit *et al.*, 1996). Sets of probes were then designed to find out how students perceive, understand and interpret arrows used in diagrams. As suggested by Kozma (1991), the questioning techniques probed students' understanding and use of arrow symbolism rather than providing an evaluation of the structure or content. To use the terminology of Lazarowitz & Penso (1992), a functional approach to probing, was used.

To assess how students make sense of the syntactic features of the diagram, the probes were designed to investigate students' abilities to observe the features of the diagram, including the stages of detection of patterns and features, selection of relevant graphical information and organisation of the information into suitable units. To allow the researcher to understand how the student was addressing the diagram, leading questions were avoided; attention was not drawn to specific arrows (until required); and the influence of one question on the responses of later ones, was limited as far as possible. Questions were therefore carefully sequenced. To guard against students applying strategies learnt during the probing process to subsequent investigations, different student populations were used for each probe set with the exception of Probe set 3. For this probe, five of the ten students interviewed had answered Probe set 2, allowing the interviewer to follow up on and gain greater insight into specific difficulties.

In Lowe's view (Lowe, 1999) probing for perceptual strategies can result in a fragmented approach to investigations. To avoid this, questions were designed to also focus on interpretation of relationships, as suggested by Lowe (1999) and Fisher *et al.* (2000). The probes therefore also assessed whether students could apply reasoning strategies to identify relevant links among important ideas in the diagram, recognise the nature of the relationship (Lowe, 1997), acknowledge the significance of arrow style and interpret the meaning of the arrow in the context of the diagram. To ensure that the student did not need to rely on memorisation and knowledge of terminology, Figure 6.2 (Chapter 6, page 121) was labelled. Although this introduced a verbal element to interpretation, thereby necessitating dual-coding (versions of which are explained by Paivio, 1986; Clark & Paivio, 1991; Mayer, 2003), the combination of verbal and graphical modes was not only considered supportive and essential, but also integral to the interpretation of the diagram, in support of the opinions of Mayer *et al.* (1995) and van Dusen *et al.* (1999). In addition to these design features of the probes, the questions were phrased using clear, concise and unambiguous language. At least one, if not both supervisors (Prof. Anderson and, at that stage, Prof. Grayson), evaluated the various probes for format, length and sequence of questions, language level and appropriateness to the investigation.

The probes were administered post instruction, as suggested by several researchers including Barman *et al.* (1995), to ensure an appropriate degree of prior conceptual understanding and cognitive development, but within 20 days of instruction or revision to reduce the effects of learning decay.

The formats and administration of the different types of probes used in the investigation (written tests, interviews and modification of diagrams) are discussed below.

- ***Format and administration of written tests***

Ideas for the design of the pen and paper tests were selected from written tests used in biology and chemistry investigations (e.g. Haslam & Treagust, 1987; Treagust, 1988) and explained by Tamir (1989) and Duit *et al.* (1996). These tests consisted of probes (or questions) of either a semi-guided nature (see Glossary for definition) or of a multiple-choice type with justification of choice.

Broad, free-response probing has been used successfully by a number of researchers (e.g. Tamir, 1989; Anderson *et al.*, 2000; Stylianidou *et al.*, 2002) to investigate suspected difficulties yet still allow unanticipated difficulties to emerge (Grayson *et al.*, 2001). However, as the diagrams selected for the probes (Figures 6.2 and 6.3, Chapter 6, page 121) were considered to be of a medium level of complexity, it was considered prudent to provide some guidance to students. Therefore students' attention was focused on specific requirements, certain features or particular regions of the diagrams, but students were still allowed to respond freely. I termed this type of probe, semi-guided (see Appendix 1.1, page 233, and 1.3, page 242 for examples).

To focus more specifically on the outcomes of the semi-guided probes, multiple-choice diagnostic tests were used that drew suggestions from Haslam & Treagust (1987), Treagust (1988), Tamir (1989), Lazarowitz & Penso (1992), Barman *et al.* (1995) and Odom & Barrow (1995). However, the methods described by these authors are traditionally used to test conceptual understanding of science and biology topics. I therefore modified the design of the probes in order to focus the investigation on the nature and existence of particular perceptual and reasoning difficulties with the processing of arrow symbolism rather than on conceptual understanding of the topic. Examples of the multiple-choice probes are provided in Appendices 1.2 (page 235) and 1.6 (page 248).

The multiple-choice questions consisted of a choice of several options including distractors, followed by a free-response justification for the selected option. The options included a correct answer (or propositional knowledge statement) and several distractors drawn from misconceptions (as suggested by Tamir, 1989) that emerged from previous probes. As the researcher could count up the frequency of each option selected, the multiple-choice component provided data suitable for a quantitative approach. On the other hand, the free-response (justification) component was a descriptive or explanatory element of the probe and therefore provided responses suited to a qualitative approach. In the opinion of Treagust (1988), the free-response justification helps to remove the guess factor and allow the researcher to clarify students' reasoning behind a particular choice of answer, particularly if a distractor is selected (Tamir, 1989). They also provide a higher diagnostic potential than the options on their own, and therefore tend to eliminate the 'noise' distractors. In a very few cases, the free response justification did not agree with the selected choice or was left blank by students. Further probing during interviews would be necessary to find out why these few students did not answer as instructed. Without this knowledge, the answers did not contribute to the understanding of the USE of arrows and were therefore not included in the quantitative results.

In addition to detailed instructions, students were instructed in the techniques required to answer the questions. Spaces were left on the question sheet for students' answers to facilitate answering, maintain students' focus and to ensure that the questions and answers could be readily correlated during assessment. The researcher was available throughout the process to explain the procedure if necessary.

- ***Format and administration of interviews, including student modification of diagrams***

White & Gunstone (1993) describe clinical interviews about events as a conversation that an expert has with one student to check the students' ability to recognise the presence of a concept and interpret information. This form of probing has gained in popularity (Bowen, 1994) with the greater recognition of constructivist ideas and, in the opinion of White & Gunstone (1993) and Krishnan & Howe (1994), has become a powerful tool for testing hypotheses and identifying difficulties. In fact, Nakleh & Krajick (1996), Odom & Barrow (1995) and Duit *et al.* (1996) suggest they be used in conjunction with written probes to form part of triangulation. According to White & Gunstone (1993), interviews are flexible, have no limit to what may be revealed, can be combined with other probes, can be open (interviewee is invited to explain a broad concept) or specific (the interviewer asks direct questions), can move from general to specific with ease and can be used to probe any form of knowledge. In addition to these factors, Cohen *et al.* (2000) recommend interviews as they allow greater depth, clear up misunderstandings, encourage co-operation and rapport and allow a truer assessment of what the respondent believes. Furthermore, unexpected or unanticipated answers may still emerge.

Like in the 3 phase single interview approach (3P-SIT) developed by Schönborn and Anderson (Schönborn, 2005), Cohen *et al.* (2000) also suggest the 'funnel' type of interview that starts broad and narrows to more specific questioning. This method allows the interviewer to delve ever deeper into the respondents' understanding to gain a better understanding of difficulties exposed in previous probes. In addition, workers such as Bowen (1994) and Lewalter (2003) have used think-aloud protocols (where the interviewee expresses thinking verbally) to record cognitive and metacognitive processing during interviews. I therefore decided to include interviews in the research protocol, despite the fact that they tend to be time consuming. They also demand expertise in their analysis (Tamir, 1989; Barman *et al.*, 1995; Duit *et al.*, 1996) and require the establishment of rapport and neutral ground between the interviewer and respondent (Cohen *et al.*, 2000). In the design of the interviews, procedural ideas and guidelines of various researchers such as Posner and Gertzog (1982), Lincoln & Guba (1985), White and Gunstone (1993), Bowen (1994), Duit *et al.* (1996), Cohen *et al.* (2000) and Schönborn (2005) were used.

Following the suggestions of Barman *et al.* (1995), I interviewed each student individually to eliminate the possibility of social dynamics interfering with students' responses. On the other hand, Duit *et al.* (1996) suggest that the effect of environment is strongest on individuals. Therefore, to ensure that students felt at ease and to minimise atypical behaviour, the familiar classroom environment was selected for interviews at times when other students were not around. Students were also engaged in general conversation prior to the interviews to establish rapport, trust and a conversational tone. The intentions of educational research were explained in order to shift the emphasis of the interview from the student on to the interviewer. However, the researcher's interest in arrow symbolism *per se* was not divulged in order to reduce the possibility of the student answering what she expects is required of her, or creating answers to please the interviewer (Duit *et al.*, 1996). The researcher maintained eye contact with the student without being threatening. To reinforce equality, the student interviewee was seated alongside the researcher on a similar chair. Each interview was allocated an hour as suggested from the pilot studies. All interviews were conducted in a similar manner and environment to accommodate validity of testing.

Students were encouraged to think aloud and point out features of the diagram being discussed and, where appropriate, modify or draw markings on, the diagram. For this purpose, I supplied a pointer for the student to demonstrate her pattern of accessing the information; pencil and variously coloured pens for students to modify the diagrams when appropriate; paper for the trial run; and, one or more copies of the diagram under discussion. Training exercises were conducted to familiarise students with the think-aloud method and practice the technique of using the pointer. For this purpose I provided diagrams of simple food chains and food webs that use arrow symbolism and were familiar to students.

Researchers require mental effort to ask the right questions, so careful and thorough preparation of the interview design was undertaken based on an inductive analysis of previous probes. An outline of the interview protocol was devised according to the guidelines of Cohen *et al.* (2000) and Schönborn (2005), detailing the steps of the interview, a suggested order to follow when conducting the interview, directives for the interviewer to follow during probing, suggested instructions and questions for the student, guidelines for the interviewer to check the progress of the interview from free-response, through guided to specific questioning and to ensure thorough coverage of the topic according to existing difficulties (see Appendices 1.3 and 1.5, pages 242 and 246 for the suggested formats developed for probing Figures 6.2 and 6.3 (Chapter 6) respectively). A series of questions in approximate order from general, free-response questions at a superficial level (such as 'What does this diagram tell you?') to more specific and targeted questions at a deeper level (such as 'What is the meaning of that arrow in the context of the diagram?'), was designed to lay the foundation of, and guide the interview. This provided comprehensive coverage of the topic and particularly of the difficulties already exposed from previous probes by inductive analysis. It also made data collection systematic and similar for each student, thereby enhancing comparability. However, I used the less formal type of interview suggested by Cohen *et al.* (2000), whereby the interviewer was given the flexibility to modify the sequence or wording of questions where necessary to follow up on student responses as such questions cannot be prepared in advance. In this way, I was able to probe more deeply into specific issues and unanticipated difficulties emerging with particular students (Schönborn, 2005). I also endeavoured to control and vary the level of questioning to maintain interest and enthusiasm and change the direction of questioning to circumnavigate stumbling blocks and return to the difficulty by another route. To prevent interviewer fatigue, only one or two interviews were scheduled per day and not back-to-back.

Interview techniques suggested by White & Gunstone (1993) were included to maintain open channels of communication and control the dynamics of the interview in order to encourage students to co-operate fully and respond freely during the interview. Questions were kept clear, sharp and focussed on the topic to elicit specific answers. Prompting or encouragement was provided only when necessary, and neutrality was maintained by avoiding leading questions and refraining from showing emotion or passing judgemental comments that might inhibit further responses. Although the student was allowed plenty of time to reason with the diagram and formulate answers, I maintained a steady pace and structured approach. When necessary, students' responses were summarised and the interview was directed in a different direction. I continually monitored the students for signs of tiring. Throughout the interview, notes were made on the students' verbal and non-verbal responses (including the modification of the diagrams) as suggested by Duit *et al.* (1996). Asking the student for ideas on improving the diagram and then thanking the student for her participation closed the interview.

Using the guidelines suggested by Duit *et al.* (1996) and Cohen *et al.* (2000), every interview was audio-taped and the tapes transcribed verbatim with all pauses, emphases, interruptions, gestures, tones of voice etc. as soon as possible, in preparation for analysis. In addition, and following Jacobs *et al.*'s procedure (Jacobs *et al.*, 1999), the interviews about the stylised diagram (Figure 6.2, Chapter 6) were also videotaped. This method of recording allowed sophisticated analysis of both planned and unplanned observations as the tapes could be watched and re-watched for different dimensions of the recorded verbal and physical behaviour. The transcripts were compared to the audiotapes, written notes and videotapes to prevent the transcription becoming de-contextualised and possibly subjective. The author read through the data several times, as suggested by Johnson & Gott (1996), to ensure a thorough search for a range of difficulties, and to allow objectivity. Although the data emerged in units of meaning, a sense of holism in the interview was maintained – a consideration noted as important by Cohen *et al.* (2000). Misconceptions and ideas that differed from those of the propositional statements prepared and verified by experts, were identified as difficulties (as recommended by Treagust, 1988), categorised according to the nature of the patterns (as proposed by Lincoln & Guba, 1985) and compared to, and verified with, the existing difficulties from previous probes. The author supported her interpretations with students' own words (as suggested by Nakleh & Krajick, 1996), using the comments that appeared most informative (as recommended by Duit *et al.*, 1996).

Development of propositional statements

As recommended by Glenberg & Langston (1992), White & Gunstone (1993) and McNamara (1994), I developed for each of the probes, a set of scientifically acceptable answers or propositional statements. Propositional statements for the interpretation of diagrams selected for the evaluation process discussed in Chapter 5 are provided in Figure 5.3, page 93. Propositional statements for each probe used for the investigations into student interpretations (discussed in Chapter 6) are detailed in Appendices 1.1 to 1.6, pages 233 – 248. The content of the propositional statements was checked by the author against experts' opinions of the relevant scientific knowledge using various reference sources including Wright (1989) and Roberts *et al.* (1993) and literature on graphic principles (e.g. those proposed by Kosslyn, 1989). The propositional statements for the evaluation in Chapter 5 were critiqued by my supervisor (Prof. Anderson) for accuracy of knowledge, for the inclusion of all relevant data and for appropriateness of expression. Three biology educators from St. Anne's Diocesan College and Prof. Anderson moderated the propositional statements for the probes used in

Appendices 1.1 – 1.6. Feedback was provided to the researcher, and in a few cases, the statements were modified in order to reach consensus. These statements were used to guide the analysis of probes and thereby reduce subjectivity. During analysis of the responses to the probes, a few additional acceptable answers were recognized and the propositional statements further modified accordingly. The cyclical process of modification is illustrated in Figure 3.1, below.

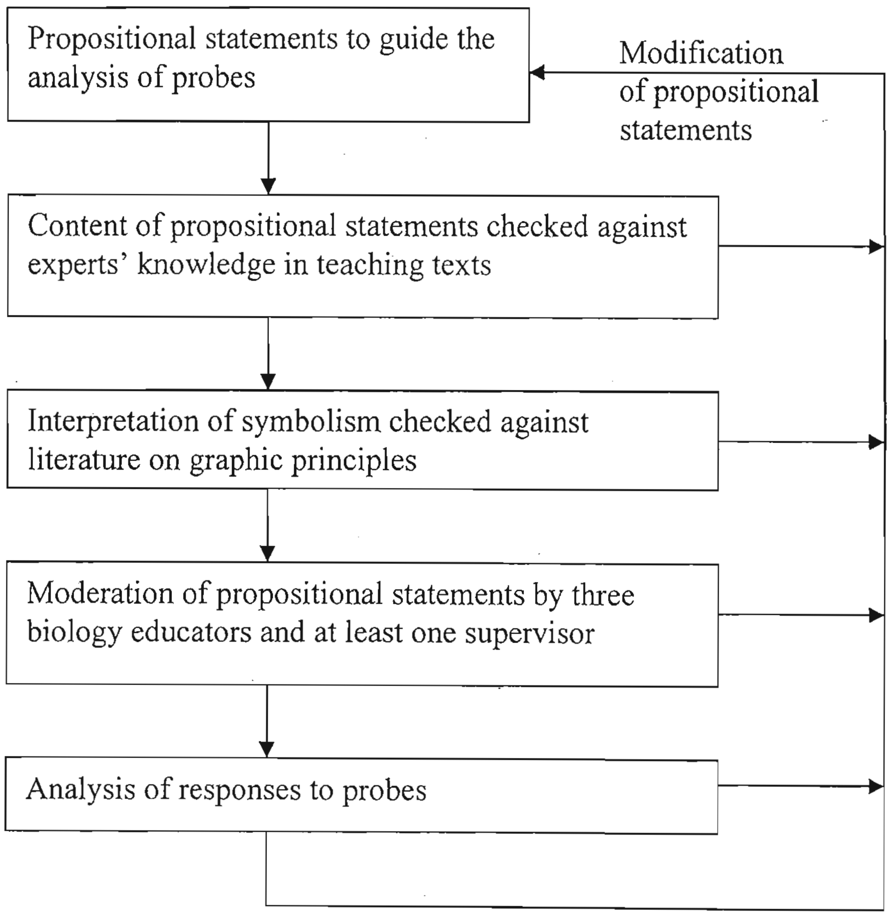


Figure 3.1 Diagram to illustrate the cyclical process of modification used to develop the propositional statements.

Sampling strategy

As Cohen *et al.* (2000) claim, the quality of research depends not only on the methods and instrumentation used but also on the sampling strategy. Therefore the population from which to draw the sample for the investigation was carefully considered. Guided by the suggestions of de Berg & Treagust (1993) and Staver & Lumpe (1993) for focussing the study, the investigation was limited to Grade 11 and 12 students. Readily accessible sample populations were selected by using students at one girls-only school, but drawn from the classes of four different educators over a period of three successive years. Although convenient to use, the sample could be considered limited and homogeneous and therefore unrepresentative of a country or world trend. Therefore the findings obtained from the investigation would, at most, be considered partially established (Grayson *et al.*, 2001). Although Cohen *et al.* (2000) suggest that in a homogeneous group only five or six respondents may be sufficient for obtaining qualitative data, I decided to sample as large a group as possible in order to quantify the data that emerged. Entire mixed-ability class groups of between 25 and 60 students answered each written probe and at least 10 students were interviewed. Apart from five students who were specifically selected for the Probe 3 interviews, the interviewees were randomly selected (but had to be willing to participate in the process). Details of the student populations sampled are provided in Table 6.1 (page 124).

Analysis of data

- ***Qualitative analysis of data***

The inductive method of analysis, described by Lincoln & Guba (1985, page 203) as 'a process aimed at uncovering embedded information and making it explicit', and advocated by various researchers including Lincoln & Guba, 1985; McMillan & Schumacher, 1993; Gall *et al.*, 1996 and Johnson & Gott, 1996, was deemed appropriate to explore the data obtained from the various probes.

Students' responses to the probes were analysed and synthesised by comparing them to the propositional statements and to responses to questions probing similar information. As new evidence and patterns of meaning emerged from the data, greater insight was gained into the identity and nature of difficulties with the interpretation of arrow symbolism allowing identifying descriptions to be written. The emerging patterns distilled from the data were sorted into categories (developed in what Duit *et al.* (1996) termed, the spiral interpretation process) according to their nature. The resulting categories were then coded. By grouping similar information, broad categories of information were defined.

This 'new' knowledge about student difficulties informed the development of subsequent probes, allowing questions to become more specific. In turn, responses became less free, more focused and more specific to each difficulty. For example, for the probes on Figure 6.2 (Chapter 6, page 121), the difficulties exposed during the semi-guided probes were used as distractors in the multiple-choice probes. Similarly, the difficulties that emerged during the multiple-choice probe helped to define questions used in the interviews. In this way successive probes allowed elaboration of difficulties suspected from previous responses but still allowed further, unanticipated difficulties to be exposed. In this way the categories of difficulties emerged from student responses to written and interview questions rather than having been predetermined.

Bisanz *et al.* (1994), however, warned that the process of inductive reasoning should be carefully controlled if the conclusions are to be plausible. I therefore included safeguards including careful comparison of responses to similar questions within a probe and to similar questions between probes and between different student groups. I also used this method in conjunction with the 4-level framework (Grayson *et al.*, 2001) as explained in the next paragraph.

- ***Use of the 4-level framework (Grayson et al., 2001) to analyse data***

The 4-level framework of Grayson *et al.* (2001), illustrated in Figure 3.2 (page 45), was used to identify and classify the difficulties that emerged during analysis of student responses to written and interview questions, and to guide the process of progressively gaining greater insight into the nature of each difficulty. This method of classification therefore supports the naturalistic and qualitative form of inquiry used in these investigations.

The hierarchical nature of the 4-level framework provides for the classification of the difficulties (alternative conceptions) at four levels according to the amount of insight the researcher has about the nature of the difficulty, thereby allowing a systematic and focussed exploration of the difficulties. Using this framework, unanticipated difficulties emerging unexpectedly from free-response probes were classified on the framework at level 1. The emerging difficulties, now described as suspected, could then be moved up the framework to level 2. Difficulties suspected on the basis of teaching experience and literature reports or following analysis of diagrams according to specified criteria, but which had not been systematically investigated, were also classified at level 2. Classification at level 1 and 2 tends to be subjective. More specific probing into the nature of the level 1 and 2 difficulties, including with interviews, yielded greater insight into the nature of the difficulties, allowing them to be classified, more objectively, at higher levels on the framework, namely at level 3 or 4. Level 3 difficulties, researched in a limited context and carrying a description, are classified as partially established. Level 4 difficulties are well established, having been researched in various contexts (such as different cultural or educational groups).

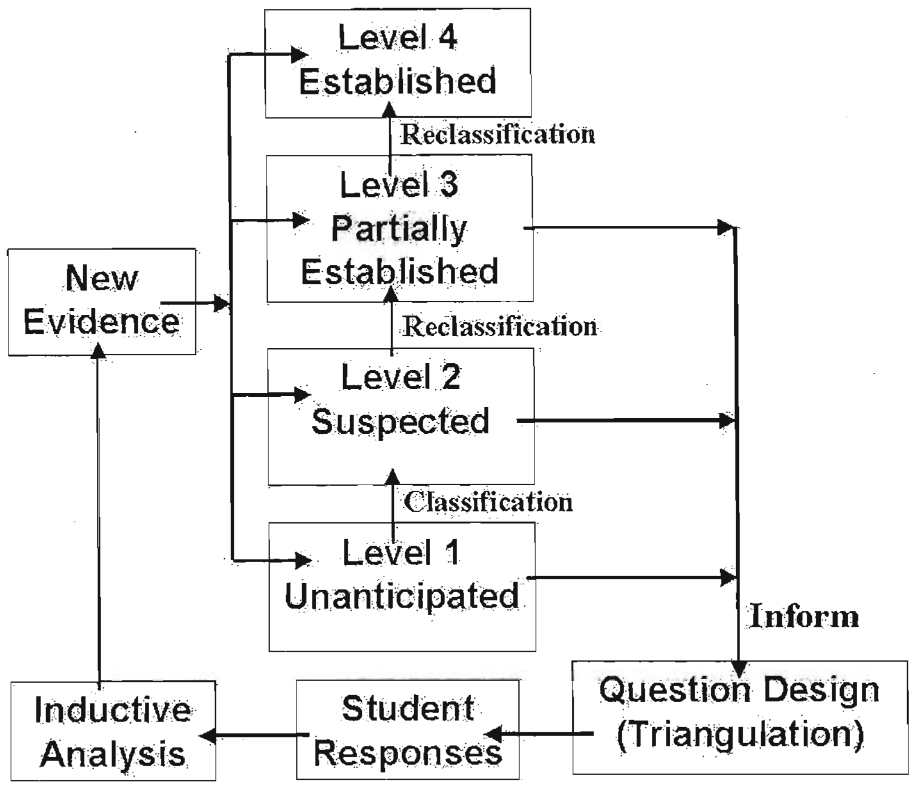


Figure 3.2 Diagram showing the framework of Grayson *et al.* (2001) that was used to identify and classify student difficulties.

The cyclical nature of the framework (shown in Figure 3.2 above) allowed the data (knowledge of a difficulty) obtained from responses to probes and interviews to inform the design of further, more focussed probes. By using multi-methods (comprising similar probes and interviews on different diagrams, as well as different types of probes and interviews on the same diagram), the results obtained from the probes could be compared. In this way, triangulation was supported. In turn, inductive analysis of the responses to the questions informed the level of classification. This cyclical process may continue until a stable description at level 4 is obtained. Both the format of the questions and the descriptions of the difficulties changed as the difficulty was promoted through the levels, resulting in a clear and precise idea of the difficulty. Consequently, by classifying difficulties according to the 4-level framework (Grayson *et al.*, 2001) both the validity of the data and the reliability of the process were increased.

- ***Quantitative analysis of data***

The results were also quantified by dividing the number of students with each difficulty by the total number of students who answered the question. The incidence was then expressed as a percentage. Incidence quoted for free-responses are considered to be minimum values as the nature of the question allows a range of responses and other students who may experience the same or similar difficulties may not have expressed it. Therefore only incidences emerging from multiple-choice probes (which restrict the choice of responses by providing only one correct and several suspected difficulties) were reported on in Chapter 6, Tables 6.3 (page 132) and 6.5 (page 146). I do not claim that these incidences are concrete as the nature of responses and of interpretation tend to be subjective. However, the incidence should give an idea of the extent of the difficulties encountered by students interpreting arrow symbolism.

3.2.3 Validity and reliability

During the design and implementation of the above methods, the validity and reliability of the evidence was considered, as, according to White & Gunstone (1993) and Johnson & Gott (1996) only evidence that is carefully evaluated can carry implications for teaching and learning - the intended outcomes of this investigation.

3.2.3.1 Validity

Validity, a requirement of both quantitative and qualitative research, ensures that the data collection tools determine what they are designed to measure (Sanders & Mokuku, 1993; Cohen *et al.*, 2000). Validity was therefore addressed in all of the various stages of the investigation, including the stages of design, data gathering, data analysis and data reporting (Cohen *et al.*, 2000). Although various types of validity are described by researchers (e.g. Sanders & Mokuku, 1993; White & Gunstone, 1993; Johnson & Gott, 1996; Gall *et al.*, 1996; Cohen *et al.*, 2000), only those types most pertinent to the study will be discussed.

Validity of quantitative data applicable to this study

Cohen *et al.* (2000, page 105) suggest that validity of quantitative data 'might be improved through careful sampling, appropriate instrumentation and appropriate statistical treatments of the data.' Multiple-choice questions were used for two of the probe sets as this type of probing provides suitable data for quantification. Furthermore, the information being investigated was meticulously sampled, with findings of the evaluations and difficulties with interpretation of arrow symbolism categorised and recorded in spreadsheets and grids. All calculations were checked for accuracy. The incidence was recorded by creating frequency distributions and by calculating the percentage of the total for each category. By inspecting the frequency distribution, the range and incidence of each category could be easily seen (Rogan, 2005). As these were descriptive statistics opposed to inferential statistics, statistical analysis using Chi-squared or similar tests was not advisable (Rogan, J., 2005, pers comm). I did, however, calculate the respective standard deviations (designed to measure the extent to which scores deviate from their mean) to compare the incidences of difficulties for the two categories of difficulties that emerged, as reported in Chapter 6.

Validity of qualitative data applicable to this study

In qualitative investigations such as this one, validity can be addressed through the honesty, depth, richness and scope of data obtained, the extent of triangulation and the objectivity of the researcher. In this investigation into the use of arrow symbolism in biology diagrams, I therefore addressed the following issues through internal validity, content validity, construct validity and external validity.

a. *Was the design and administration of the instruments used in the investigation appropriate to the aims of the investigation?*
b. *Were the respondents suitably selected and prepared for the task?*
c. *Was objectivity promoted and subjectivity controlled as far as possible within the constraints of qualitative research?*
d. *Was the investigation comprehensive and representative?*
e. *Are the results generalisable to the wider population, cases and situations?*
f. *Was triangulation an integral feature of the investigation?*
g. *Was neutrality established?*

Each question is briefly addressed below.

a. *Was the design and administration of the instruments used in the investigation appropriate to the aims of the investigation?*

Internal validity describes the extent to which the explanations of the findings are true to the sample from which the data was collected (Anderson & Arsenault, 1998; Cohen *et al.*, 2000). Lincoln & Guba (1985), McMillan & Schumacher (1993) and Cohen *et al.* (2000) suggest various ways that credibility can be addressed, several of which feature in these investigations.

1. Face validation was carried out to check that the probes were suitably developed.

A supervisor and at least one fellow-researcher and /or teaching colleague passed judgement on the format of all written probes and the intended format for interviews to detect potential problems. Modifications could be implemented prior to the probes being presented to students. Critique was sought on:

- The suitability of the instructions for completing the probes
- The appropriateness of the level of sophistication of the probes, including language level for Grades 11 and 12 students, the targeted sample group, as suggested by Odom & Barrow (1995)
- The suitability of the length of the probes
- The sequencing of questions
- The quality of the questions
- The clarity of purpose.

Modifications were made where deemed appropriate. For example:

- Probe set 1.1 was initially too long and too focussed. Only two questions (detailed in probe set 1.1, page 233) were retained.
- Probe set 1.6 (page 248) initially of 30 questions, was considered too long and was therefore divided into two parts, Section A and Section B.
- The wording in several probes was re-phrased.

2. Pilot studies were conducted.

The semi-guided probes were not piloted on a separate group of students. Firstly, the probes consisted of few questions that were, after modifications, considered by supervisors to be appropriately broad to allow students to respond in a free manner. Furthermore, no problems were encountered during application of the probes and the probes yielded the required information. The probes were therefore accepted as suitable. The multiple-choice probes on Figures 6.2 and 6.3 (page 121) were piloted on small groups of students to check that the instructions and questions were clear to the students and that the distractors were appropriate. In addition, pilot interviews on both Figures 6.2 and 6.3 were conducted and transcribed to check on the suitability of the interview format. In both cases, the responses were analysed for potential problems and the analyses checked by an expert. Modifications were made to the probes where deemed necessary. For example, interviewer techniques were honed.

3. The accuracy of arrow presentation was evaluated against expert opinion.

A comprehensive set of criteria (see Table 5.1, Chapter 5, page 95) informed by an exhaustive survey of over 100 literature sources as well as input and opinion of students, educators and a graphic designer was developed, against which to evaluate the presentation of arrow symbolism in the diagrams used in the probes. The results of the evaluations informed the design of the probes and alerted the researcher to potential problems prior to the diagrams being presented to students.

b. Were the respondents suitably selected and prepared for the task?

For the investigation of student interpretation of arrow symbolism, six groups of respondents were drawn from the classes of four educators over three successive years. All students had recently been instructed in the relevant subject area. Pre-tests were given to check that students had a level of conceptual understanding in the context of the probes and could achieve at least 40% on higher grade. Although honest responses cannot be guaranteed, probing was conducted in a non-threatening way and students were encouraged to answer freely. Students were also assured that they were not being assessed on a personal level.

c. Was objectivity encouraged and subjectivity controlled as far as possible within the constraints of qualitative research?

Objectivity was promoted (and subjectivity controlled) in the following ways.

1. As already noted, the presentation of arrow symbolism was evaluated using the comprehensive set of criteria (Table 5.1, Chapter 5) based on experts' opinion.

2. As it is difficult to determine what constitutes a valid test for the complex and multi-modal process of understanding, the study of students' interpretations of arrow symbolism was based on research frameworks successfully used and adequately described by other researchers.

3. Propositional knowledge statements, against which to check the responses to probes, were developed (as described in Section 3.2.2.2, page 30) and verified by experts.

4. The emerging information was reviewed by colleagues for adequacy and objectivity.

d. Was the investigation comprehensive and representative?

Lincoln & Guba (1985) advise that validity increases as the scope and representativeness of the data broadens. I addressed this in several ways.

1. Content validity is addressed by using instruments that are comprehensive and fairly cover the domain (Cohen *et al.*, 2000), in this instance of arrow symbolism. The investigation included both the evaluation of arrow presentation (Chapter 5) and assessment of students' interpretations of arrow symbolism (Chapter 6) in different diagram types (Figures 6.2 and 6.3). For each of the six probes, at least one or more supervisors, fellow-researchers and /or teaching colleagues was asked to pass judgement on whether the probes adequately covered all of the features of arrow symbolism used in the diagrams.

2. By providing opportunities for various skills of communication to be tested, mode validity (as defined by White & Gunstone, 1993) was also tested. The various probes required different techniques of expressing or demonstrating understanding. These included written explanations during semi-structured probes; selection and justification of the choice of a propositional statement from several distractors in multiple-choice probes; verbal discussion and explanation during interviews; and drawing techniques to modify diagrams.

3. Persistent observation of the data using numerous examples, study groups and successive probes in both the studies on arrow presentation (Chapters 4 and 5) and student interpretations of arrows (Chapter 6) established the relevance of the findings. The investigations were intensive and prolonged, stretching over three years, incorporating six separate probes, each of which was presented to different groups of students.

4. Furthermore, continual revision of the hypotheses (termed negative case analysis) as more data became available from further evaluations of diagrams and responses to successive probes, reinforced the idea that the emerging theories were applicable to all relevant cases.

e. Are the results generalisable to the wider population, cases and situations?

External validity explains the degree to which results can be compared and generalized to wider populations, cases and situations (Anderson & Arsenault, 1998; Lincoln & Guba, 1985; Cohen *et al.*, 2000). According to Gall *et al.* (1996), a high level of incidence may suggest a high level of external validity of the data.

The generalisability of the set of criteria developed in Chapter 5 was demonstrated by using the criteria to effectively evaluate a relatively large number of diagrams (614), in seven biology textbooks. Some degree of inappropriate presentation of arrow symbolism was revealed for each criterion. However, as six of the seven textbooks were South African publications, evaluating a wider selection of textbooks would enhance the investigation. Extensive probing was done of a relatively large number of students (over 200) from the classes of four different educators over three successive years. Although relatively high incidence of certain difficulties emerged, high percentages of students gave acceptable responses (compared to the propositional statements). This was in itself a good indication of the validity of the probes. However, the sample of students was drawn from a single school and further research is indicated to ensure comparability and generalisability beyond the immediate community. If validity holds, the level 3 difficulties that emerged during this investigation could be promoted to level 4 of the framework (Grayson *et al.*, 2001).

f. Was triangulation an integral feature of the investigation?

Triangulation is a strategy recommended by researchers (e.g. Lincoln & Guba, 1985; McMillan & Schumacher, 1993; Gall *et al.*, 1996; Bell, 1999; Cohen *et al.*, 2000) to improve validity, as reliance on one method of investigation only may bias the researcher's view. By combining the approaches of using the same method on different occasions and different methods on the diagrams under study, as suggested by Johnson & Gott (1996), and evaluating the comparative results, more accurate descriptions could be developed. The validity of the investigation was therefore strengthened and confidence in the results was fostered. In this dissertation, triangulation was satisfied as follows:

1. Various types of probes were used: semi-guided, multiple-choice with justification, interviews and student modification of diagrams
2. All types of probes were repeated on both of the selected diagrams (Chapter 6, Figures 6.2 and 6.3)
3. The probes were used on different occasions using several different sample populations
4. Emerging data was corroborated. The student responses were compared to the descriptions in the various categories and subcategories of difficulties to determine patterns, similarities and differences in the emerging data.

Although cognisance was taken of difficulties with incidences of less than 8%, they were not reported on for two reasons:

1. In the interest of brevity, and
2. The difficulty, shown by only one or two students, may have resulted from transient responses that needed further investigation to be considered at Level 3 on the 4-level framework of Grayson *et al.* (2000).

f. Was neutrality established?

For communication to be successful, the researcher should understand the intentions of the student and vice versa (Domin, 1996). However, according to the theory of constructivism, the cognitive and conceptual structures of people vary. Johnson & Gott (1996) suggest that there is a 'translation interface' for communication between two individuals, in which underlying meaning can differ. They further suggest that an area of neutral ground (an area of largely but never completely, undistorted communication) should therefore be established between the student and researcher to facilitate meaningful discourse. To maintain neutral ground, a neutral approach to the task was maintained, with the researcher avoiding leading questions and questions expressed in ways that may have taken the task out of neutral ground (e.g. beyond the understanding of the student). Valid insight into the nature of the data and sources of difficulties was thereby fostered.

3.2.3.2 Reliability

According to Johnson & Gott (1996), reliability refers to the replicability of the study on other occasions and in other instances. Theoretically (although not possible as every person's knowledge is unique and changes continually) replicability should remain stable over time, over groups of respondents, between observers and over equivalent instruments (Cohen *et al.*, 2000). Although necessary for validity, reliability is in itself not sufficient for validity. In other words, an unreliable probe will not be valid, but a reliable probe may be invalid (White & Gunstone, 1993; Bell, 1999). To improve reliability, data and findings should be controllable, predictable, consistent and replicable (White & Gunstone, 1993; Bell, 1999; Cohen *et al.*, 2000). In this dissertation, reliability was addressed as follows:

1. In Chapter 5, I compared my evaluations of arrow presentations to those of the graphic designer and used the same set of criteria to evaluate the arrow symbolism in all diagrams.
2. In Chapter 6, measures taken to ensure reliability included the following:

- The investigation of interpretive ability required a series of different types of probes. These included multiple-choice probes that are considered to have a high reliability.
- The same series of probes (semi-guided, multiple-choice probes, clinical interviews and student modification of diagrams) was used in parallel investigations on students' interpretation of arrow symbolism in different types of diagrams (Figures 6.2 and 6.3). Similar results were obtained for successive probes on each diagram and similar results for comparable criteria across the probes used in the different tasks.
- To avoid inter-rater differences (McMillan & Schumacher, 1993), all questionnaires were marked /rated by the same researcher. However, to improve inter-coder reliability, samples of student responses to written probes and transcripts of interviews were read by other researchers to gauge their level of agreement of the interpretations, as recommended by White & Gunstone, 1993; Phelps, 1994; Anderson & Arsenault, 1998. If necessary, the descriptions of difficulties were reclassified until consensus was reached.
- Although the reliability of methods can be controlled, Phelps (1994) warns that the subjective nature of humans cannot be controlled. I nevertheless endeavoured to maintain a high level of motivation and interest. Explicit instructions, suitable to Grade 11 and 12 students, were given orally and in written form. In addition, the researcher was on hand throughout the probing process to answer questions related to the process. Further, interviews were conducted with students who were willing to participate in the programme.

Using these methods, I attempted, and I believe succeeded in controlling factors that may threaten reliability including the situational factors, test-marker factors and instrument variables discussed above. However, excessive emphasis on reliability goes against the principle of uniqueness required of a naturalistic study (Cohen *et al.*, 2000) and can reduce the assessment of mode validity explained above (White & Gunstone, 1993). I considered it important for ideas to emerge and therefore encouraged students to respond freely. Also student knowledge is forever changing even during answering of probes, so repeatability of data is difficult.

Conclusions about validity and reliability in this study

Complete validity and reliability can never be claimed. Rather the degree of validity and reliability should be considered (Cohen *et al.*, 2000). Confidence in the validity and reliability of the data collected increases with sample size, generalisability, the number of measurements made, preferably at different times and ideally with different instruments, and with the range of dependent ideas that are examined. I have explained how I considered and controlled these various factors within the scope of this study. I am therefore confident that the results of the investigations of the presentation and interpretation of arrow symbolism were achieved within acceptable levels of validity and reliability.

3.2.4 Ethical issues

Appropriate ethical clearance was obtained to perform the study. The nature and purpose of the study was fully explained to the headmaster, Mr D. Wilkinson of St Anne's Diocesan College, the school that the students attended; to the supporting educators who helped to administer the written probes; and to the students participating in the investigation. The students were briefed about the procedures and duration of the tasks that they were required to do, as well as about the potential benefits (including personal feedback) that could be derived from participation. Although students were encouraged to participate, involvement was voluntary and students were free to withdraw from the project without penalty. Permission was granted from the headmaster and from the students to use and publicise student responses, including audio- and videotaped and transcribed interview data, on the understanding that the students would remain anonymous.

3.2.5 Concluding remarks

The above discussion highlights my choice of methods for the investigation into the presentation and interpretation of arrow symbolism in biology diagrams based on the methods of previous researchers. Not only did I motivate for the procedures adopted and argue for their validity and reliability, but I also explained the limitations of the methods and the counter-measures that were used to minimise their effects.

CHAPTER 4
AN ANALYSIS OF ARROWS AND HOW THEY ARE USED IN TEXTBOOK DIAGRAMS

4.1 INTRODUCTION

As reported in the literature review (Chapter 2), the last few decades has seen an unprecedented escalation in the use of diagrams in educational resources, especially the use of stylised and abstract types as explanatory tools (e.g. Kress & van Leeuwen, 1996; Pinto *et al.*, 2000). Such diagrams use symbolism including arrow symbolism to convey their 'message' (e.g. Lowe, 1991; Henderson, 1999; Ametller & Pinto, 2002). This would suggest that arrow symbolism is widely used in textbook diagrams, including for the teaching and learning of science subjects. However, contrary to my expectations, a review of the literature revealed limited research on the use of arrow symbolism in diagrams in science textbooks (e.g. Schollum, 1983; Henderson, 1999; Ametller & Pinto, 2002) and particularly in biology textbooks (e.g. Barman & Mayer, 1994; Barman *et al.*, 1995). As there appears to be a dearth of information on arrow symbolism in biology diagrams, I needed to establish the importance of, and need for, a systematic study of arrow symbolism in this field. I therefore turned to the very source of such information and reviewed the presentation of arrows in biology textbook diagrams as part of the preparatory investigation for this study.

4.2 RESEARCH QUESTIONS

In this study I addressed Research Question 1 (Chapter 1): *How much of a problem is arrow symbolism in biology diagrams?* To answer this question, I made use of various types of evidence, discussed below and summarised in Figure 4.1, page 56. This included the literature presented in Chapter 2 and the literature and content analysis results obtained from addressing the following sub-questions:

a. What types of diagrams occur in biology textbooks and what is the prevalence of arrow symbolism in such diagrams?
b. What is the diversity of mode of arrow presentation (style and spatial organisation), including conventions, in biology textbook diagrams?
c. For what variety of purposes are arrows used in biology textbook diagrams?
d. For what range of meanings are arrows used in biology textbook diagrams?

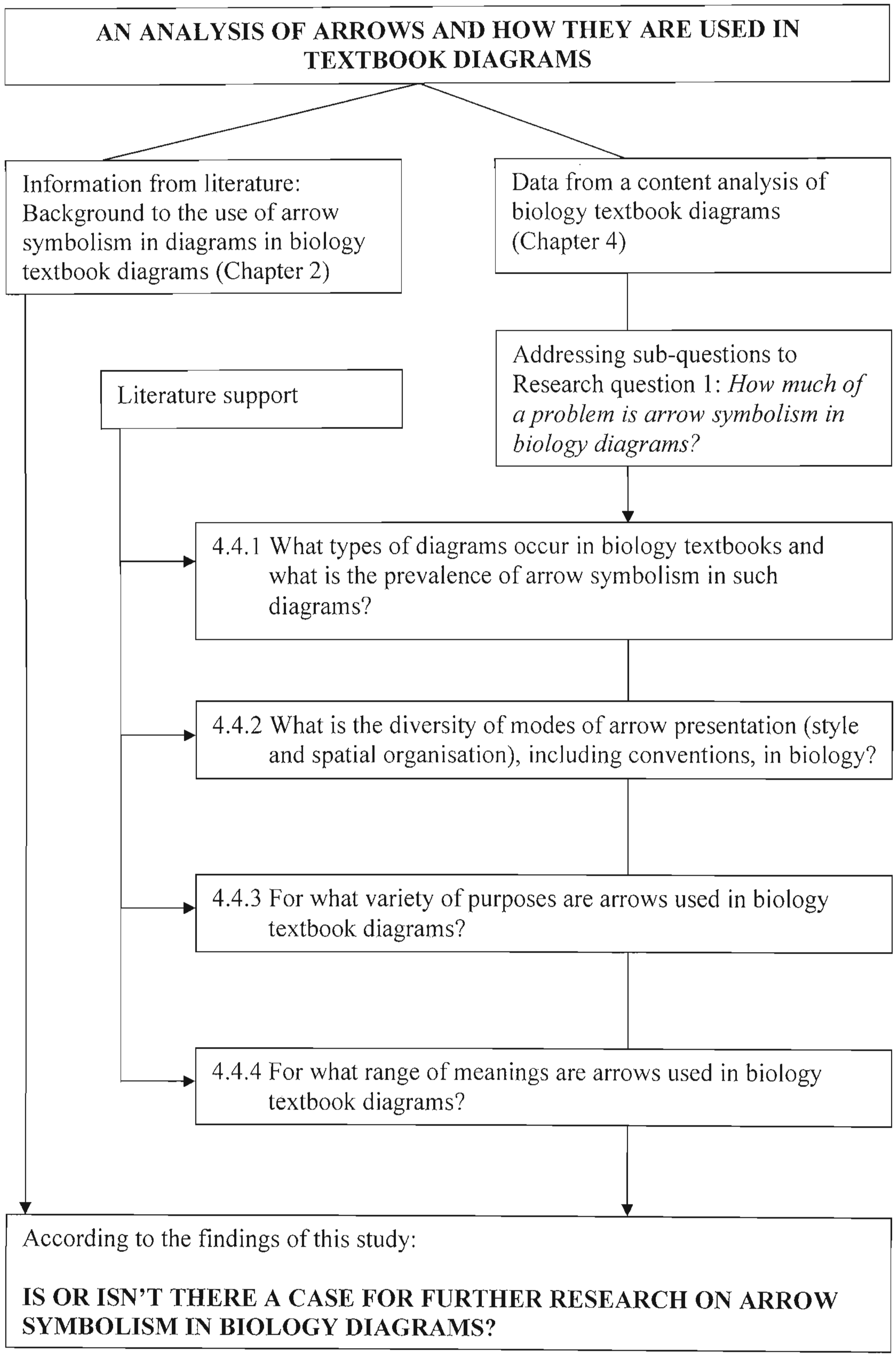


Figure 4.1 Summary of the different types of evidence used to analyse the use of arrow symbolism in biology textbook diagrams.

4.3 METHODS

4.3.1 Selection of textbooks for content analysis

Information obtained from a convenience survey (Cohen *et al.*, 2000) of 50 KwaZulu-Natal teachers in 35 schools and various publishing houses was used to select the three most popular series of South African textbooks (Ashwell *et al.*, 1999a and 1999b; Degenaar *et al.*, 1999 and 2000; Ayerst *et al.*, 2000a and 2000b) and a comprehensive British text /reference book (Roberts *et al.*, 1993) from four different publishing houses. All the books were currently being used in the teaching of biology to Grade 11 and 12 students in schools in the KwaZulu-Natal region of South Africa. Each South African series consisted of two books, one for Grade 11 and one for Grade 12 students, while Roberts *et al.* (1993) comprised a single book covering topics taught in both years of study. These seven books were then subjected to content analysis as described below.

4.3.2 Content analysis of textbooks

The above four research questions were addressed by content analysis methods (Cohen *et al.*, 2000; Bell, 2001), explained in Chapter 3, Section 3.2.2.1, page 27. A complete census (Rogan, 2005) was undertaken of all 3218 diagrams in the selected textbooks. These findings were supported by a survey of relevant literature. The following are details of how each research sub-question was addressed:

1. Types and prevalence of diagrams and prevalence of arrow symbolism in diagrams

The types of diagrams presented in the selected textbooks were identified and categorised according to their structural and functional similarities and differences, drawing ideas from previous diagram researchers such as Alesandrini (1984), Lowe (1986 and 1993b), Larkin & Simon (1987), Hill (1988), Wheeler & Hill (1990), Lohse *et al.* (1991), Kress & van Leeuwen (1996), Henderson (1999), Cheng *et al.* (2001), Stenning & Lemon (2001) and Blackwell & Engelhardt (2002). Three types of diagrams were identified namely realistic, stylised or abstract types as defined in the Glossary (see Diagram types). The results of this analysis are presented as both the number and percentage of each type of diagram in each of the selected textbooks. The prevalence of diagrams in each of the textbooks was ascertained quantitatively and the results expressed as the average number of diagrams per page. The occurrence and prevalence of arrow symbolism in diagrams and in each type of diagram was then determined and expressed as the number and percentage of diagrams with arrow symbolism.

2. Diversity of mode of arrow presentation

The diversity of modes of arrow presentations (arrow styles and spatial organisations, including commonly used conventions) was determined in the selected biology books. Using the results of the content analysis and descriptions suggested by the literature (e.g. Lowe, 1993b; Kress & van Leeuwen, 1996), a taxonomy of spatial organisations was produced (see Table 4.3, page 64).

3. Purposes of arrow symbolism

The purposes for which arrow symbolism is used in the selected textbooks were also established, categorised and correlated with the types of spatial organisations and commonplace arrow styles.

4. Meanings of arrow symbolism

The range of meaning attributable to arrows as connectors between elements of the diagram was analysed and matched to ideas in the literature.

4.4 RESULTS AND DISCUSSION

4.4.1 What types of diagrams occur in biology textbooks and what is the prevalence of arrow symbolism in such diagrams?

The content analysis of the textbook diagrams yielded the results presented in Table 4.1, page 59.

Prevalence of diagrams and importance of considering their use in textbooks

The number of diagrams per page in the textbooks analysed ranged from an average of 0.64 to 1.9 diagrams per page, with an overall average of 1.1 diagrams per page (Table 4.1, page 59). In other words there was, on average, at least one diagram on every page. These results reinforce the opinions of other researchers that modern science textbooks have a large number of diagrams (Gould, 1977; Reid & Miller, 1980; Evans *et al.*, 1987; Hill, 1988; Lowe, 1988a; Reid, 1990a; Eltinge & Roberts, 1993) that form an integral part of science texts, thereby providing an important role in the communication of science concepts. Thus diagrams are an important consideration in using textbooks and, therefore, demand the attention of graphic researchers.

Table 4.1 The prevalence of diagrams and of arrow symbolism in each diagram type (realistic, stylised and abstract) in the selected textbooks reviewed.

	All diagrams				Diagram type											
					Realistic				Stylised				Abstract			
Textbook	Total no.	Av. per page	No. with arrows	% with arrows	No.	% of total diags.	No. with arrows	% with arrows	No.	% of total diags.	No. with arrows	% with arrows	No.	% of total diags.	No. with arrows	% with arrows
Ayerst *et al.* (2000a)	366	1	63	17	173	47	2	1	174	48	48	28	19	5	13	68
Ayerst *et al,* (2000b)	291	0.8	117	40	48	16	0	0	174	60	77	44	69	24	40	58
Ashwell *et al.* (1999a)	379	1.3	93	25	161	42	2	1	182	48	69	38	36	9	22	61
Ashwell *et al.* (1999b)	402	1.2	179	45	91	23	0	0	222	55	116	52	89	22	63	71
Degenaar *et al.* (1999)	220	0.7	57	26	25	11	1	4	184	84	49	27	11	5	7	64
Degenaar *et al.* (2000)	212	0.6	105	50	1	0	0	0	149	70	58	39	62	29	47	76
Roberts *et al.* (1993)	1348	1.9	393	29	641	48	5	1	477	35	282	59	230	17	106	46
Total	3218		1007		1140		10		1562		699		516		298	
Average for the books analysed	460	1.1	143	31	163	35	1	≤ 1	223	49	100	45	74	16	116	58

Prevalence of each diagram type (realistic, stylised and abstract) and importance of considering its presentation

Examples of all three types of realistic, stylised and abstract diagrams were found in the textbooks. The data relating to the categorisation of diagrams into these types indicated a clear predominance of stylised diagrams (with a total of 1562 or 49% of the 3218 diagrams analysed) over both realistic and abstract representations, which showed prevalence of 35% and 16%, respectively. The high proportion of diagrams in the stylised and abstract categories (65% of all diagrams) suggests that design criteria, including symbolism, and their intended cues to diagram functions, should be integral to an analysis of diagrams and, therefore, an important target of research. This is supported by suggestions from the literature (e.g. Lowe, 1988c) that both the type of diagram, and how it is used, should be contemplated.

Prevalence of arrow symbolism and the importance of considering its use in diagrams

The prevalence of arrow symbolism was also determined and the results presented in Table 4.1. These findings indicate that between 17% and 50% (with an average of 31%) of diagrams studied use arrow symbolism. Using the average of 1.1 diagrams per page, diagrams with arrow symbolism, therefore, occur on approximately every third page. This supports similar data presented by Schollum (1983), relating to science textbooks read by 13/14 year olds, and reinforces the importance of arrow symbolism in textbook diagrams. Considering only the stylised and abstract categories of diagrams (as, on average, less than 1% of realistic displays employ arrow symbolism), the prevalence of diagrams using arrows rises to an average of 48%. As there are more stylised diagrams than abstract diagrams, most arrow symbolism (70%) occurs in the former. However, arrows are used, on average, in 58% of abstract diagrams compared with 45% of stylised diagrams. The results (presented in Table 4.1) therefore indicate the widespread use of arrow symbolism in a range of diagrams and strongly emphasise their importance in the presentation and interpretation of diagrams.

Not only do the data in Table 4.1 show a marked increase in the use of arrow symbolism going from realistic to stylised to abstract diagram types, but also an increase in arrow prevalence going from the Grade 11 to Grade 12 books. For example, 17% of diagrams in the Grade 11 book of the Ayerst *et al.* (2000a and 2000b) series have arrow symbolism compared with 40% in the Grade 12 book. Presumably, this also indicates a shift in emphasis from structure to process. These results further highlight the importance of arrow symbolism in biology diagrams, particularly at higher Grade levels.

4.4.2 What is the diversity of mode of arrow presentation (style and spatial organisation), including conventions, in biology textbook diagrams?

The mode of presentation including both style of presentation of individual arrows, spatial organisation or arrangement of arrows in the diagram, and arrow conventions, were considered in the content analysis of the selected textbooks.

Diversity of styles of presentation

Categorisation of arrow styles in the selected textbooks revealed over 100 styles of presentation including variations in both the head and the shaft of arrows. The styles also included a variety of shapes (such as curving, tapering, forked, interrupted line, indented), as well as a variety of sizes, widths, lengths, colours, shading and stippling, directions, ways of converging, diverging, joining, overlapping, intercepting, and so on. Most were two-dimensional representations, but some arrows were drawn to represent three-dimensional, solid, or hollow structures. Various variables affecting arrow style were identified and are presented in Table 4.2. Such extreme diversity of arrow style clearly established the great significance of arrow symbolism in biology diagrams and the importance of doing research in this area.

Table 4.2. Variables identified in the selected textbooks that affected the diversity of arrow style.

Variable	Shaft/s	Head/s	Tail/s (origin)
Tail defined	-	-	Defined /not distinctly defined from shaft. IF DEFINED:
Size	Length	Size (relative to shaft)	Size (relative to shaft)
	Width (line thickness)		
Shape	Line shape (curved, straight, twisted etc.)	Head shape (considering points and sides of 'triangular' shape)	Tail shape (e.g. flared, pronged)
	Taper		
Format	Solid line, dashed, dotted	-	-
Fill	Fill (bold, stippled, no fill etc.)	Fill (bold, stippled, no fill etc.)	Fill (bold, stippled, no fill etc.)
Colour	Colour	Colour	Colour
Combined arrows	Split or merge	Uni- /bi-directional (position of heads)	-
	Point/s of split /merge		
	Number of shafts joining	Number of heads	Number of tails
Special effects	Slashed (e.g. by: /)	Position relative to shaft (e.g. mid-shaft)	-
	3 -dimensional format	3 -dimensional format	3 -dimensional format

Importance of considering styles of arrows

The results of the literature survey strengthened the above assertion that it is important to consider arrow style when using and researching arrow symbolism in biology diagrams. For a start, the styles of presentation affect the interpretation (whether literal or causal) of the symbolism, in the context of the related elements of information (termed referents or participants). Tversky *et al.* (2000, page 229) aptly explained the importance of arrow style: 'arrows suggest certain physical properties that have cognitively compelling conceptual interpretations'. All features of the presentation of arrow symbolism, such as placement, pointing direction and physical characteristics of arrows, including shape, colour and dimensions, are important in determining the potentially broad and sometimes abstract meaning of the diagram (Lowe, 1993b; Hardin, 1995; Kress & van Leeuwen, 1996). However, the diversity of arrow styles is also attributable to artists' licence in an attempt to create eye-catching displays, with possibly little regard or thought for the intention of the arrow symbolism (Wheeler & Hill, 1990). This further suggests that one area of diagram research should focus on evaluating the style of presentation of arrow symbolism to ensure that its presentation is in accordance with its intentions.

Diversity of spatial organisations using arrow symbolism

Perini (2005) claims that spatial properties of symbols are 'the defining feature of visual representations' (page 259) and that the 'meaning of diagrams is determined by the two-dimensional array of atomic characters [units within the diagram]' (page 260). It is therefore important to consider the spatial organisations of arrows, as arrows may be used to create links between referents, thereby creating layouts of information to specify associations between the elements.

Realistic diagrams (in accordance with the nature of their definition), usually only have arrows for the purpose of pointers for labelling or indicating positions, while stylised and abstract categories of diagram may have pointers but more commonly use informative arrows to communicate relationships and therefore purpose. Arrows in stylised diagrams are presented in combination with other structural and spatial elements in a diversity of spatial organisations, while arrows in abstract diagrams (e.g. flow diagrams) link text or frames containing text, creating spatial presentations of non-spatial information. Arrows may be presented singly (one arrow per diagram) or in a multiple context either as discrete arrows (each arrow functioning on its own to determine individual meaning), or collectively (two or more arrows per functional unit), or as a combination of both discrete and collective formations. Such diversity clearly results in a wide variety of spatial organisational formats that could prove confusing to a novice in biology.

Taxonomy of arrow spatial organisations

To make sense of the diversity of spatial organisations in the textbook diagrams, I devised a taxonomy of arrow formats based on the findings of this study and ideas in the literature (Lowe, 1993b; Kress & van Leeuwen, 1996). In this taxonomy (Table 4.3), I divided the diversity of arrow spatial organisations into three groups: discrete, collective and combinational presentations. I termed the first group discrete presentations to refer to individual arrows linking two elements of information, for example:

Water ⟶ Jug

Discrete presentations occur either singly in a diagram or as 'stand alone' arrows in a multiple context.

Sub-categories include arrows used as pointers (for labelling or indicating position) and informative arrows detailing information about the relationships within the diagram or between diagrams in a compositional display (related diagrams linked by arrows to show particular relationships).

I termed the second group of spatial organisations, collective presentations, to refer to groups of arrows that, together, form units of information. These were divided into four sub-categories namely chains, groups, networks and mixed displays (formed from any combination of chains, groups and networks). A range of chain formations, commonly called flow charts (see definitions by Maribe (1997) and Paquette *et al.* (2006)), showing sequences in single or multiple lines (Lowe, 1993b) were identified and categorised into three basic chain patterns, namely linear, cyclic and cascade-type spatial organisations (Hull, 2003). These in turn were termed simple, semi-complex and complex, depending on the degree of interconnections used in the arrangement.

Table 4.3 Taxonomy of the spatial organisations of arrow symbolism used in biology diagrams developed from a content analysis of the seven selected textbooks.

Type of arrow presentation	Category of spatial organisation	Sub-category of spatial organisation
Discrete (individual arrows linking two elements of information, either as single arrows in a diagram, or as 'stand alone' arrows in a multiple context)	Pointers (arrows referring to one referents only) indicating:	Labels
		Position
	Informative (arrows referring to two referents, detailing information about the relationships within the diagram or between diagrams)	Specifying a singular relationship
Collective (groups of arrows that together specify meaning)	Chains e.g. flow chart (layouts showing sequences in single or multiple lines – simple to complex depending on the degree of interconnections used in the arrangement)	Linear (a single line of arrows in a straight horizontal or vertical format)
		Cascade (arrows in a step-wise layout)
		Cyclic (a circular pattern of arrows)
	Groups: Parallel arrows (each distinct)	Oppositely aligned
		Similarly aligned
	Groups: Connecting (joined at some point)	Branching: Converging
		Branching: Diverging
		Coupling
	Networks (patterns of multiple arrows in arrangements as per sub-categories)	Tree diagrams (not necessarily formally divergent and usually in a bottom-up layout)
		Hierarchy (systematically divergent, showing linear relationships, with a top-down, or sometimes left-right, layout)
		Genetic diagrams (specifically showing genetic relationships, systematically divergent showing lateral and vertical associations, with a top-down, or sometimes left-right, layout)
		Network maps (a strong central-outward layout and /or cross connections e.g. concept maps)
	Mixed (any combination of networks, chains, groups)	
Combinational (any combination of discrete and collective presentations)	Identify each presentation individually	

Grouped arrows were sub-divided into parallel-arranged arrows (either oppositely- or similarly- aligned) and connecting, or joined, arrows (including diverging and converging arrows and coupled formations). The four types of network diagrams identified were hierarchies and genetic diagrams (both of which usually use a systematically divergent and top-down spatial organisation, or occasionally a left-right format), tree diagrams (which may be less formally divergent, and usually in a bottom-up layout), and network maps. Network maps show a strong central-outward tendency, as in content maps, often with cross connections as in concept maps, although the latter were not evident in the textbooks analysed. I termed the final group of spatial organisations, combinational presentations to refer to any combination of both discrete and collective arrows in a single diagram.

Importance of considering spatial organisations of arrows

Spatial organisations, including the order and appearance of, and distance between, units (elements) of information, are an integral part of diagram presentation. Such patterns may carry specific information about, and therefore influence interpretation of, the scientific content represented in the diagram and give clues to the significance or purpose of the arrow symbolism, including about relationships between elements of the diagram (Kress & van Leeuwen, 1996; Stylianidou *et al.*, 2002). The diversity of spatial organisations revealed in the content analysis is testimony to the range of messages that can be cued. This diversity could, in itself, be confusing to students, but more so if the types of patterns do not promote the intended purposes of the diagrams. Moreover, the way that multiple arrows are arranged in spatial organisations may influence the way they are perceived in accordance with the Principles of Perceptual Organisation (Kosslyn, 1989; MacEachren, 1995; Kress & van Leeuwen, 1996). As this will, in turn, influence the interpretation of the diagram, it is important to consider these principles when using and designing diagrams with arrow symbols. This information therefore suggests that it is most important to do research into the presentation of arrow patterns in diagrams.

Use of conventions of modes of presentations (styles and spatial organisations) and importance of considering them

Despite the fact that such a multitude of variations in modes of presentation (styles and spatial organisations) could create difficulties for the interpreter, a survey of the available literature revealed that commonly accepted modes of presentation are few in number, are not universal or consistent (Lowe, 1993b; Henderson, 1999), and have only limited formal rules governing their use (Guri-Rozenblit, 1988b; Lowe, 1993b). Although the language of 'conventions' may be recognisable, it is often generated intuitively (Garland, 1979; Salomon, 1984). In addition, 'conventions' tend to be culturally specific (Szlichcinski, 1979; Kress & van Leeuwen, 1996) and therefore not necessarily obvious to the reader (Lohse *et al.*, 1991; Wheeler & Hill, 1990; Scaife & Rogers, 1996). In addition, they may be misunderstood as a result of communication between the authors and the graphic designers of diagrams (Garland, 1979; Lowe, 1993b), resulting in inconsistent design and ambiguous interpretation (Guri-Rozenblit, 1988b). Furthermore, diagrams with different purposes may use different conventions, requiring different strategies for their interpretation (Henderson, 1999).

In the present study, analysis of the textbooks revealed various expected conventions of style to cue for specific scientific concepts, such as those shown in Table 4.4.

Table 4.4 Examples of arrow conventions (or commonplace styles) used to cue for specific scientific concepts.

Commonplace style	Scientific concept
Zigzag or wavy arrow shaft	energy, photon, radiation, convection, conduction, light waves or sound waves
Broadening or narrowing of arrow shaft	change in magnification
Dotted, attenuated or interrupted line for arrow shaft	many purposes such as inhibition of processes controlled by enzymes or hormones
Combination of curved and straight arrow (see Figure 5.4)	chemical coupling e.g. ADP /ATP reaction
Arrow broken by a slash	interruption of process

The expected conventions of style included zigzag or wavy lines to indicate for example: energy, photon, radiation, convection, conduction, light waves or sound waves; broadening of arrows to show magnification; a dotted, attenuated or interrupted line for many purposes such as inhibition of processes controlled by enzymes or hormones; and a coupled presentation (see Figure 5.4, Chapter 5, page 107) to represent the ADP /ATP reaction. Such presentations were present in several diagrams and could therefore be termed commonplace. However, the commonplace styles could not be termed conventions, as they were neither restricted to single intentions, nor consistent within or between textbooks. For example a broken arrow shaft, commonly intended to show inhibition, was also used to show reaction pathways in two of the textbook diagrams analysed (Ayerst *et al.*, 2000b, page 121; Degenaar *et al.*, 2000, pages 166, 168). Occasionally the styles were not even consistent within diagrams, with the same arrow style having more than one purpose. Also arrows illustrating magnification were depicted in a variety of styles within each textbook, with shafts tapering from broad to narrow and vice versa. In addition, arrows were sometimes accompanied by various additional cues such as squares or circles. Such apparent disregard for universality strengthened my case for future research into the devising of such conventions for arrow styles used in biology.

Certain spatial organisations are used more consistently. In the textbooks selected for analysis, chain and network formats were commonly used to explain processes (see Table 4.3). In fact, Winn (1993) suggested that such formats have become so familiar that they may be regarded as conventions. Consequently, an expectation of purpose relative to the format may facilitate the intended interpretation, thereby improving comprehension, especially, according to Winn & Solomon (1993) when the content represented in the diagram is unfamiliar. In addition, competent western readers of text, use, and have come to expect, the convention of left to right and centre out (as in network maps), top to bottom (as in hierarchies and genetic diagrams), or bottom-up (as in tree diagrams) types of scanning (Goldsmith, 1987; Lowe, 1991; Winn, 1993; Winn & Solomon, 1993; Henderson, 1999). In both instances, spatial organisations presented contrary to expectations, or unawareness of the purpose of the format, may cause confusion. This further suggested that there is a strong case to research the use (including design and interpretation) of arrow symbolism.

Concluding remarks about considering the modes of presentation of arrow symbolism

The findings of the content analysis undertaken in this study revealed a vast range of styles and spatial organisations. This supports the suggestion of Scaife & Rogers (1996) that both style and spatial organisation are important aspects of mode of arrow presentation. Furthermore, the message portrayed by the modes of presentation may code for a particular message, often dependent on the particular context of the diagram. Students using arrows may therefore be confused. These findings therefore suggest that both aspects of mode of arrow presentation should be the target of ongoing research.

4.4.3 For what variety of purpose are arrows used in biology textbook diagrams?

The task (or purpose) of a diagram is defined in terms of the visual features in the display (Bennett & Flach, 1992; Kress & van Leeuwen, 1996). Arrows added to static structural diagrams can convey functional properties (Heiser & Tversky, 2006). Hardin (1995) suggested four ways that arrows can be used to promote the purpose or functions of the diagram namely to:

- Point out information
- Identify information
- Direct actions (implying direction), and
- Connect or link referents in relationships

Tversky *et al.* (2000, page 229) summed up the purposes by saying that 'arrows suggest asymmetry, direction, in space, in time, in motion, in causality', although they also referred to the study by Horn (1998) which noted 250 purposes of arrows.

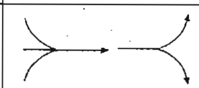
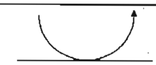
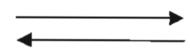
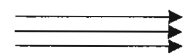
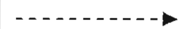
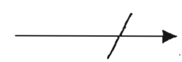
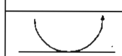
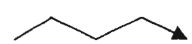
In the present study, the content analysis of the selected textbooks revealed a range of purposes (Table 4.5) for which arrows can be used including (among other more specific functions), directing attention to structures; indicating direction, magnitude and magnification; specifying stages or relationships within a process or sequence; and creating links between information in a diagram.

Classification of the purposes of arrow symbolism

In order to highlight the relevant links between mode of presentation and purpose, I used the framework suggested by the taxonomy of categories of spatial organisation (Table 4.3) to categorise arrow purpose. These provided the eight sub-categories A – H listed in Table 4.5, page 69. Categories A – D provide the scaffold of the discrete (single) arrows for both the pointer and various types of informative purposes. Category E caters for the purposes of the various types of chains, categories F and G for the intentions of groups of arrows, and H for the purposes of network formats. A ninth category (I) provides for the purposes of commonplace styles of arrow presentation. Within these 9 categories, thirty-seven broad sub-categories (Table 4.5, 1 – 37) of arrow purpose were identified in the analysed textbooks.

Table 4.5 A broad classification of arrow presentation (spatial organisations A – H, and style I) with corresponding purpose or intentions, 1 – 37, found in the seven biology textbooks analysed.

Type of presentation and category of arrow		Illustration	Purpose of arrow	
DISCRETE (arrows considered in their individual capacity)				
A	Single arrows used as pointers to direct attention to a single element (denoted by e)		1	Labels (Schollum, 1983; Hill, 1988; Henderson, 1999) i) Titular (give verbal information in words or titles) ii) Annotational (adding notes, give explanations)
			2	Position i) Indicative (directing attention to particular features (Lowe, 1993)) ii) Instructional (e.g. detailing instructions e.g. in an experimental process)
B	Single arrows in an informative capacity, presented between diagrams within a compositional display (a display composed of interlinked diagrams) to show a selected portion, (and therefore often associated with a circle, square or other identification means):		3	Identification of a specific entity or portion
			4	Magnification
C	Single, one shaft double headed arrows (head at each end) to inform a bi-directional spatial intention, for example:		5	Bi-directional chemical equations (either simultaneous or successive)
			6	Measurement (Schollum, 1983; Henderson, 1999) including range, scale, size, extent, distance
			7	Gradient
			8	Transects and sections
D	Single arrows of various styles presented between two elements (e), for purposes of informing about:		9	Affiliation (connections between elements)
			10	Direction (indicating direction (not spatial change) for concepts such as flow, movement, diffusion, osmosis etc. relative to referent)
			11	Rotation 
			12	Unidirectional chemical equations
			13	Results
			14	Graph axes
			15	Forces /Vectors (Schollum, 1983; Henderson, 1999)
			16 – 20	Various aspects of change noted in the collective category E.
COLLECTIVE (two or more arrows per functional unit)				
E	**Chains**			
	A collective of arrows in chain (e.g. flow chart) formation (in a variety of patterns such as linear, cyclic, cascade), to show change in a process (16), change in structure (17), sequential relationships (18), change in time (19) and change in space (20). (Schollum, 1983; Henderson, 1999)		16	To show progression within a process (causal relationships) e.g. biochemical processes
			17	To show changes in complexity or development of a structure (structural change) e.g. growth patterns, life cycles

E			18	To specify sequential dependencies (relationships between organisms e.g. food chains and webs)
			19	To map time lines and cycles (temporal change) (e.g. Winn & Holliday, 1981)
			20	To indicate directional progression (spatial change) of movement or flow (e.g. Schollum, 1983; Henderson, 1999)
F	**Grouped, connecting arrows**			
	Branched arrows to show convergence or divergence - two or more arrows presented as one arrow with either split tails (converging arrows) or split heads (diverging arrows)		21	Alternative pathways in process, development, sequence or direction
			22	Divergence or convergence, in various specialised circumstances e.g. light rays
			23	Fusion, fertilisation, gamete formation
	Coupled arrows in various patterns – two or more arrows contacting at some point of the shaft, but retaining their individuality:		24	Parallel reactions including release or uptake and transfer e.g. in chemical reactions
G	Grouped, parallel arrows (oppositely and similarly aligned)		25	Alignment of one entity to another either oppositely (see diagram for 26) or similarly aligned (see diagram for 27)
			26	Bi-directional reversible (successive) chemical reactions
			27	Several parallel similarly aligned to show the frequency effect (emphasis) e.g. for pressure (Kress & van Leeuwen, 1996)
H	**Networks**			
	Hierarchies (Divergent arrows in a top-down or left-right layout)		28	Whole /part (Set /subset) relationships (Lohse *et al.*, 1991; Lowe, 1993)
			29	Classifications (class membership) (Lohse *et al.*, 1991; Lowe, 1993)
	Genetic diagrams (Divergent and convergent arrows from top, down)		30	Genetic (showing combinations and possibilities between generations)
	Tree diagrams (Divergent arrows from bottom, up)		31	Evolutionary relationships
	Maps (Divergent arrows from a central frame)		32	Content maps
DISCRETE OR COLLECTIVE CATEGORIES				
I	Commonplace styles for specifying particular purposes Some arrows, if presented in a commonplace style, were relevant to more than one group and were therefore assigned to both.		33	Broadening or narrowing shaft to show change in size; amount; magnification
			34	Dotted, attenuated or interrupted line for many purposes e.g. inhibition, being less conspicuous
			35	Arrow broken by a slash to indicate interruption of process
			36	Curved arrow associated with chemical coupling
			37	Wavy or zigzag line to indicate energy transformations

The content analysis revealed that discrete arrows may be used as pointers (Category A) either to label, identify or annotate features of the diagram (Subcategory 1) or to give verbal information in words or titles (Subcategory 2). The verbal information may direct attention to particular positions or features, or give instructions (for example, in experimental methods). Discrete informative arrows (Category B), drawn between diagrams in a compositional display (see Glossary), are used to direct attention to a specific entity or portion of a diagram (3), often for the purpose of indicating magnification (4). For this purpose, arrows are often associated with an identification means such as a square or circle. Double-headed arrows (C) show bi-directionality (5), for example in chemical equations; measurements (6) for a variety of purposes (including range, scale, size, extent and distance); gradients (7); and transects and sections (8).

Our results also revealed that single arrows of various styles presented between elements (D), can show a range of purposes such as affiliation (9); direction without spatial change (10); rotation (11); unidirectional chemical equations (12); results (13); as graph axes (14); and forces (15). Single arrows are also used to show various specific and singular aspects of change such as, a cause-effect relationship or one stage progression (16); a change in complexity or development of structure (17); the dependence of one organism on another as for example in a feeding relationship (18); a temporal change such as in time lines (19); and directional progression or spatial change between two points (20). However, purposes 16 to 20 were also evident in multiple contexts (Group E) where a variety of chain formations (collectives of arrows in sequential formations such as linear, cyclic and cascade patterns) were used to show stages of progression within a process. Examples include biochemical processes (16); sequences of change in complexity or development (17); sequences of dependencies such as in food chains and webs (18); time lines and cycles (19); and sequences of directional progression (20), for example to indicate processes involving movement or flow.

In addition to chain formations (Group E), the collective category includes groups of arrows (Groups F, G) and networks (Group H). Arrows that are grouped and connected (F) are usually in branch format to show: alternative pathways in processes, development, sequence or direction (21); divergence or convergence for particular phenomena such as light rays (22); and stages of fusion, fertilisation and gamete formation occurring in the reproductive process (23). Coupled arrows (F) generally showed parallel reactions in chemical processes (24), including uptake, release and transfer. Parallel-arranged groups of arrows (G), in a variety of patterns, either similarly or oppositely aligned, are used to show alignment (25); bi-directional reversible reactions (26); and the frequency effect for emphasis (27). Networks (H) include, hierarchies for whole /part relationships (28) and class membership in various classifications (29); genetic diagrams to show the variety of combinations and possibilities between generations (30); tree diagrams for evolutionary relationships (31); and maps of content (32).

I have noted a few of the commonly accepted styles (Waller, 1981; Hardin, 1995; Henderson, 1999) that suggest specific purposes (Group I). Examples include, the broadening or narrowing arrows for change in size, amount or magnification (33); the dotted, attenuated or interrupted line for, among other purposes, showing inhibition (34); the arrow broken by a slash to indicate interruption in a process (35); and the curved arrow associated with chemical coupling (36); the wavy or zigzag lines may indicate energy, radiation, convection, conduction, light and sound waves (37). In a few instances, the commonplace style of the arrow may specify scientific content. For example, the zigzag arrow is widely used to indicate energy. Some arrows, if portrayed by a commonplace style, may be common to more than one group and should therefore be assigned to both.

The categories listed in Table 4.5 are numerous but by no means exhaustive. Many other styles and purposes of arrow presentation occur in other biology books, such as the mid-line arrowhead (————▶————) used as a connective (Kress & van Leeuwen, 1996).

Importance of considering the purposes of arrow symbolism

The literature confirms the results that arrow symbolism aids in clarifying purpose in a range of ways. Arrows serve as pictorial cues (Beck, 1984) to direct attention to particular features (Lowe, 1993b), including the labelling of important parts of diagrams (Schollum, 1983; Hill, 1988; Henderson, 1999). Arrows also provide links between information (Waller, 1981; Ametller & Pinto, 2002) to illustrate and emphasise relationships and interactions between related elements (Kress & van Leeuwen, 1996), thereby representing various types of sequences, such as in processes and change of state or energy, as well as spatial change, including movement from point to point, or movement of, or within a structure or system. They may also show temporal change such as an evolutionary time line (Ametller & Pinto, 2002), and causal relationships (Lowe, 1993b). The purpose of the arrows may be narrative, such as an expression of an action, or conceptual, or a combination of both (Kress & van

Leeuwen, 1996). It may also refer to magnitude (often associated with the style of presentation) such as vectorial magnitude in physics (Kress & van Leeuwen, 1996; Jiminez-Valladares & Perales-Palacios, 2001), or quantity.

The literature, however, warns against synonymy, the term used to describe the use of similarly styled arrows that serve two or more functions within one diagram (see examples referred to in Schollum (1983), Henderson (1999) and Ametller & Pinto (2002)), and polysemy, or using differently styled arrows with similar functions (Pinto *et al.*, 2000), either of which could prove confusing.

The broad spectrum of purpose revealed by these and other results could be confusing for students, particularly if the arrow symbolism is inappropriately presented, or if the student lacks the necessary strategies and conceptual understanding to interpret the symbolism. To clarify these issues, research into the purposes for which arrow symbolism is used, and the presentations relative to those purposes, is therefore strongly recommended.

4.4.4 For what range of meanings are arrows used in biology textbook diagrams?

As already discussed, information presented as arrows is used in a diversity of modes of presentation and for various purposes. Arrows in isolation are, however, meaningless. They need to be bound to their referent in order to have any meaning. Thus the purpose of each arrow will have a specific meaning according to its presentation in the context of the diagram, as noted by Hardin (1993 and 1995); Roth (2002); Perini (2005) and Heiser & Tversky (2006). In fact, according to Heiser & Tversky (2006, page 590) arrows 'can convey many different relations, some simultaneously'. In the words of Ittelson (1996, page 182): 'it [referring to a single marking, which in this report would apply to an arrow] *generates* a range of *possibilities* by means of a *divergent, open-ended* process.' Many different words can therefore be used to convey meaning to the arrow (Heiser & Tversky, 2006). The reader has to express or verbalise the intended meaning of the arrow taking into consideration its style, spatial organisation and purpose in the context of its relationship with other diagram elements.

The diversity of meaning of arrow symbolism in the textbooks analysed

In the content analysis of the textbooks, the combined effects of the diversity of style, spatial organisation and purpose of arrow symbolism within diagrams representing a wide spectrum of scientific content demanded that the sense of every arrow be determined individually. Predictably, this resulted in a vast range of meaning. In addition, there is seldom a single way of interpreting an arrow relationship. The same intentions can be expressed in a variety of ways, (possibly depending on the level of expertise of the reader) and still 'mean' the same. Therefore an almost inexhaustible range of meanings and interpretations was found to be possible.

Some of my interpretations coincided with meanings suggested by Fisher (1990), in which relationships or interactions are interpreted as physical (e.g. *under, near, connected to*), temporal (e.g. *precedes, follows*), logical (e.g. *causes, produces*), or hierarchical (e.g. *member of set, type, example*). A variety of conjunctions were identified, including many of those suggested by Geva (1983) such as for causal relations (e.g. *due to*), for progression in a process (e.g. *first, next, then*), for contrastive or alternative conjunctions (e.g. *however, on the other hand, at the same time*), and for conclusions (e.g. *in conclusion, to sum up*). According to Hardin (1995, page 346), the design of arrows may also suggest a range of 'adverbs and adjectives'. In line with these findings, the literature survey recounted that arrow meaning can range from literal interpretations to causal relationships (Pinto & Ametller, 2002). Table 4.6 gives selected examples of arrow meanings (Column 3) used in various contexts (Column 2) in the different language categories of conjunctions, adverbs, adjectives, verbs and nouns (Column 1).

The results also showed that, in most cases, the arrow symbol was best described by verbs (such as *becomes, forms, absorbs, releases, stimulates*), or verbs associated with a preposition to form verb phrases (such as *moves to, results in, diffuses to, fuses with, is absorbed by*). In other words, symbolism used in diagrams constitutes a visual language with a structure and with functions analogous to verbal language (Heiser & Tversky, 2006), the grammar of which is described by Kress & van Leeuwen (1996). They suggest that the participants can be likened to nouns and the arrows between them, as verbs, together forming clauses. The interpretation of meaning in diagrams therefore demands a high level of vocabulary (Kosslyn, 1989) and, therefore, literacy. In fact, Geva (1983) suggested that teaching text structure could improve the construction and coherence of flow charts.

Table 4.6 Selected examples of meanings for arrows in different contexts to illustrate that arrows substitute for various categories of language. Examples are taken from Geva (1983); Fisher (1990); Hardin (1995); Pinto & Ametller (2002); Heiser & Tversky (2006) and from the content analysis conducted for this study.

Language category	Context	Examples
Conjunctions	Physical	*under, near, connected to*
	Temporal	*precedes, follows*
	Logical	*causes, produces*
	Hierarchical	*member of set, type, example*
	Causal relations	*due to*
	Progression in a process	*first, next, then*
	Contrastive or alternative conjunctions	*however, on the other hand, at the same time*
	Conclusions	*in conclusion, to sum up*
Adverbs	Directional	*laterally, forward, outward, inward, backward, up, down, in all directions,*
	Substitutes	*alternatively, variously, separately*
	Manner of motion	*slowly*
Adjectives	Descriptive patterns	*cyclical, increasing, decreasing, curved*
	Manner of motion	*fast*
	Magnification	*increasing (size), decreasing (size)*
Verbs	Action	*absorbs, releases, stimulates, inhibits, secretes, pumps, fuses, enter, exerts*
	Motion	*flows, rotates, pushes, pulls, raises, opens, closes, travels*
	Outcomes /causes	*becomes, forms, accumulates, causes, produces, lifts*
Verb phrases (verb + preposition)	Action	*moves to, results in, diffuses to, fuses with, is absorbed by, slows down*
Nouns	Processes	*dispersal, contraction, fusion, separation, pathway, direction*

Importance of considering the meaning of arrow symbolism

Both the results of the content analysis and the literature survey showed that arrows in diagrams are codes for a message (a word or sequence of words) which the reader must understand if the message is to be read as intended (Kosslyn, 1989), especially as the code may be quite critical at higher levels of scientific communication (Pinto *et al.*, 2000). However, the particular meaning attached to individual or groups of arrows (even within each arrow style and purpose) is in many cases specific to, and governed by, the context of the diagram (Hunter *et al.*, 1987). This necessitates domain specific knowledge of the subject matter (Lowe, 1993b) to ensure appropriate interpretation. If the scientific content of the diagram is unfamiliar to the reader a host of possible explanations may be possible, but probably not scientifically accurate. To further complicate the issue each sub-domain of a field, such as biology, has its own characteristic set of relations (Fisher, 1990) and therefore meanings for arrows. Biology shares vocabulary for concepts – however, there is no vocabulary for describing links between concepts. There is also evidence to suggest that, early in their study of high school science, students may not be particularly adept at seeing diagrams in terms of relationships (Lowe, 1987b) or, if perceived, may not be named or made explicit – an essential step in determining meaning. This suggests that non-representational elements such as arrows, that do not represent visible entities (Lowe, 1993b), should therefore be used with caution with students.

Such evidence leads me to construe that the level of expertise (see Experts and Novices, Table 3.2, page 24 and related discussion) and past experience in the field, coupled with the reader's level of vocabulary, would influence the words used to describe the meaning of the arrow relationship. The diverse messages, conveyed by arrow symbolism but governed by few conventions, may therefore be misleading to a novice. This suggests that the design of diagrams should be evaluated to ensure that their message is not only clear to experts, but also suited to the learning level and prior knowledge of students so that they do not misunderstand the intended meaning. Clearly, therefore, there is also a strong case for doing research into the meaning of arrow symbolism in the context of diagrams.

4.5 CONCLUSIONS AND IMPLICATIONS

Current literature suggests that the more functional approach to the teaching of biology, as well as the technological advances (e.g. Pinto *et al.*, 2000) in the production of learning materials, has precipitated the introduction and increasing inclusion of arrow and other symbolism into textbook diagrams. In this regard, the content analysis of biology textbooks undertaken in this research has shown that arrow symbolism is used extensively in diagrams, particularly in stylised and abstract types, and is, therefore, an important consideration when selecting diagrams for students to use.

To ensure that students have the confidence to use diagrams effectively, the diagrams, including the arrow symbolism used in them, should be appropriately designed and presented and students should have the required resources to interpret them. The high prevalence of arrows in both abstract and stylised diagram types suggests that evaluations of arrow symbolism in biology diagrams are essential.

The results of the investigation show that not only could the wide range of modes of presentation (arrow style and spatial organisation) and purpose of arrow symbolism prove confusing, but also that there is little conformity between and, sometimes, even within diagrams. In addition, if the graphic principles used in the creation of diagrams using arrow symbolism are not adhered to, the presentation of arrow symbolism may be inappropriate to the purpose of the diagram and may therefore impact negatively on its interpretation. This suggests that research into the design and use of arrow symbolism is essential to ensure appropriate presentation with intentions that are explicit to students.

The significance of the arrow as a cue depends on several interacting factors: the type of spatial organisation, the context of the diagram (and therefore the nature of the information linked by the arrow), the purpose of the arrow in the diagram, the position of the arrow relative to other information displayed in the diagram, and the physical characteristics or style of the arrow itself (Kosslyn, 1989; Lowe, 1993b). To understand the meaning of the arrow, and therefore the full intention of the diagram, each of these factors should be considered for each arrow individually, as well as how it is incorporated with other arrows in the diagram. Research is therefore needed to determine whether the meaning of the arrow symbolism in diagrams is clear and whether students have the appropriate strategies for accessing arrow symbolism in order to accomplish the interpretive process.

In conclusion, the great diversity and complexity of arrow symbolism shown by the results of this study constitute a strong case for further research into a wide range of issues pertaining to the use of arrow symbolism in biology diagrams. These, *inter alia*, include issues of arrow style, spatial organisation, conventions, purpose and meaning. In this regard, the role of the researcher is to investigate questions such as: Does presentation (design) of arrows used as notation convey a correct and unambiguous message? How does presentation affect student interpretations? If students experience difficulties, what is the nature of the difficulties that arise? Thus based on these findings, I contend that there is a very strong case for more extensive and in-depth research into arrow symbolism in biology diagrams.

CHAPTER 5
DEVELOPMENT AND APPLICATION OF A SET OF CRITERIA FOR EVALUATING THE EFFECTIVENESS OF ARROW SYMBOLISM IN BIOLOGY DIAGRAMS

5.1 INTRODUCTION

In 1993, Eltinge & Roberts stated: 'Because of the dominant role of text books in high school science curricula, it is important that science educators evaluate them carefully, paying particular attention to the images of science they present.' Research on science textbooks (e.g. Storey, 1990 and 1991) has shown that many materials in textbooks, including diagrams (e.g. Abimbolo & Baba, 1996) and accompanying multimedia, are not meaningful. In support of this, Lowe (1997) has stated that diagrams are 'of very questionable value because of the limited attention paid to instructional design issues' while Petre & Green (1993) have commented, 'Graphical representations share a problem with textual ones: quality is not guaranteed.' Therefore to improve the effectiveness of textbooks, diagrams should be analysed (Hill, 1988) and improved (Levin & Mayer, 1993). This means that the graphic design of diagrams should be appropriate to the context (content and purpose), the graphic design should be easy to use (Kosslyn, 1989) and require limited information processing to understand the symbolism. Research has shown that pictorial support can sometimes be facilitative, but it has also shown that inappropriate forms of presentation can hinder mental model formation, even in students with good prior knowledge (Schnotz & Bannert, 2003). More specifically, reasoning and conceptual difficulties have been attributed to the incorrect, misleading or confusing presentation of symbolism including arrows in science diagrams (e.g. Schollum, 1983; Jiminez-Valdares & Perales-Palacios, 2001). Quality diagrams are therefore essential to enable scientifically acceptable mental models to be formed.

The findings presented in Chapter 4 showed that the biology textbooks selected for this study use a variety of diagrams, many of which employ arrow symbolism as cues in a diversity of modes of presentation (spatial organisations and styles), for a variety of purposes and with almost unlimited possibilities of meaning. In order to realise this meaning, the communication intended by the symbolism, should be effective. This presupposes that diagrams, including all factors pertaining to spatial organisation, style, purpose and meaning, are presented in accordance with graphic design principles governing the syntactic, semantic and pragmatic areas of diagram design (Garland, 1979; Brody, 1984; Goldsmith, 1987; Hunter *et al.*, 1987;

Kosslyn, 1989; MacEachren, 1995; Kress & van Leeuwen, 1996). In this regard, Beck's following statement about designing diagrams is also applicable to arrow symbolism in diagrams. He stated: 'When designing combined and interrelated visual cues, careful consideration must be given to the necessity, prominence, and reciprocity of the cues' (see Glossary) (Beck, 1984, page 215). A set of criteria that considers all these factors can provide an objective means (within the limitations of content analysis, which always has some element of subjectivity) of evaluating the quality of design of all arrows or diagrams with arrow symbolism in biology textbooks. Such criteria would, of course, be from an expert's perspective and therefore their application would need to be evaluated against student opinion and actual performance when interpreting arrow symbolism. The latter is addressed in Chapter 6.

5.2 RESEARCH QUESTIONS

To investigate whether arrow symbolism in diagrams is used effectively to promote the communication of intended ideas (Research Question 2), the following sub-questions were addressed:

a. From an expert's point of view, is arrow symbolism appropriately designed in biology textbook diagrams? In this regard:

b. Can a suitable tool, such as a set of criteria, be developed for evaluating arrow symbolism?

c. Are criteria for the evaluation of arrow symbolism generalisable to all diagrams using arrow symbolism?

5.3 METHODS

A three-stage cyclical approach (Figure 5.1) was used to develop a suitable set of criteria for evaluating the effectiveness of arrow symbolism in diagrams. The three stages included criteria design, honing and validation, and application. Literature on graphic design principles and my findings about the diversity of arrow presentation were used to develop an initial set of criteria (Stage A; Figure 5.1). This set was then honed and validated by a cyclical process, using input from a variety of sources and stakeholders, into a final set of criteria (Stage B). The final set of criteria was then applied to a large number and range of diagram types in order to confirm its generalisability (Stage C). Each of these stages is discussed below.

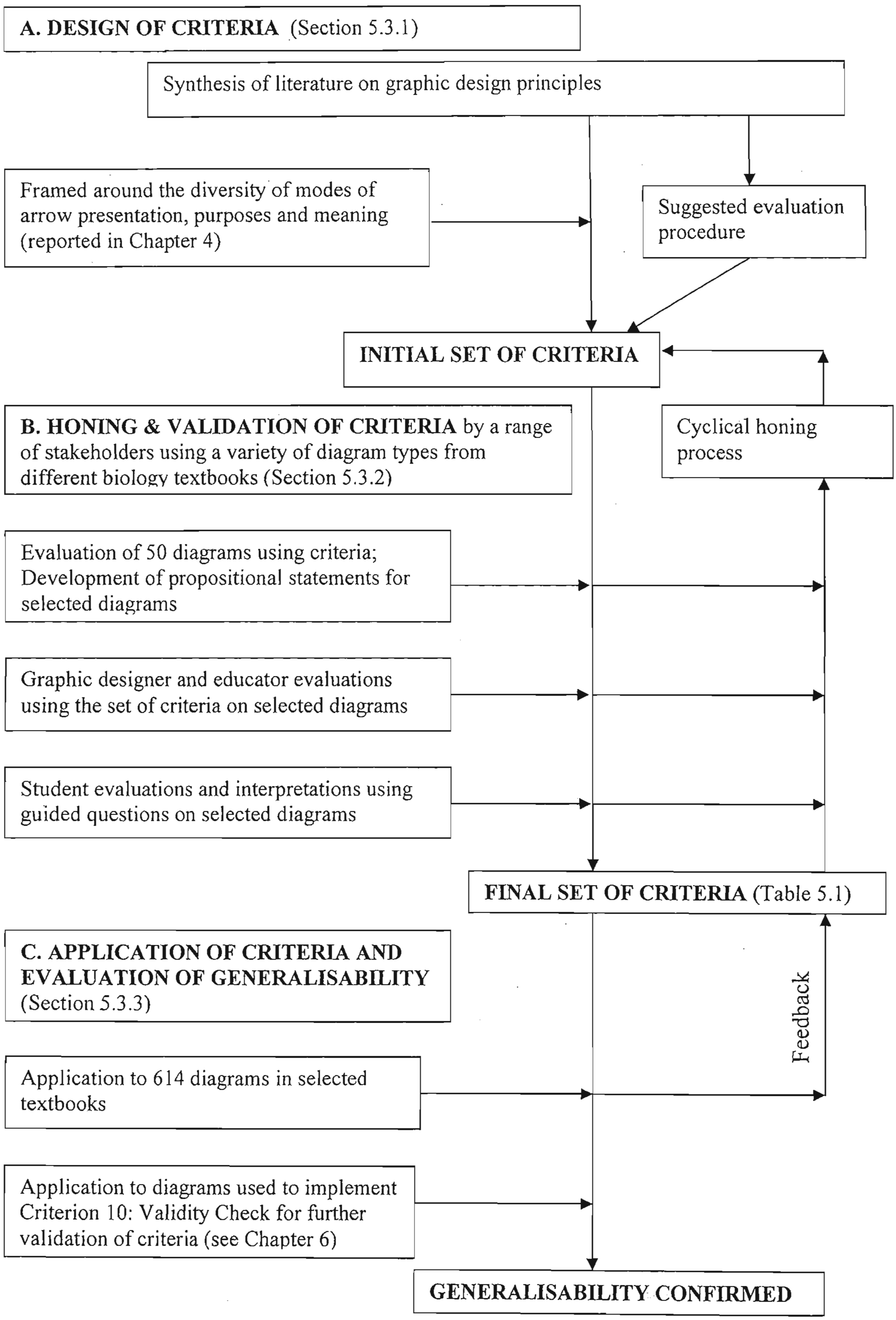


Figure 5.1 Overview of the cyclical process used to develop criteria for the evaluation of arrow symbolism.

5.3.1. Designing an initial set of criteria (Stage A, Figure 5.1, page 81)

To decide which graphic design principles are important for the construction of diagrams with arrow symbolism, and what criteria should be used to evaluate the effectiveness of arrow symbolism in textbook diagrams, I explored various sources of information including:

a. Information about the diversity of arrow use in diagrams from the content analysis reported in Chapter 4.

b. A synthesis of the literature on graphic design principles for the presentation of diagrams in general (e.g. Kosslyn, 1989; MacEachren, 1995; Kress & van Leeuwen, 1996) as well as for the design of arrows specifically (e.g. Hardin, 1993 and 1995; Henderson, 1999).

c. Literature on methods and criteria used to evaluate the presentation and design of diagrams (e.g. Beck, 1984; Fleming, 1987; Goldsmith, 1987; Kosslyn, 1989; Leonard & Penick, 1993; Staver & Lumpe, 1993; Abimbola & Baba, 1996; Collier, 2001).

d. Studies on student difficulties with interpretation of diagrams (e.g. Ametller & Pinto, 2002).

These sources of information, regarded as the ideas of experts, were used to develop an initial set of criteria (Stage A, Figure 5.1). The influence of this information on the development of the set of criteria will be discussed in the Results and Discussion (Section 5.4, page 94).

5.3.2. Honing and validating the criteria (Stage B, Figure 5.1, page 81)

The initial set of criteria was honed into a final, comprehensive and more logically organised set of criteria (presented in Table 5.1, page 95) by means of the cyclical modification process (explained in Figure 5.1). To more rigorously evaluate the criteria, this process included the input of a range of both expert and novice diagram users. Evaluators included a graphic designer (Diploma in Graphic Design, Natal Technikon), four educators (B.Sc. degrees with biological or biochemical majors, plus teaching qualifications of HDE (Higher Degree in Education) or B.Ed (Batchelor of Education) degree and 16 Grade 11 students. By doing this, I was confident that the criteria are valid tools for the evaluation of arrow symbolism.

The validation procedure included:

a. The selection of 50 diagrams covering a range of diagram types (examples of which are presented in Figure 5.2, pages 84 - 92) selected from the six selected Grade 11 and 12 South African textbooks (Degenaar *et al.,* 1999 and 2000; Ashwell *et al.*, 2000a and 2000b; Ayerst *et al.*, 2000a and 2000b) currently used for the teaching and learning of biology in KwaZulu-Natal, South Africa. Each diagram was selected for specific features. For example, Figure 5.2.3 showing the cell cycle and Figure 5.2.18 showing the nitrogen cycle, are examples of abstract diagrams in which only words and arrows are used in cyclical spatial organisations. Figure 5.2.26 uses colour-coded arrows to show hormone changes. In Figure 5.2.2 the verbal elements are presented as labels, whereas in Figure 5.2.18 they are incorporated into box or arrow-shaped frames. There are several examples of the stylised category of diagrams including Figures 5.2.2, 5.2.5 and 5.2.9. Figure 5.2.2 shows detail of the structure of the Malpighian corpuscle using two arrows of similar style to show magnification of a portion of a diagram and direction of blood /filtrate flow. Figure 5.2.5 uses several styles, sizes and colours of arrows in a repetitive format to show hormonal control of the menstrual cycle. Figure 5.2.9 uses several sizes of arrows in the same colour to show the circulation pattern in a locust.

b. Evaluation of the 50 diagrams using the criteria.

c. Selection of representative examples of diagrams (Figures 5.2.2, 5.2.3, 5.2.5, 5.2.9, 5.2.18 and 5.2.26) from the 50 diagrams for further evaluation. Development of propositional knowledge statements (presented in Figure 5.3, page 93) for these diagrams based on the prior evaluations to be used as a benchmark for responses arising from further evaluation.

d. Evaluation of selected diagrams by a graphic designer (as an expert) (Figures 5.2.2, 5.2.3 and 5.2.5) and four educators (as experienced diagram users) (Figures 5.2.3, 5.2.5, 5.2.9 and 5.2.18) using the criteria, as well as by 16 students (as novice diagram users) (Figures 5.2.3, 5.2.5 and 5.2.26) using carefully guided questions modified from the procedures suggested by Abimbolo & Baba (1996) and Ametller & Pinto (2002). As the various evaluations were for the purpose of honing and validating the criteria, not for comparison, it was not considered necessary to use the same combinations of diagrams for all of the evaluators. Examples of the evaluations are presented in the Results and Discussion (Section 5.4).

5.3.3 Evaluating the generalisability of the criteria (Stage C, Figures 5.1, page 81)

To assure the suitability of the criteria in a multiple context, the criteria were applied to a large sample (Staver & Lumpe, 1993) of 614 diagrams using arrow symbolism in the six selected Grade 11 and 12 South African textbooks (Degenaar *et al.*, 1999; 2000; Ashwell *et al.*, 2000a; 2000b; Ayerst *et al.*, 2000a; 2000b). Content analysis procedures modified from the methods of Bell (2001) and Cohen *et al.* (2000) were employed (see Chapter 3, Section 3.2.2.1, page 27). For each criterion, the frequency of diagrams using particular inappropriately presented arrows was expressed as a fraction of the total number (614) of diagrams and as a percentage. These frequencies are presented in Table 5.1 (page 95), while selected examples of inappropriate presentations are discussed in Section 5.4 (page 94).

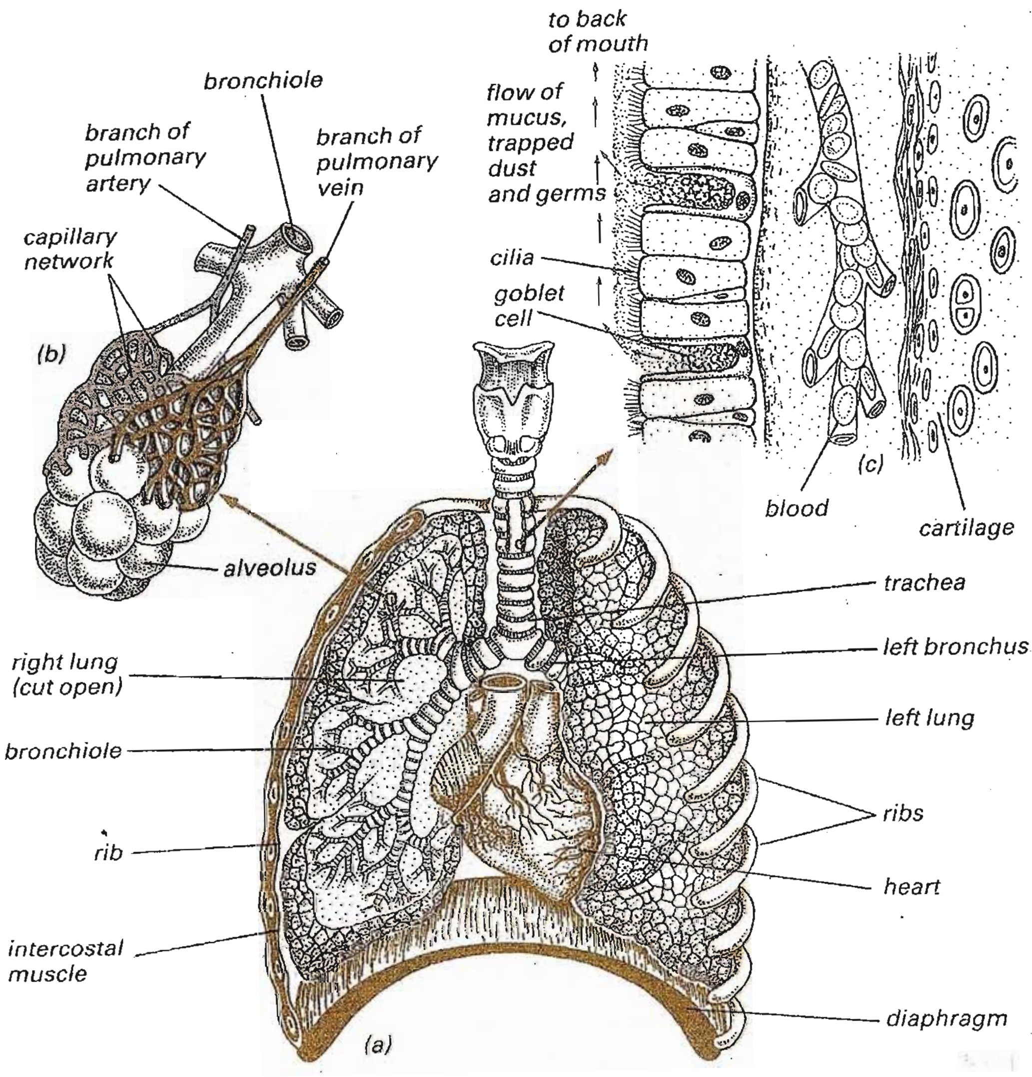


Figure 5.2.1 Ayerst *et al.* (2000b) p. 201

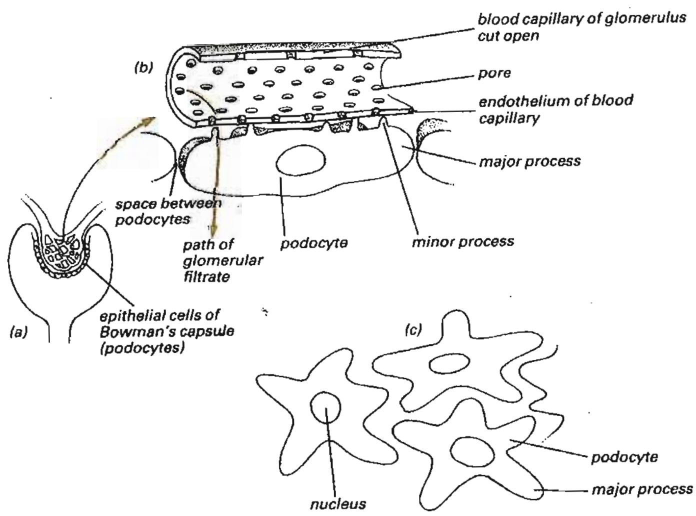


Figure 9.6
Podocytes
(a) Position of podocytes in the Malpighian body;
(b) relationship between podocytes and the blood in the capillaries of the glomerulus;
(c) surface view of podocytes.

Figure 5.2.2 Ayerst *et al.* (2000b) p. 228

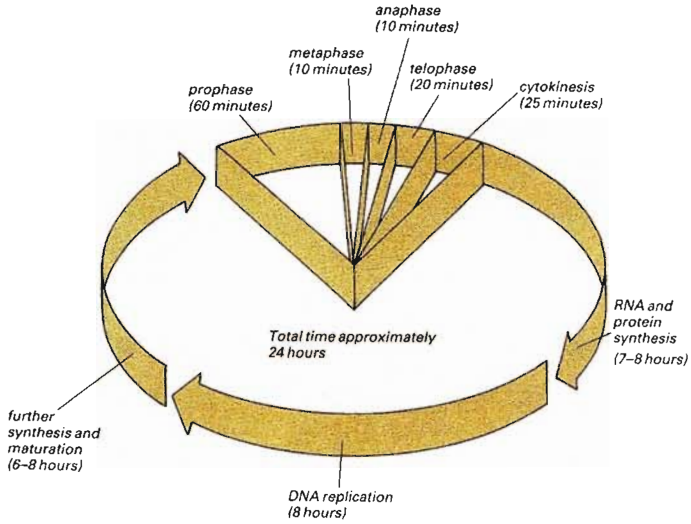


Figure 19.2
The cell cycle

Figure 5.2.3 Ayerst *et al.* (2000a) p. 281

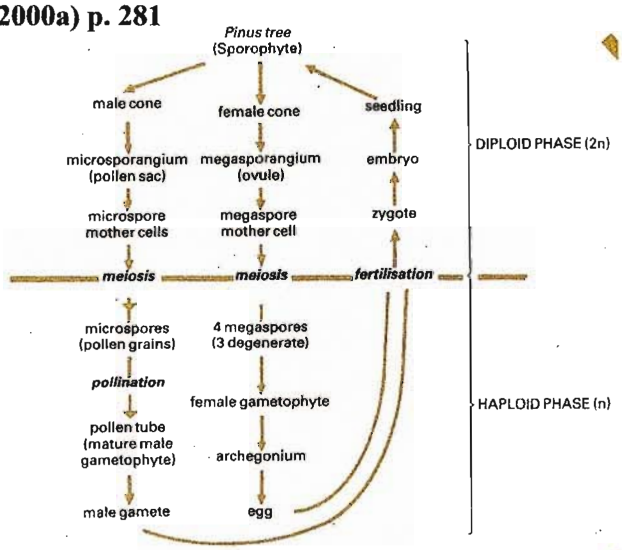


Figure 6.13
Diagram showing alternation of generations in life cycle of *Pinus*.

Figure 5.2.4 Ayerst *et al.* (2000a) p. 85

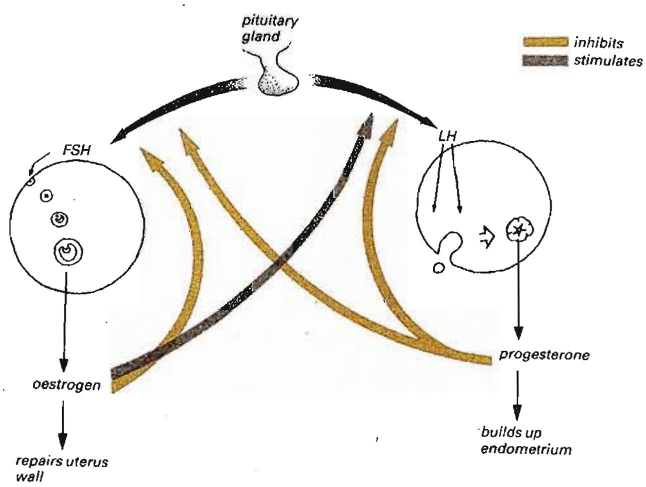


Figure 21.11
The control of the menstrual cycle.

Figure 5.2.5 Ayerst *et al.* (2000a) p. 345

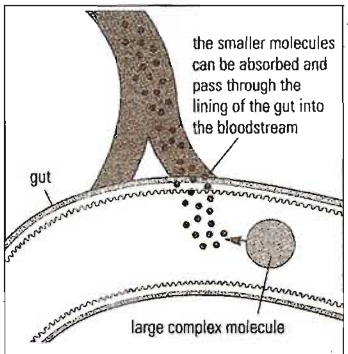


Figure 7.6 *Breakdown of large particles into small molecules*

Figure 5.2.6 Ashwell *et al.* (1999b) p. 109

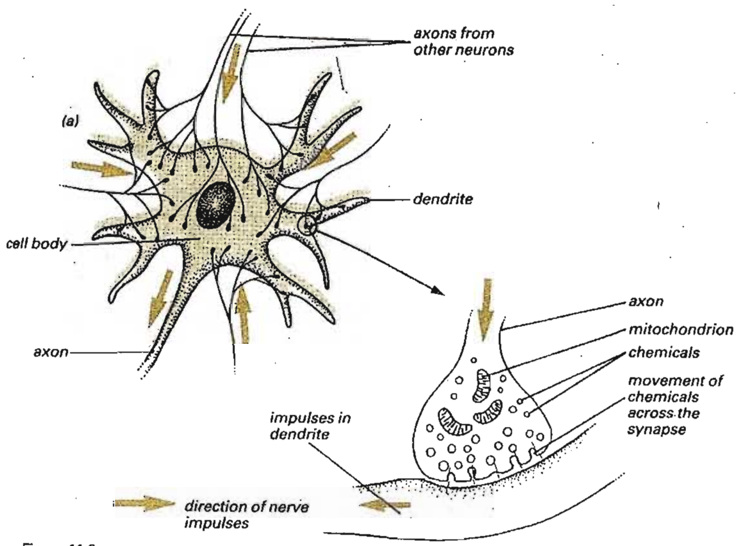


Figure 11.3
(a) Synapses on a motor neuron.
(b) A highly magnified synapse.

Figure 5.2.7 Ayerst *et al.* (2000b) p. 251

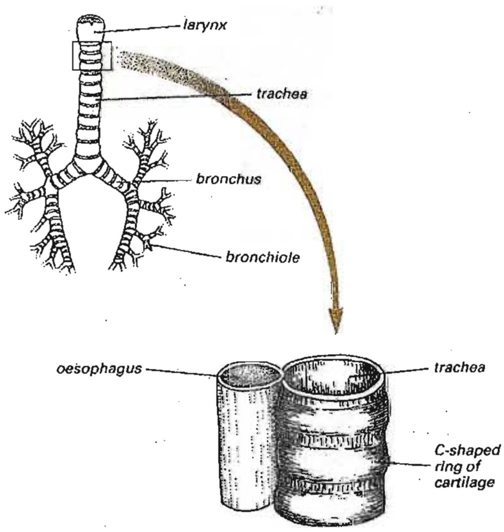


Figure 8.2
The structure of the trachea.

Figure 5.2.8 Ayerst *et al.* (2000b) p. 200

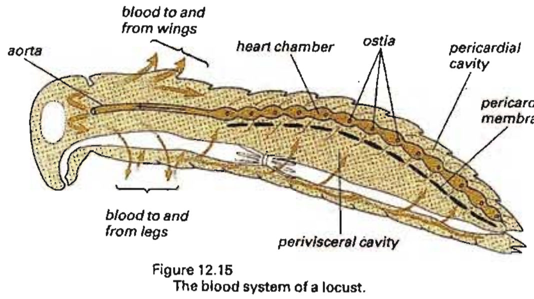


Figure 5.2.9 Ayerst *et al.* (2000a) p. 185

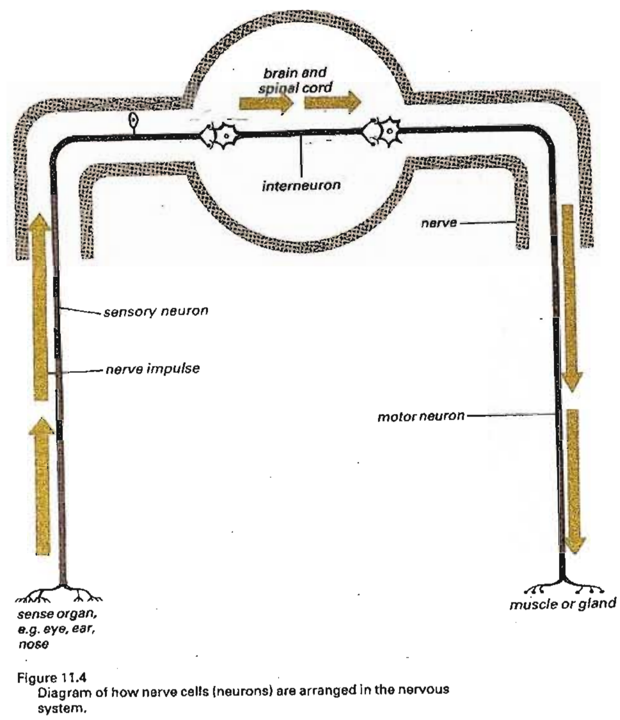


Figure 5.2.10 Ayerst *et al.* (2000) p. 252

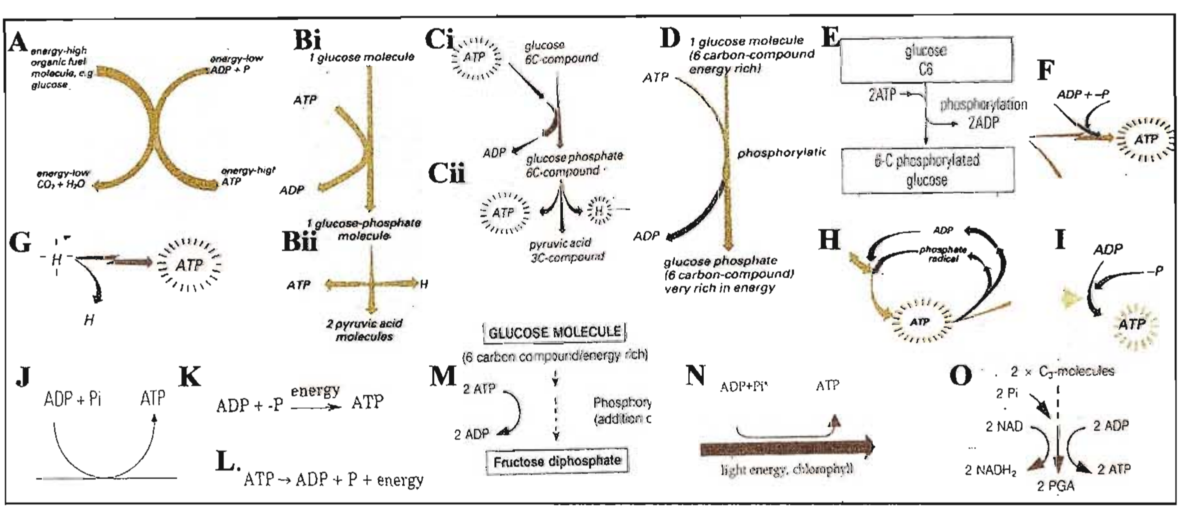


Figure 5.2.11 A – O adapted (portions of diagrams selected and reduced in size) from Ashwell *et al.* (1999b) pp. 132, 134; Ayerst *et al.* (2000b) pp. 110, 120, 121, 142-149; Degenaar *et al.* (2000) pp. 166, 168.

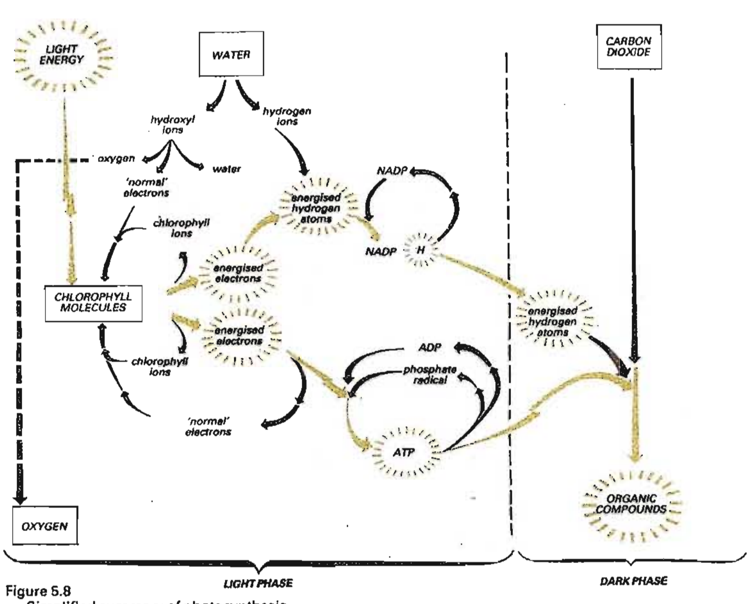


Figure 5.8
Simplified summary of photosynthesis.
(Note the energy pathway from light energy to the organic (carbon) compounds.)

Figure 5.2.12 Ayerst *et al.* (2000b) p. 121

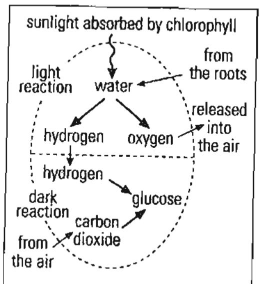


Figure 6.11 Summary of light and dark phases

Figure 5.2.13 Ashwell *et al.* (1999b) p. 99

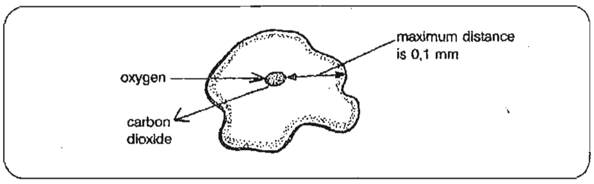


Figure 3.4 *Amoeba species is so small that diffusion is a rapid enough process to supply its needs*

Figure 5.2.14 Degenaar *et al.* (1999b) p. 110

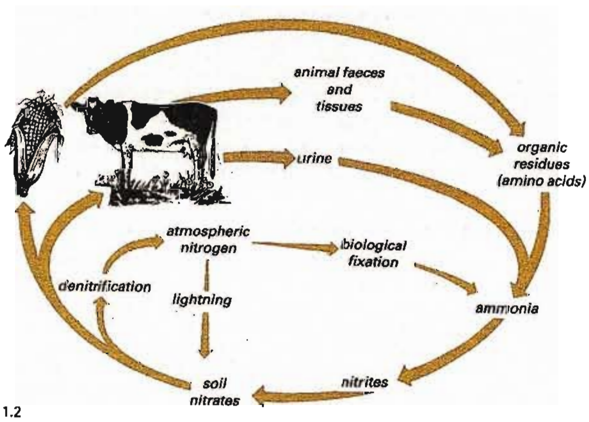


Figure 1.2
The nitrogen cycle.

Figure 5.2.15 Ayerst *et al.* (2000b) p. 3

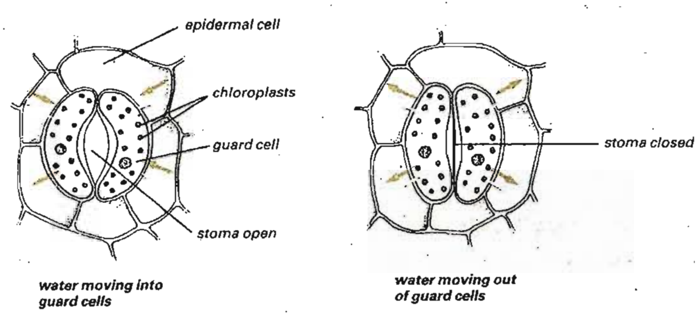


Figure 3.14
Diagrams showing direction of water movement resulting in the opening and closure of stomata.

Figure 5.2.16 Ayerst *et al.* (2000b) p. 85

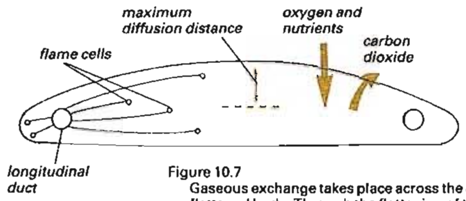


Figure 10.7
Gaseous exchange takes place across the entire surface of the flattened body. Through the flattening of the body the surface/volume ratio is increased and the diffusion distance is decreased.

Figure 5.2.17 Ayerst *et al.* (2000a) p. 143

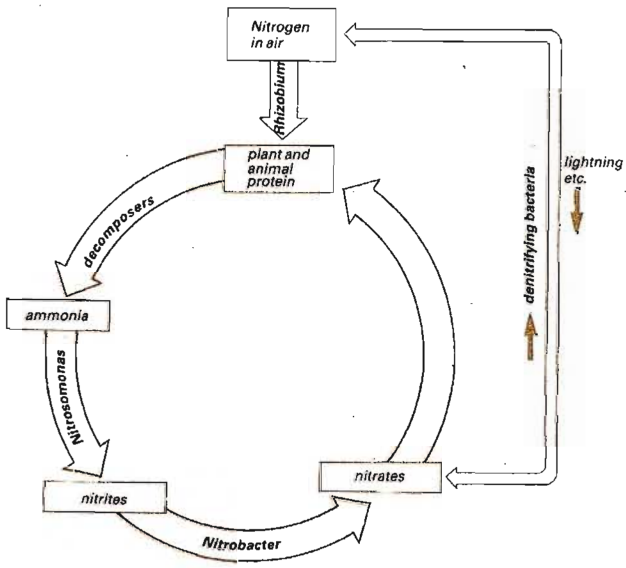


Figure 1.6
The nitrogen cycle.

There are three main types of bacteria in the nitrogen cycle.

Figure 5.2.18 Ayerst *et al.* (2000a) p. 9

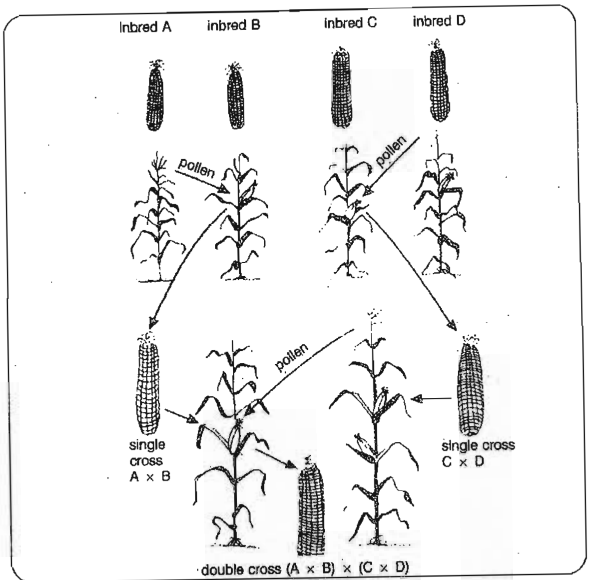


Figure 5.19 *Diagram of double-cross method for producing hybrid maize by controlled and artificial pollination*

Figure 5.2.19 Degenaar *et al.* (1999) p. 297

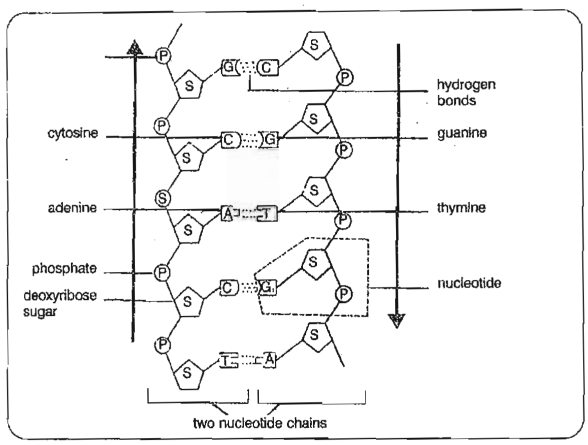


Figure 5.2(a) *A diagrammatic representation of the biochemical structure of DNA*

Figure 5.2.20 Degenaar *et al.* (1999a) p. 227

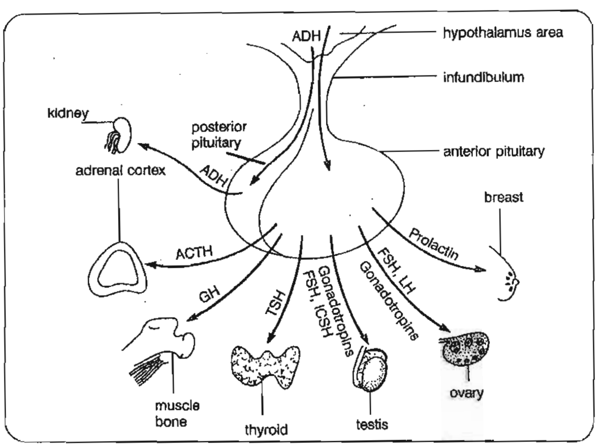


Figure 5.29 *A diagram to illustrate the structure of the pituitary gland*

Figure 5.2.21 Degenaar *et al.* (1999b) p. 256

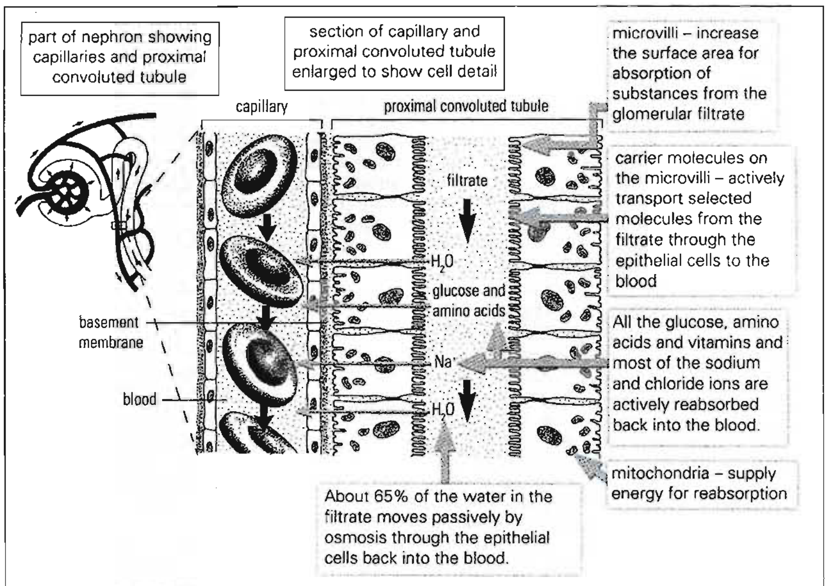
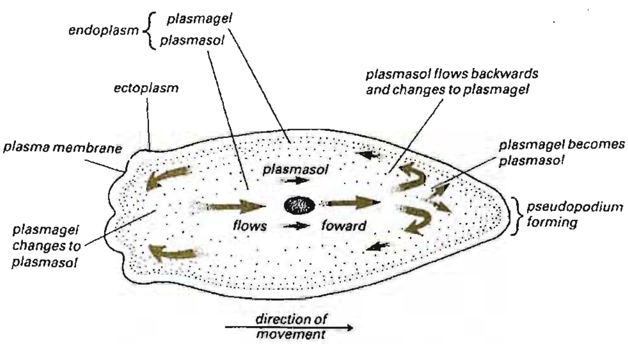


Figure 10.8 Selective reabsorption in the proximal convoluted tubule

Figure 5.2.22 Ashwell *et al.* (1999b) p. 177



(a) Amoeboid movement is caused by protoplasmic streaming and a continuous 'sol' to 'gel' and 'gel' to 'sol' transformation.

Figure 5.2.23 Ayerst *et al.* (2000a) p. 114

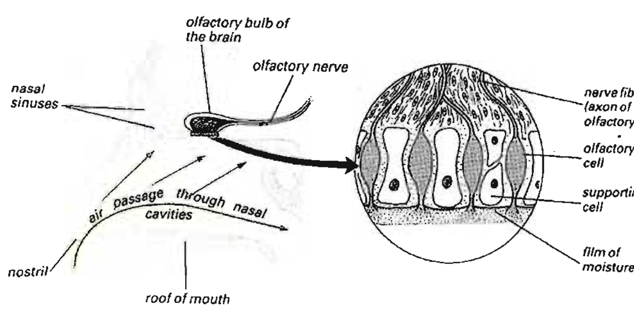


Figure 12.4
The smell (olfactory) organs.

Figure 5.2.24 Ayerst *et al.* (2000b) p. 280

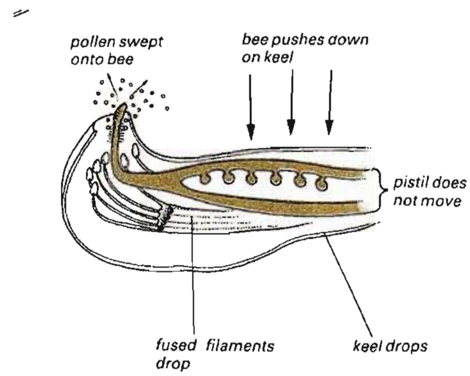


Figure 5.2.25 Ayerst *et al.* (2003a) p. 98

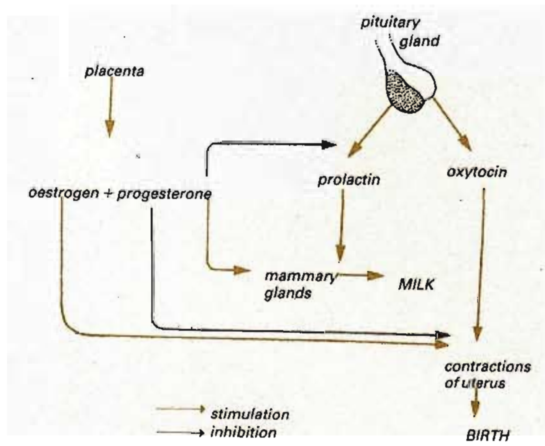


Figure 22.6
Hormone changes at birth.

Figure 5.2.26 Ayerst, et al. (2000a) p. 369

Figure 5.2 Examples of arrow presentations in selected biology textbooks (Ashwell *et al.*, 1999a; b; Degenaar *et al.*, 1999; 2000; Ayerst *et al.*, 2000 a; b) used to develop and apply the criteria summarised in Table 5.1, page 95. Except for the group of diagrams in Figure 5.2.11 where some of the diagrams have been reduced in size, all diagrams are presented in the same size and colours as the originals.

Figure 5.2.2
Intention of diagram: See caption (b): To show the relationship between podocytes and the blood in the capillaries of the glomerulus.
Purpose of arrow symbolism: One arrow shows a portion of the glomerulus magnified. The other shows the direction of flow of the blood/filtrate.
Meanings of arrows: magnified/showing detail; and pathway of filtrate (as labelled)
Evaluation: Arrows in similar style show different purposes (Criterion 5bi). As they are also of similar style, and are presented close together, they imply a sequence or continuity effect, thereby creating an unexpected emergent property (Criterion 2c). The label on the second arrow could therefore apply to both.

Figure 5.2.3
Intention of diagram: See caption: To show the cell cycle
Purpose of arrow symbolism: Each arrow represents a stage in the cell cycle.
Meanings of arrows: Stage and length of cycle as labelled e.g. DNA replication (8hours)
Evaluation: Three arrows imply three stages, instead of four (Criterion 7a), as stated in the text (Criterion 8b).
The size of the segment of the pie chart showing mitosis is out of proportion to its meaning (Criterion 7a).

Figure 5.2.5
Intention of diagram: See caption: The control of the menstrual cycle. This is shown in two stages, the first controlled by FSH, the second by LH.
Purpose of arrow symbolism: To show the effects (inhibitory and stimulatory) of hormones on the process of menstruation. The relationship between the source (gland) and target organ of each hormone is provided. The presentations detail the sequences and the negative feedback process.
Meanings of arrows: See key to black, grey and orange colours.
Upper black arrows: produces
Upward facing grey arrow: stimulates
Upward facing orange arrows: inhibits
Small straight arrows from top downward on both sides: stimulates/causes; produces/releases; causes
Block shaped arrow: becomes/changes into/forms
Evaluation: There are several styles of arrow coding for different purposes. However, there is no consistency, with similar styles coding for different purposes (Criterion 5bi). For example, the large black arrows mean 'produces' as well as 'stimulates'. The key only refers to the four upward arrows (Criterion 7b), as other arrows do not mean 'stimulates' or 'inhibits'. Poorly positioned upward-facing arrows (Criterion 6b) end on the shaft of the upper black arrows. Poorly placed arrows (Criterion 6a) from LH having no specific targets causes confusion (Criterion 7a). The intention of the very differently styled arrow to the corpus luteum is obscure (Criterion 5a). The upward-facing arrows from oestrogen are poorly aligned.

Figure 5.2.9
Intention of diagram: See caption: [To show direction of flow of blood in] the blood system of a locust.
Purpose of arrows: directions of blood flow
Meanings of arrows: flows in this direction/to/from/through/out
Evaluation: The arrows showing blood flow to (no return of blood is shown) the legs and wings are poorly placed (Criterion 6a) as they pass through a solid line, possibly implying to the novice, that blood flows through the exoskeleton (Criterion 7a). The arrows showing blood flow to and from the heart chamber are very small (Criterion 1a) and small in proportion to other features (Criterion 1b). In addition, there is very poor figure-ground differentiation as both the arrows and background are the same orange colour (Criterion 1c). The caption does not cue for arrow functions (Criterion 7b).

Figure 5.2.18
Intention of diagram: See caption: To show the nitrogen cycle
Purpose of arrows: To link the stages in the nitrogen cycle and show the controlling agent/s of each.
Meanings of arrows: Controlling agent (name supplied) produces; produces; turns it into
Unnamed arrow: absorbed by; used by; made into; used for
Evaluation: Unnamed arrow in similar style to arrows showing functions of bacterial agents, but coding for a different function (Criterion 5bi). Arrow for denitrifying bacteria is in different style to other arrows (Criterion 5bii). It could be confusing to have arrowheads at both ends implying bi-directional processes and still have additional arrows to show the effects of the denitrifying bacteria and lightning (Criterion 7a).

Figure 5.2.26
Intention of diagram: See caption: To show the consequences of hormonal changes at birth.
Purpose of arrows: To show hormonal stimulation and inhibition of processes associated with the birth of a baby.
Meanings of arrows: stimulates; inhibits; releases; secretes; results in
Evaluation: The arrows are similarly styled despite different meaning (Criterion 5b). Although the key stipulates that orange arrows code for stimulation, 5 of the 8 orange arrows do not refer to stimulation by hormones (Criterion 5a). Positioning of arrows is not explicit to show whether the hormone or its release from a gland is stimulated or inhibited (Criterion 6b). The caption does not imply consequences of hormone changes – the focus o the diagram (Criterion 7a).

Figure 5.3 Examples of propositional knowledge statements for diagrams (Figures 5.2.2, 5.2.3, 5.2.5, 5.2.9, 5.2.18 and 5.2.26) used to validate criteria.
The criteria noted in the above propositional statements refer to those presented in Table 5.1 (page 95).

5.4 RESULTS AND DISCUSSION

An initial set of criteria was formed based on design features and principles suggested by experts' ideas and on the diversity of modes of arrow presentation (reported in Chapter 4) as described in Section 5.3 (page 80) and Stage A of Figure 5.1 (page 81). Application of the honing and validation processes described in Stage B of Figure 5.1, including my evaluations of arrow presentations in the 50 selected diagrams, the evaluations of the expert graphic-designer, the experienced diagram users (four educators) and of the 16 novices (students) supported the inclusion of the criteria and informed their description.

As a result of the cyclical processes of design, validation and honing, a set of nine categories of criteria for analysing the presentation of arrow symbolism was developed. The final set of criteria is presented on Table 5.1, page 95. Criteria 1 – 8 were designed to evaluate the syntactic, semantic and pragmatic aspects of arrow symbolism (Kosslyn, 1989) and are therefore suitable to evaluate the diversity of modes of presentation (spatial organisation and style), purpose and meaning of arrow symbolism reported in Chapter 4. Criterion 9 enabled a combinational treatment, as suggested by Bell (2001), to allow experts to moderate evaluations where necessary and decide on the overall suitability of the diagram. Thus experts might still consider a particular diagram as a potentially useful learning tool despite it containing elements of inappropriate arrow symbolism. Criteria 1 – 9 are detailed in Table 5.1 and illustrated by reference to diagrams in Figure 5.2, pages 84 - 92.

A tenth criterion, namely Criterion 10: Validity Check was included in the set of criteria to establish whether the potential problems with arrow symbolism, as predicted by experts applying Criteria 1 – 9, would lead to actual interpretation difficulties among students. In this way the researcher did not want to make the wrong assumption that what experts think might be a problem for novices, may not necessarily be a problem for students. This thinking was in line with the discussion in Chapter 3 (Table 3.2) with respect to expert-novice knowledge and skills.

Application of the set of criteria to arrow symbolism in the 614 selected diagrams (Part C, Figure 5.1) yielded a wide range of frequencies for all the tested criteria in all of the syntactic (Criteria 1 – 3), semantic (Criteria 4 – 7) and pragmatic (Criterion 8) dimensions. The generalisability of the criteria was therefore confirmed.

Table 5.1 List of developed criteria (Criteria 1 – 9) for evaluating inappropriate presentation of arrow symbolism and the results of their application to 614 diagrams.
Column 2 refers to examples of diagrams (Figure 5.2) in which arrow symbolism is inappropriate. Column 3 gives the frequency of presentation of inappropriate arrow symbolism for each criterion as a percentage and as a fraction of the total 614 diagrams. The data is grouped according to the syntactic (1 – 3), semantic (4 – 7) and pragmatic (8) dimensions of arrow presentation.

CRITERIA (see Glossary for definition of terms used)	Example from Fig. 5.2	Frequency Total /614	%
1. ARE ARROWS SUITABLY VISIBLE? Evaluate for:			
a. Suitable size for visibility (e.g. Smith, 1979; Kosslyn, 1989).	7, 9	10	2
b. Size relative to other features of the diagram (e.g. Smith, 1979).	1c	89	14
c. Figure-ground discrimination (arrows distinct from background) (e.g. Waller, 1981).	9	91	15
2. IS THE SPATIAL ORGANISATION OF THE DIAGRAM SUITABLY ORGANISED TO ALLOW APPROPRIATE PERCEPTION? Evaluate for:			
a. The arrangement and spread of elements in the diagram to encourage appropriate perceptual precedence (global /local attention) (e.g. Navon, 1977).	2	14	2
b. Grouping of arrows to form perceptual units:			
i) Clearly differentiated explicit /outer boundaries	1, 2	17	3
ii) Easily discernable implicit /inner boundaries (e.g. Reid, 1990a).	12	37	6
c. Presentation of the Principles of continuity, proximity, similarity and frequency to enable appropriate grouping, thereby avoiding illusion, distortion and unexpected emergent properties (e.g. Winn, 1993).	2, 7, 11O, Bii, 22	57	9
d. Suitable number of arrows /groups of arrows for perception (no gaps no extras /no clutter) (e.g. Szlichcinski, 1979; Kosslyn, 1989; Lowe, 1989).	2, 10, 11C, H	72	12
3. IS THE LEVEL OF COMPLEXITY APPROPRIATE? Evaluate for:			
Suitable number of inclusions (arrows /arrow groups) for information processing at relevant level of readership (complexity), using scale of 1 – 5 (low), 6 – 10 (medium), over 10 (high) (e.g. Kosslyn, 1989; Chandler & Sweller, 1991).	4, 5, 12 26	24	4
4. IS SPATIAL ORGANISATION SUITED TO THE CONTEXT? Evaluate for:			
The suitability of repetitive and /or recognisable spatial organisations for content and /or purpose of the diagram. Consider the patterns of collective presentations, namely networks, chains, groups and mixed formats (Chapter 4, Table 4.3) (e.g. Kosslyn, 1989; Ittelson, 1996).	4, 5, 26	6	1
5. IS THE STYLE OF ARROW SUITABLE FOR THE CONTEXT? Evaluate for:			
a. Suitability of arrow style, including commonplace styles, for the content and /or purpose of the diagram using the variables influencing the diversity of arrow style (Chapter 4, Table 4.2) (e.g. Kosslyn, 1989; Kress & van Leeuwen, 1996).	5, 8, 11C, D, M, O, 12	104	17
b. Variation /consistency in style to avoid synonymy & polysemy			
i) Variation of style for different purposes (e.g. Ametller & Pinto, 2002)	2, 19	36	6
ii) Consistency of style within purpose (e.g. Lowe, 1993b).	5, 18	33	5
c. Conformity of style for particular purpose within diagrams, context and textbook (e.g. Waller, 1981; Kosslyn, 1989; Kress & van Leeuwen, 1996).	11	161	26
6. ARE ARROWS PLACED /POSITIONED FOR EXPLICIT RELATIONSHIPS: Evaluate for:			
a. Relevance of placement of arrows between referents (e.g. Kosslyn, 1989).	5, 13, 15	156	9
b. Positioning of arrow origin and arrowhead relative to referents (e.g. Kosslyn, 1989).	14, 16,17	247	13
7. ARE CUES SUITABLE FOR ASSIGNING MEANING? Evaluate for:			
a. Harmony between modes of presentation, content and purpose including appropriate syntactic emphasis (including salience), to achieve the intended meaning (e.g. Kosslyn, 1989; Thompson, 1994).	3, 5	135	22
b. Provision of appropriate and sufficient propositional guidelines (including caption, annotations, labels, key, legend and proximal text) (e.g. Lowe, 1997; Mayer, 1997).	2, 4, 20, 21	121	20
8. IS THE LEVEL OF DESIGN SUITED TO THE READER'S FRAME OF REFERENCE? Evaluate relative to:			
a. Learning level (including age and competence according to Grade) (e.g. Winn, 1993).	2, 4, 5,12	70	11
b. Culture (including the compatibility of the spatial organisation with students preferred direction of reading according to their culture) (e.g. Serpell & Boykin, 1994).	6	13	2
9. COMBINATIONAL TREATMENT of arrow symbolism (relative to student level) A subjective evaluation based on 1 – 8 to decide overall suitability of the diagram.		185	30
10. CRITERION VALIDITY CHECK: Design questions informed by criteria 1 – 9 to check presentation of arrow symbolism against student interpretation (See Chapter 6).			

In the subsections below, I present qualitative and quantitative evidence for the inclusion and validation of each criterion as part of the final set of criteria (Table 5.1). The importance of including each criterion will be explained using the graphic design principles and other relevant guidelines, such as procedural guidelines and findings of experts reported in the literature. This evidence will be supported by quotes from the evaluations of students, educators or the graphic-design expert during the developmental stages of the criteria. In addition, I will supply quantitative evidence obtained from the application of the final set of criteria to the 614 diagrams. Inappropriate presentations are selectively supported with relevant examples (Column 2, Table 5.1) and quotations.

In many cases, the presentation of arrow symbolism in a diagram was inappropriate to multiple criteria, necessitating several references to a diagram. When examining Table 5.1, and the accompanying discussion, the reader is referred to the Glossary for clarification of the meaning of the numerous graphic terms used to describe the criteria.

5.4.1 Criterion 1: Are the arrow features suitably visible?

Evaluate for: Suitable size for visibility (Criterion 1 a), size relative to other features of the diagram (Criterion 1b) and figure-ground discrimination (Criterion 1c).

Criterion 1 was included on the strength of reports in the literature outlining difficulties encountered by students when diagram features are not suitably visible. This is because the process of transferring perceptual images to short term memory will only be successful if the images (in this study, arrows) are detected. To detect arrows, the reader needs to discriminate (Kosslyn, 1989) or recognise their visual differences (MacEachren, 1995) from other features of the diagram such as lines, colours and regions. Failed or inadequate discrimination could affect the length of time students need to detect and identify symbols (Remington & Williams, 1986) and therefore adversely influence the process of interpretation (Reid, 1984; 1990a; Fleming, 1987; Kress & van Leeuwen, 1996). Criterion 1 (Table 5.1) was therefore introduced to evaluate for the syntactic dimensions of arrows. This includes Criterion 1a to evaluate for the minimum size required for visibility (Smith, 1979; Kosslyn, 1989; Hardin, 1995); Criterion 1b to evaluate the relative discriminability or arrow size relative to other symbolism or information in the diagram (Smith, 1979; Hardin, 1995); and Criterion 1c for visibility of the arrows relative to their background, termed figure-ground differentiation

(Krampen, 1965; Waller, 1981; Reid, 1990a; Rock & Palmer, 1990; MacEachren, 1995). The importance of including Criterion 1 was further validated by the following quotations from two educators (E1, E2) for Figure 5.2.9.

> E1: If you don't know they're there, you'll never see them. (Criterion 1a)
> E2: It is only on close inspection [i.e. 20cm from eye to page] that they [arrows to the pericardial cavity] are evident as arrows rather than shading. (Criterion 1a)
>
> E2: The pericardial arrows are very difficult to see, as they are virtually the same colour as the background.... (Criterion 1c)

Thus clearly both educators found problems with arrow visibility in terms of arrow size (Criterion 1a) and clarity relative to background (Criterion 1c).

Application of this criterion by the researcher to the 614 diagrams also revealed that in 2% of diagrams (Table 5.1) the arrows were too small to be readily seen. For example, the arrows showing the movement of chemicals across the synapse between the synaptic knob and dendrite in Figure 5.2.7(b) could be considered too small to discriminate (Criterion 1a). Furthermore, in 14% of diagrams, the arrow size was large enough to be detected but unsuitable relative to other surrounding features in the diagram (Criterion 1b). This problem is illustrated in Figure 5.2.1 part (c) in which the relatively small arrows, showing the flow of mucus in the mucous membrane, are difficult to discriminate from the surrounding detail and from the closely positioned labels. Thus in this case, the functional intention of the arrow is lost. Poor figure-ground discrimination (Criterion 1c) was a problem in 15% of diagrams including Figure 5.2.9, in which the arrows showing the flow of blood into the heart chamber are of similar colour and colour intensity to that of the background.

5.4.2 Criterion 2: Is the spatial organisation (layout) of the diagram suitably organised to allow appropriate perception?

Investigation of the literature on graphic design principles (Section 5.3.1, page 82) revealed that the spatial organisation of diagram features could have a significant effect on interpretation. This is because for features such as arrows to be effective, their arrangement or spatial organisation in a diagram should be apparent to the reader (Thompson, 1994). To achieve this, the literature revealed that the spatial variables (Gropper, 1970) should be considered, including the position of the diagram on the page; the spacing (spatial frequency) of the elements (e.g. arrows) and labels; the orientation of the elements to each other; and the sequence in which the elements are encountered (Lowe, 1993b; Colin *et al.*, 2002). In cases where these elements including arrows, are inappropriately presented in a diagram, students may incorrectly interpret the meaning of the diagram (Winn, 1993). Thus in response to the above, and other literature, I introduced Criteria 2 a – d to evaluate whether arrows are appropriately arranged to achieve the intended patterns and interpretations, instead of possibly leading the eye in unanticipated directions that might cause misinterpretation of a diagram.

5.4.2.1 Evaluate for: The arrangement and spread of arrows in diagrams to encourage appropriate perceptual precedence (Criterion 2a).

The spacing of elements, including arrows, may influence perceptual precedence or the region of the diagram to which the reader first pays attention (Navon, 1977; Frisby, 1986; Roth, 1986), particularly if accompanied by some form of localised salience (or prominence) such as boldness, shape or attracting colour (Bennett & Flach, 1992). Inappropriate perceptual precedence may promote an inadvertent focus (either locally or globally) or the emergence of unexpected properties (Bennett & Flach, 1992). For example, diagram (b) of Figure 5.2.2 is presented more prominently (in terms of size, salience and position) than diagram (a), thereby drawing the eye to diagram (b) first. The significance of diagram (a) as the reference for diagram (b) is therefore lost or reduced. The graphic-design expert (G-E), in support of this criterion noted this problem by stating the following:

> G-E: a should be positioned higher than b – tend to look at b first.

In the application of Criterion 2a to the 614 diagrams, I considered that students' focus may be adversely affected in 2% of diagrams in which the arrows were spread over too large an area, too closely packed or poorly arranged. In these cases, the intended patterns of arrows may not be appreciated. Thus, it is important to have Criterion 2a as part of the set of criteria for evaluating spatial organisation of arrows in diagrams.

5.4.2.2 Evaluate for: Grouping of arrows to form perceptual units (Criterion 2b).

Unit binding of related features (e.g. Szlichcinski, 1979; Winn, 1993; Songer & Mintzes, 1994; Stern & Robinson, 1994; Henderson, 1999) by an individual will only be successful if the units of information are easily separable from other information. In this regard, Criterion 2b was introduced to evaluate for both explicit (clearly marked outer boundaries), such as the obvious circular shape of Figures 5.2.3 and 5.2.18, and clearly identifiable implicit (or implied) boundaries (Reid 1990a) forming units of information within the diagram. For example, in Figure 5.2.4, implicit boundaries, formed from the three columns of information and the two phases (haploid and diploid), divide the diagram into six internal units. Implicit boundaries will not be clear if the elements of the diagram are closely presented. For example, the following quotations from the graphic-design expert (G-E 1 – 3), referring to Figure 5.2.2, constitute clear evidence for this problem and why it is important to evaluate for it:

G-E1: a + b (are) too close together
G-E2: linking arrow between a + b could be used differently to allow for better spacing of a + b
G-E3: linkage not adequately shown

Our evaluations of the 614 diagrams showed that explicit boundaries (Criterion 2bi) were not effective in 3% of diagrams (Table 5.1), mainly where the diagrams including arrows were poorly separated from text or from other diagrams in a compositional display. For example, the closely presented diagrams in Figure 5.2.1, showing the breathing system (a), infundibulum (b) and mucous membrane (c), appear crowded and compromise the clarity of the arrow linkages. Implicit boundaries (Criterion 2bii) were difficult to identify in 6% of diagrams (Table 5.1) including complex presentations such as Figure 5.2.12 where numerous arrows diverge in many directions from several points in the diagram. In addition, some arrows are relatively distant from their referents. Thus from the above literature, evaluations by the graphic-design expert and evaluation of the 614 diagrams, it is clear that both Criteria 2bi and 2bii should be important members of the set of criteria for the evaluation of arrow symbolism.

5.4.2.3 Evaluate for: Presentation of the Principles of Continuity, Proximity, Similarity and Frequency for appropriate grouping of arrows (Criterion 2c).

The problems associated with grouping are governed by the many and varied Principles of Perceptual Organisation (Kosslyn, 1989; Stern & Robinson, 1994; MacEachren, 1995; Kress & van Leeuwen, 1996) discussed in Chapter 2 and defined in the Glossary. Appropriate presentation of diagram techniques such as continuity, proximity, similarity and frequency can be used positively to communicate the message of the diagram. However, poorly applied presentation techniques may initiate illusions (Finke, 1990; Winn, 1993) or unexpected emergent effects not found in the component parts (Roth & Frisby, 1986) and not intended by the designer of the image (Finke, 1990). In addition, Hill (1988, page 32) noted that: 'Students attend not only to the relevant aspects but also to other aspects which we do not anticipate and thus some diagrams mislead them.' Based on this evidence from the literature, I introduced Criterion 2c to evaluate for any unexpected emergent properties that might result from the presentation techniques that I considered most appropriate to arrow symbolism, namely those of continuity, similarity, proximity and frequency effects, either individually or in combination. Their importance as cues to successful interpretation of arrow symbolism and therefore the importance of evaluating them as part of the criteria necessitates a brief explanation of each.

According to the Principle of Continuity (Kosslyn, 1989) a series of symbols is perceived as a continuous line. Whether, in fact, it is seen as a single entity or not, will have a marked effect on the interpretation of the diagram (Henderson, 1999). Thus it is important to evaluate for this problem as part of one of the criteria (Criterion 2c). For example, the closely presented and similarly styled arrows in Figure 5.2.23 encourage the eye to follow the arrows, as a unit, in a circular pattern. This pattern clearly shows the path of flow of sol in the *Amoeba* and thereby the purpose of the diagram. However, in Figure 5.2.11B(ii), the eye is drawn laterally, unintentionally and incorrectly implying a linear connection between ATP and H, whereas they are both products of the glucose-phosphate molecule. Furthermore, in Figure 5.2.22, a continuity effect is suggested by the horizontally placed large grey arrows used as label lines, pointing into the tubule and appearing to be in sequence with the slim grey arrows (indicating the path of absorption of water, glucose and amino acids and sodium ions from the tubule). As the continuity effect is unintended, difficulties may occur during interpretation of the diagram. The two upward arrows (one of which labels information about filtrate flow) in contrary direction to the downward arrows indicating direction of filtrate flow are also potentially confusing. So, in some diagrams (such as in Figure 5.2.23) the continuity effect is intended and facilitative and in other diagrams (such as Figures 5.2.11 B(ii) and 5.2.22) it is not.

The Principle of Similarity states that similar features (e.g. arrows) tend to be grouped during perceptual discrimination (e.g. Fleming, 1987). For this reason, arrows drawn in similar (or different) styles could be associated with the same (or different) purposes. To avoid possible conflicting presentations, it is necessary to evaluate for the purposes of similarly and differently styled arrows. A relevant criterion was therefore included as a sub-category of Criterion 2c. For example, in Figure 5.2.24, the similarly styles arrows grouped within the nasal cavity are correctly perceived as a unit representing the same phenomenon, the pathway of air; whereas the black arrow in the same vicinity, but of different style, is detected as showing a separate purpose, namely magnification.

According to the Proximity Principle, arrows that are closely positioned suggest a group

(Kosslyn, 1989; Winn *et al.*, 1991; Stern & Robinson, 1994). It was therefore important to include a criterion to ascertain whether closely positioned arrows are intended as a unit. For example, in Figure 5.2.11 diagram O, Pi, because of its proximity to NAD, appears to be more associated with NAD than with the ADP /ATP conversion that it should be associated with. It is reasonable to expect that this presumably unintended presentation could lead the student to form inappropriate mental models of the metabolic pathway chemistry. Another example of an illusory effect is found in Figure 5.2.7, where the key giving the intended meaning of the arrow is unfortunately presented close to, and directly in line with, the dendrite, creating an illusion that the arrows are associated. However, as they point in opposite directions, they are in conflict and prove confusing. On the other hand, in Figure 5.2.25, the group of three larger arrows (correctly perceived as a single unit) is effective in using the frequency effect to emphasise the downward force intended by the diagram designer.

The frequency effect, used for syntactic emphasis or to show the multiplicity of the process may be expressed by the number, size and spread of arrows in repeated groups. Since an inconsistent number of arrows in repeated groups within a diagram may suggest alternative meanings, it was also considered important to evaluate for this potential problem as part of Criterion 2c.

According to the application of the criteria to the 614 diagrams, arrows were inappropriately grouped in 9% of the evaluated diagrams, thereby incorrectly illustrating continuity (4%), similarity (1%), proximity (1%) and frequency (1%) effects (Table 5.1), when not intended by the diagram designer. For example, in Figure 5.2.2, the positioning of the two arrows of similar style in close proximity implies an unintended continuity effect, such as to show sequence or direction of flow. However, the first arrow is intended to show magnification and the second, direction of flow – two unrelated issues. This is therefore clearly an unexpected emergent effect or illusion that could lead to difficulties with interpretation of the intended message. In his evaluation of Figure 5.2.2, the graphic-design expert (G-E), not being familiar with the domain knowledge of the diagram, incorrectly presumed a continuity effect, thereby confirming this potential problem and justifying the inclusion of Criterion 2c:

> G-E: arrow from (a) is not close enough to beginning of arrow in (b).

Thus the above evidence constitutes a strong motivation for including Criterion 2c in evaluations of arrow symbolism in diagrams.

5.4.2.4 Evaluate for: Suitable number of arrows /groups of arrows for perception (no gaps, no extras, no clutter) (Criterion 2d).

Reports in the literature, as well as the graphic-design expert, suggest the inclusion of this criterion. In accordance with the Simplicity Principle (Thompson, 1994) and to ensure efficient communication of the intended message, various reports suggest that the diagram should be simple (Szlichcinski, 1979) and portray one concept, using only the information needed to interpret it (Thompson, 1994). The important thing is that the purpose of the diagram should warrant, and be enhanced by, the number of perceptual units (Szlichcinski, 1979). Diagrams should therefore be uncluttered, economical and sharply focused (Lowe, 1989). However, limiting the number of arrows could cause gaps in arrow display that might confuse or mislead the reader (Kosslyn, 1989) and also severely limit the number and variety of meaningful relationships that, according to Lowe (1988b), are a major role of arrow symbolism. Thus, all information necessary for the intended message should be included, but also (depending on the diagram) no more than is absolutely necessary. Based on this literature, I decided to include Criterion 2d to evaluate for gaps in arrow presentation (which may jeopardise continuity), unnecessary additional arrows (which may lead to confusion), and 'clutter' of arrows (which may hamper discrimination) including the formation of groupings. This decision was further supported by the following remark by the graphic-design expert about Figure 5.2.2:

> G-E: The diagram is very busy = too many arrow/label lines for available space

During the application of the criteria to the 614 diagrams, further examples of unnecessary multiple arrows obscuring the intended relationship were found in Figure 5.2.11, diagrams C and H that show several arrows connecting ADP to ATP. Similarly, in Figure 5.2.10, two different size arrows represent the nerve impulse through each of the afferent and efferent neurons, where one would suffice. The extra arrows may suggest unintended stages or processes: in this case, two stages of transmission. Alternatively, the change in size of the arrow from shorter to longer arrow, and vice versa, may be interpreted as acceleration or deceleration, respectively. Therefore in addition to the syntactic impact, an unsuitable number of arrows could also be semantically misleading. Altogether, as high as 12% of diagrams suffered from an unsuitable number of arrows, suggesting the importance of this criterion.

5.4.3 Criterion 3: Is the level of complexity appropriate?

Evaluate for: Suitable number of inclusions (arrows /arrow groups) for information processing at the relevant level of readership (complexity).

Synthesis of the literature revealed that there is ample literature (e.g. Kosslyn, 1989; Chandler & Sweller, 1991; Sweller & Chandler, 1994; Henderson, 1999; Mayer, 2003) to support the fact that too much information such as too many arrows, even if well presented, may increase the complexity level of the diagram and therefore the extraneous cognitive load (Bodemer *et al.*, 2004). In turn, a high level of complexity may impact negatively on interpretation (Szlichcinski, 1979; Reid & Miller, 1980; Fleming, 1987; Kosslyn, 1989; Reid, 1990a; Henderson, 1999) suggesting that it is important to evaluate for complexity. Although Evans *et al.* (1987) suggest that a wide range of factors influences complexity, various methods of analysis used by previous researchers (e.g. Willows *et al.*, 1981) consider only the number of elements or inclusions (see Glossary). According to this principle, a count of 1 – 5 inclusions is considered as low complexity, 6 – 10 as medium, and more than 10 as a high level of complexity. As this method reduces subjectivity, although not entirely, I adopted the same method for Criterion 3. I also considered the number of arrows against the ability and experience of the reader (Criterion 8a), as experience may reduce the difficulty of coping with complexity (Evans *et al.*, 1987). Criterion 3 was therefore included in the set of criteria to evaluate for the suitability of the number of arrows in the diagram for information processing at the relevant level of readership. This decision was suggested by the following student comments (S1 – 4) about Figures 5.2.5 (S1; S2) and 5.2.26 (S3; S4) that confirmed the need to include a criterion to evaluate complexity:

> S1: I find this drawing extreamly [extremely] confusing, all different arrows pointing everywhere.
> S2: The four arrows in the middle immediately confuse me.
> S3: There are also far too many arrows therefore I don't know which arrows to look at first and it begins to get very confusing.
> S4: Too confusing, where do you start? There are arrows everywhere leading in all directions.

When this criterion was applied to the 614 diagrams (Table 5.1, page 95), four percent of diagrams, mainly abstract diagrams of life cycles (e.g. Figure 5.2.4) and biochemical pathways (e.g. Figure 5.2.12) and processes (e.g. Figure 5.2.5), were adjudged to be of a high level of complexity, incorporating many arrows. In my opinion, these diagrams were unsuitable for the level of information processing expected of Grade 11 and 12 students. Thus Criterion 3 is clearly a crucial member of the set of criteria detailed in Table 5.1.

5.4.4 Criterion 4: Is the spatial organisation suited to the context?

Evaluate for: The suitability of recognisable spatial organisation for content and /or purpose of the diagram. Consider the patterns of collective presentations, namely networks, chains, groups and mixed formats (Chapter 4, Table 4.3)

As for the other criteria, various findings reported in the literature supported the inclusion of Criterion 4. For example, Ittelson (1996) found that spatial organisation or patterns of arrow arrangement (presented in Chapter 4, Table 4.3, page 64) could facilitate top-down processing by giving clues to diagram content and purpose, thus promoting the process of search in diagrams (Larkin & Simon, 1987; Winn, 1993). Therefore, and according to the Principle of Acceptability (Kosslyn, 1989), spatial organisation should be compatible with the context (Lowe, 1993b; Schnotz & Bannert, 2003). For example, a cyclical process should be presented by an easily recognisable cyclical pattern (Storey, 1991). Based on this, I included Criterion 4 to evaluate for the effectiveness of the spatial organisation relative to the context of the diagram. During the validation task, students found the cyclical nature of Figures 5.2.2 and 5.2.18 appropriate to show the cell and nitrogen cycles respectively. However, they (Students: S1 – 3) found the 'mirror image' presentation of two ovaries in Figure 5.2.5 (S1 – 3) and 5.2.26 (S4) confusing as shown by the following quotations:

S1: The diagrams being split into two pictures makes them seem like a different cycle or happening. The arrows confuse you and don't help with the order of the happenings.
S2: The fact that there are two ovaries shown confuses me because I don't know which one to follow.
S3: I am confused about the two different drawing[s] of the same thing.
S4: Also don't know whether together [referring to paired arrows showing inhibition and stimulation] they would cancel each other, or which is stronger.

During application of Criterion 4 to the 614 diagrams only 6 diagrams (1%) were considered to have an inappropriate format. For example, the presentation of the life cycle of the Pine (Figure 5.2.4), contrary to its descriptive title, is not conspicuously 'circular'. The above data therefore constitutes further justification for including Criterion 4 to evaluate the appropriateness of spatial organisation for the context of the diagram.

5.4.5 Criterion 5: Is the style of arrow suitable for the context?

5.4.5.1 Evaluate for: Suitability of arrow style, including commonplace styles, for the purpose of the diagram using the factors influencing diversity of arrow style (Chapter 4, Table 4.2) (Criterion 5a).

Arrow style, as with any image, has the capacity to communicate as a language (Kress & van Leeuwen, 1996) and impact on interpretation. Arrow style should therefore be explicit and relevant (Dwyer, 1970; Hardin, 1993 and 1995) and presented according to the Principles of Acceptability and Purpose-compatibility described by Kosslyn (1989). Only then can the potentially broad significance and, sometimes, abstract purpose of arrow symbolism within the diagram be fully understood (Garland, 1979; Lowe, 1993b; Szlichcinski, 1979; Kress & van Leeuwen, 1996). Thus I considered it important to evaluate whether arrow style is suitable for the context. The results of the content analysis (Chapter 4) enabled the identification of the major variables (Chapter 4, Table 4.2, page 61) that can influence the physical characteristics of arrows and therefore arrow style including the shape, colour and dimensions of the arrows. I therefore decided to use these variables to evaluate the style of arrows relative to the purpose of the diagram (Criterion 5a). The following quotation from a student about Figure 5.2.5 further supports the inclusion of Criterion 5a:

> S: I don't know why the arrow [to the corpus luteum] is drawn open at the back.

In addition, and most significantly, evaluation of the 614 diagrams revealed that the style of arrow did not suit the intended purpose of the symbolism in as many as 17% of diagrams. This problem is shown by the broken arrows (commonly used to show inhibition) used in Figure 5.2.11M and O to show a reaction pathway and in Figure 5.2.12 to show diffusion of oxygen; the thin to wide arrow representing the relative energy levels in ATP and ADP in Figure 5.2.11C and D; and the broad to narrow taper illustrating magnification in Figure 5.2.8. These arrow styles and presentations confuse rather than elucidate the purpose of the diagram and are therefore potentially problematic. Thus, clearly, Criterion 5a is an essential member of the set of criteria given in Table 5.1.

5.4.5.2 Evaluate for: Variation /consistency in style to avoid synonymy and polysemy (Criterion 5b).

Criterion 5b was introduced because various experts have recommended avoiding synonymy (Lowe, 1993b; Henderson, 1999; Ametller & Pinto, 2002; Colin *et al.*, 2002; Stylianidou *et al.*, 2002), and polysemy (Geva, 1983; Lowe, 1993b) unless an explanation is provided for the changed intention of the arrow symbolism (Waller, 1981; Lowe, 1993b). In both cases interpretation of the purposes of the arrow symbolism may be compromised and students could be confused or misled. I therefore recognised the importance of including Criterion 5b to evaluate for both consistency of style within purpose (Criterion 5bii) and the variation of style for different purposes (Criterion 5bi). For Criterion 5bi, the purpose of a particular arrow style was potentially ambiguous if the style, including size, was not depicted sufficiently differently from arrows of different purpose. For example the graphic-design expert, not familiar with the biological concepts portrayed in Figure 5.2.2, erroneously presumed that the same size and style of the arrows in diagrams (a) and (b) coded for the same purpose:

> G-E: same size – same purpose

Application of Criterion 5bi to the 614 diagrams revealed that the problem exists in 6% of diagrams evaluated. For example, in Figure 5.2.19 similar arrows are used to show the various functions of transfer of pollen, magnification of the cob, and position of the cob on the plant. The nett result is confusion. The following student quotation, questioning the lack of consistency of arrow style within purpose in Figure 5.2.5, justifies the inclusion of Criterion 5bii:

> S1: Why did the hormones from the pituitary have large black arrows whereas the hormones oestrogen and progesterone have small black arrows?

To further illustrate this problem, arrow style was not consistent within purpose in 5% of the 614 diagrams evaluated. For example, in Figure 5.2.18, the denitrifying bacteria should have been depicted in the same format as the other four types of bacteria noted in the nitrogen cycle. To confuse the issue further, the large unnamed arrow between nitrates and plant and animal protein, is the same shape and in sequence with the arrows cueing for bacteria. However, this arrow denotes uptake of nitrates by the plant – a totally different concept. Thus the above evidence supports the inclusion of Criterion 5b for evaluating arrow symbolism in diagrams.

5.4.5.3 Evaluate for: Conformity of arrow use (Criterion 5c).

The textbook review reported in Chapter 4 showed that a few specific styles of arrow are accepted as commonplace presentations (Chapter 4, Table 4.4, page 66) in the design of diagrams (Waller, 1981; Henderson, 1999). However, a lack of conformity could result in confusion and misconceptions (e.g. Waller, 1981; Kosslyn, 1989). Based on this and similar literature, I therefore motivated to introduce Criterion 5c to evaluate for conformity of presentation of particular commonplace styles and for configurations of arrows between diagrams. Although I did not validate for this criterion specifically, application of this criterion to the 614 diagrams in the selected textbooks revealed that conformity of particular arrow styles within diagrams, contexts and textbooks was ignored in 26% of the diagrams studied (Table 5.1). For example, the accepted and most widely used format for showing coupling (shown below in Figure 5.4) is so familiar that it could be regarded as a convention (Dutkiewicz, 1982; Henderson, 1999). However, in Ayerst *et al.* (2000b) eleven different depictions of the ADP to ATP transformation occurred, but only once in the conventional way. A further five novel presentations of coupling occurred in the other two series of textbook. Some examples of the styles of presentation of the ADP /ATP reaction are given in Figure 5.2.11. To a novice, such diversity of presentation could cause confusion and therefore it is important to include a criterion (Criterion 5c) that evaluates for this problem.

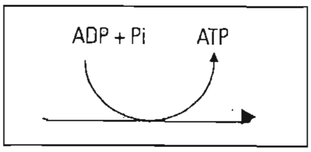


Figure 5.4 The conventional format for showing coupling.

5.4.6 Criterion 6: Are arrows appropriately placed and positioned?

Evaluate for: Relevance of placement of arrows between referents (Criterion 6a) and positioning of arrow origin and arrowhead relative to referents (Criterion 6b).

According to the Within-Mapping Principle (Kosslyn, 1989), how arrows are placed reflects the relationships among the elements of the diagram. The relationships in turn inform about the purpose. I therefore introduced Criterion 6 to evaluate for the relevance of the placement of arrows in the diagram (Criterion 6a) and the precise positioning of the arrow origins and arrowheads between referents (Criterion 6b). The following students (S1 and S2) and graphic-design expert (G-E) comments about the arrows in Figure 5.2.5 validated the inclusion of these criteria.

> S1: I also found the arrows from LH to the follicle confusing. (Criterion 6a)
>
> S2: I found it confusing how the arrows sent from the progesterone and oestrogen are merely in the middle of the arrows leaving the pituitary gland. I think it should be at a specific labelled place.
> G-E: positions of points of coloured arrows a little vague (Criterion 6b)

Student 1 (S1) referred to the confusing placement of the arrows from LH on either side of the burst follicle, but short of it (Criterion 6a), while Student 2 (S2) and the Graphic-design expert (G-E) referred to the poorly positioned arrowheads (Criterion 6b). Application of Criterion 6a to the 614 diagrams revealed that in 9% of diagrams, arrows did not link the relevant referents. For example, in Figure 5.2.13, the positions of the arrows from hydrogen and carbon dioxide to glucose suggest that hydrogen and carbon dioxide are added to glucose rather than joining to form it. This could mislead students regarding the correct chemistry and conceptual difficulties could be the outcome. Further evidence for this type of problem, is found in Figure 5.2.15, in which arrows are drawn from soil nitrates to corn and a cow (both objects), and denitrification (a process). In this case, poor prior knowledge may make the student assume that denitrification is an object not a process, and that the cow eats the soil nitrates directly. In the above examples (Figures 5.2.13 and 5.2.15), scientifically acceptable interpretation is dependent on prior knowledge, an issue evaluated by Criterion 8a.

Application of Criterion 6b to the 614 diagrams revealed a similar situation in which arrow origins and arrowheads were poorly positioned in 13% of the textbook diagrams. For example in Figure 5.2.17 the small vertical arrow should extend from the outer surface to the midline in order to show the full extent of the intended diffusion distance. Furthermore, in Figure 5.2.16, the point and shaft origin of the arrows do not penetrate the membrane of the guard cell, implying diffusion to, but not into, the guard cells. Also in Figure 5.2.14, the arrows to and from the nucleus incorrectly imply the destination and origin of gases as the nucleus. In my opinion, poor presentation techniques such as those shown in the above examples (Figures 5.2.14, 5.2.16, 5.2.17) may impair interpretation of the relationship and purpose cued by the arrow. I therefore considered it important to evaluate for this potential problem as per Criterion 6.

5.4.7 Criterion 7: Are the arrow and textual cues suitable for assigning meaning?

5.4.7.1 Evaluate for: Harmony between modes of arrow presentation, content and purpose including appropriate syntactic emphasis, to achieve the intended meaning (Criterion 7a).

The following reasoning contributed to my decision to include Criterion 7. The literature reports on several Semantics Principles, such as the Between-Mapping Principle (Kosslyn, 1989), that describe the processes and limitations involved in interpreting the meaning of the arrow symbolism in the context of the diagram. As reported by Lowe (1988a, page 35), for meaning to be clear to the reader it is important that the arrow styles and purposes are represented 'in an enlightening, unambiguous and readily discernable manner'. This is because interpretation of incorrect meaning can cause confusion and possibly a loss of reader confidence (Kosslyn, 1989; Bennett & Flach, 1992). Also, the various elements (arrows) in the diagram should be presented in accordance with their importance (Wheeler & Hill, 1990), with salient features corresponding to the necessary syntactic emphasis (Goldsmith, 1987; Kosslyn, 1989; Bennett & Flach, 1992; Winn, 1993; Thompson, 1994; Lowe, 1997; Lowe, 2004) and in accordance with Thompson's (1994) guidelines for harmony. These guidelines suggest that all parts of the diagram should relate to and complement each other, portraying a unified message. Criterion 7a was therefore included to evaluate for the factors such as modes of presentation, content and purpose including appropriate syntactic emphasis, contributing to the meaning of the symbolism in the diagram. The following quotations, by an educator (E) referring to the arrangement of arrows in Figure 5.2.5 and by a student (S1) referring to the three (instead of four) arrows in Figure 5.2.3, constitute further motivation for including Criterion 7a:

> E: The meaning of the arrows is not clear in the diagram.
> S1: If DNA replication (8hrs), DNA & protein synthesis (7 – 8 hrs) and further ....(6 – 8) then how does the whole cycle take 24 hrs, this would have to include the phases.

Application of Criterion 7a to the 614 diagrams further reinforced the importance of this criterion in that 22% of diagrams were shown to lack harmony suggesting that the meaning of these diagrams may not be clear to the reader.

5.4.7.2 Evaluate for: Provision of appropriate and sufficient propositional guidelines (including caption, annotations, labels, key, legend, proximal text) (Criterion 7b).

Our initial decision to include Criterion 7b was based on the following argument and key literature. In support of Mayer's (1997) spatial contiguity principle, the dual coding (Mayer & Anderson, 1992), generative (Mayer *et al.*, 1995) and dual channel (Mayer, 2003) theories (see Glossary for details), I recognised that most diagrams should be provided with textual information or propositional guidelines to aid integration of the presented knowledge with prior knowledge (Levin & Mayer, 1993). This should include an appropriate caption; suitable annotations and labels; a key and legend; and supporting text presented in close proximity (Kosslyn, 1989; Moore *et al.*, 1993; Lowe, 1997). Such goal determinants are beneficial as they reduce unnecessary visual search (Chandler & Sweller, 1991) and guide the reader in assigning meaning to symbolism by setting the context of the diagram (Pinto & Ametller, 2002), pinpointing relations and assisting in the selection and organisation of relevant information, especially in diagrams designed to show processes (Mayer & Gallini, 1990). As readers scan diagrams according to expectations, goals can direct the learners' search patterns and strategies (Winn, 1993), thereby influencing interpretation of meaning (Szlichcinski, 1979). Because of these functions, propositional guidelines are often termed goals of search. I therefore considered it appropriate to include Criterion 7b to evaluate for the provision of appropriate cues and goals to guide interpretation of arrow symbolism. The importance of this criterion was further supported by the following quotations from students (S 1 - 3) and the graphic-design expert (G-E):

> S1: The ovaries are not labelled (I only know from lessons in class!). On the left side the "circle" in the ovary could be anything. It needs labels. As does the "hole" on the right
> S2: There is no order of time, what happens when? There should be more labels.
> S3: ....is confusing, as well as the smaller straighter arrows which are unlike the ones in the key drawing
> G-E: Text on previous page [instead of adjacent to the diagram] therefore not good.

In the above quotations, the students commented about the lack of labelling (S1, S2) or incomplete key (S3) in Figure 5.2.5, while the graphic-design expert referred to the inappropriate positioning of the accompanying text of Figure 5.2.2.

Application of Criterion 7b to the large sample of 614 diagrams (see Table 5.1) revealed that 20% of diagrams had inappropriate captions, labels or annotations. Of these, 17% ignored the intended purposes of the arrow symbolism in the diagram. For example, the functional aspects intended by the arrow symbolism in Figure 5.2.21 are ignored in the caption, which reads: 'A diagram to illustrate the structure of the pituitary gland'. Similarly, in Figure 5.2.20, the communication value of the oppositely positioned arrows is lost as they are not labelled or referred to in the caption or text. To a novice such a presentation could imply movement of one nucleotide chain contrary to the other.

Although by introducing Criterion 7b I am advocating labelling, Lowe (1993b) warns against using arrows as label lines even though it may be considered traditional to label with neat arrows (Wheeler & Hill, 1990). Instead he suggests attaching a label to the origin or shaft of the arrow saying 'Arrow shows…', as students are more likely to misinterpret arrow cues than label cues (Goldsmith, 1987). Other authors also suggest that arrows used as labels should be appropriately cued and positioned (e.g. Dutkiewicz, 1982; Kosslyn, 1989).

5.4.8 Criterion 8: Is the level of design suited to the reader's frame of reference?

5.4.8.1 Evaluate relative to: Learning level (including age and competence according to Grade (Criterion 8a).

The idea of introducing Criterion 8a was motivated by the report of Winn (1993, page 12) who stated 'Graphics are interpreted in terms of what viewers already know, what they expect the graphic to mean and so on.' (i.e. their frame of reference) and 'A misconception or an absence of prior knowledge may result in a diagram being interpreted in unsuspected ways, or in a student ignoring it because it makes no sense to him or her.' Thus diagrams should be offered at the level at which the reader understands both the 'language' of the spatial organisation (Fleming, 1987), the codes or graphic devices used in the diagram (Garland, 1979; Waller, 1981; Fleming, 1987; Wheeler & Hill, 1990; Lowe, 1993b; Henderson, 1999; Kress & van Leeuwen, 1996) and the conceptual knowledge represented by the diagram. This is in line with the model of Schönborn and Anderson (Schönborn, 2005) (see Chapter 3, Section 3.1.1, page 20). I therefore decided to include Criterion 8a to evaluate the presentation of arrow symbolism in the diagram against the learning level and competence of the student. The inclusion of this criterion was further validated by the following observations of the graphic-design expert (G-E) for Figure 5.2.5:

> G-E: Clear for brighter pupils, weaker pupils would find the arrow grouping difficult.

Application of this criterion to the 614 diagrams revealed that 11% of diagrams, including Figures 5.2.4, 5.2.5 and 5.2.12, could be considered too advanced for Grade 11 and 12 learning level unless an educator provided supportive knowledge and guidance. Thus, clearly it is important to include Criterion 8a in the list.

5.4.8.2 Evaluate for: Culture - the compatibility of the spatial organisation with students preferred direction of reading according to their culture (Criterion 8b).

Criterion 8b was included to evaluate the presentation of arrow symbolism, particularly the expected direction of reading (Gropper, 1970; Szlichcinski, 1979; Serpell & Boykin, 1994) against the culture of the reader. This was in response to literature suggestions such as that of Serpell & Boykin (1994, page 369) who stated: 'Symbols acquire meaning by virtue of their currency within a system of communication among a section of the world's population'; and that of researchers such as Waller (1981), Goldsmith (1987) and Kress & van Leeuwen (1996) who suggested that presentation contrary to the expected direction of reading could have a marked effect on interpretation.

Only 2% of the 614 diagrams did not maintain an expected 'western read'. One of the thirteen exceptions was Figure 5.2.22, in which there is a culturally unexpected, right – left read because the labels are on the right of the diagram. In another example, Figure 5.2.6, the arrows indicate that the diagram should be read from right to left, and bottom-up, both directions being contrary to that traditionally expected in South African schools. However, if students regard these directions as inconsequential, interpretation will probably not be compromised. This remains to be checked by Criterion 10: Validity Check (see results in Chapter 6).

5.4.9 Criterion 9: Combinational treatment of arrow symbolism

As a result of applying the eight criteria discussed above, designed for a thorough analysis of arrow presentation, a variety of confusing and misleading presentations were identified. However, a subsequent combinational treatment by the researcher of the results for each diagram, taking cognisance of the results for Criteria 1 – 8, waived some presentations as not detrimental to the target audience and still useful for teaching and learning. For example, although the life cycle diagram of the Pine (Figure 5.2.4) does not have a distinctly circular format, it is still useful for teaching, learning and comparing the stages in the life cycle. Nevertheless, my findings revealed that as many as 30% of diagrams in the selected textbooks used some form of inappropriately presented arrow symbolism that could mislead students. This outcome constitutes strong evidence for the importance of developing the set of criteria detailed in Table 5.1 (page 95) so that potentially inappropriately presented arrow symbolism in diagrams can be improved before they cause any learning problems among students. In this regard, the ultimate check for such potential problems is whether they actually cause any difficulties among students – a crucial issue that is addressed by Criterion 10: Validity Check.

5.4.10 Criterion 10: Validity Check: The design of questions to check student interpretations of arrow symbolism in diagrams that are deemed by Criteria 1 – 9 to be potentially problematic.

In the development of Criteria 1 – 9 presented in Table 5.1, I was mainly guided by the opinions and ideas of experts in the fields of graphic design and diagram processing. Therefore the criteria mainly constitute expert opinion about graphic design of arrow symbolism. However, extensive research has shown that it cannot be assumed that if experts regard certain presentations as potential problems, students, as novices in the field (Gillespie, 1993; Levin & Mayer, 1993; Taconis *et al.*, 2001), will necessarily have difficulty with those presentations. This is particularly true given the large differences between experts and novices with respect to knowledge and skills (see Chapter 3, Table 3.2, page 25). Thus it is absolutely essential that student understanding (Henderson, 1999) and views (Schollum, 1983) about diagrams using arrows should also be sought. Criterion 10: Validity Check was introduced for this purpose and constitutes the major focus of the studies presented in Chapter 6.

5.5 CONCLUSIONS AND IMPLICATIONS

Design principles and other general guidelines pertinent to arrow symbolism were selected from a large pool of such principles and guidelines reported for sound diagram design. Through a cyclical and iterative process, these principles were developed into eight categories of criteria. Together these criteria covered the diversity of arrow designs discussed in Chapter 4 and provided inclusive guidelines for the design and interpretation of the syntactic, semantic and pragmatic aspects of individual and groups of arrows. In addition, the inclusion of Criterion 9 provided the expert with a means for a combinational treatment. The evaluations of the students, educators and graphic-design expert in most cases confirmed my evaluations and in turn, validated the inclusion of the criteria. I therefore considered the set of criteria to be a comprehensive reference by which to systematically evaluate arrow symbolism from an expert point of view.

Successful application of the full set of criteria to the 614 diagrams, representing a range of diagram types in three series of biology textbooks, indicated the generalisability of the set of criteria. I am therefore confident that the criteria may be used to generate an expert evaluation of arrow symbolism in any biology diagram and could therefore be used to assess the quality of diagrams in textbooks. However, the graphic-design expert considered the process of applying the relatively large number of criteria rather time-consuming and impractical for purposes other than for research into the presentation of arrows. Therefore, to facilitate evaluation by people using and designing diagrams with arrows, I developed a convenient and user-friendly set of criteria and accompanying checklist presented in Table 5.2.

The criteria for this set were selected from the criteria presented in Table 5.1. Criterion 1 evaluates visibility of arrow symbolism (Criteria 1a – c, Table 5.1). Criteria 2 – 6 evaluate the syntactic (Criteria 2a – d, Table 5.1) and semantic (Criterion 4, Table 5.1) aspects of spatial organisation, including overall patterning and grouping, while Criterion 7 evaluates the level of complexity (Criterion 3, Table 5.1) and therefore also simplicity (Criterion 2d). Criteria 8 - 10 evaluate specific features of arrow style (Criteria 5 a – c, Table 5.1) and Criterion 11 evaluates the placement and positioning of arrows cueing relationships between elements (Criteria 6a - b, Table 5.1) whereas Criterion 12 evaluates for harmony of presentation. Criterion 13 evaluates for sufficient propositional guidelines (Criteria 7a – b, Table 5.1), considered essential for correct meaning to be assigned to arrow symbolism. Criterion 14 evaluates the presentation of arrow symbolism against the reader's frame of reference (Criteria 8a – b, Table 5.1). A question about the necessity for modification is included for the evaluator to decide on an appropriate course of action for any inappropriately presented arrow symbolism. Although not as detailed as the set of criteria presented in Table 5.1, I consider this set of criteria (Table 5.2) sufficient to reveal most inappropriately presented arrow symbolism in diagrams as they cover the main categories of criteria including those that showed the highest frequencies.

Table 5.2 A convenient set of criteria for diagram designers, educators and students to use to evaluate arrow symbolism in biology diagrams.

Key: Y = yes; N = no, N/A = not applicable. Guidelines for modification (Column 5) are provided in Chapter 8, Table 8.1, page 193.

CRITERIA: Evaluate the diagram by responding to the following questions:	EVALUATION			
	Y	N	N/A	Suggested modification
Visibility				
1. Are all arrows suitably visible?				
Spatial organisation				
2. Is the overall spatial organisation easily identifiable?				
3. Is the overall spatial organisation appropriate to the context (content and purpose) of the diagram?				
Perceptual units				
4. Are arrows grouped to form easily identifiable perceptual units?				
5. Are the perceptual units within the overall spatial organisation appropriately linked by arrows to promote the content of the diagram?				
6. Are the perceptual units appropriate to promote the purpose of the diagram?				
Complexity				
7. Is the level of complexity appropriate for the intended user?				
Style				
8. Is the style of arrow suitable for the purpose of the diagram?				
9. Does arrow style vary for different purposes?				
10. Is arrow style the same within purpose?				
Placement and positioning				
11. Are arrows appropriately placed /positioned for the intended relationships?				
Harmony				
12. Are the arrows presented with appropriate emphasis and in harmony with other features of the diagram, to convey the intended message?				
Propositional guidelines (textual cues)				
13. Are sufficient propositional guidelines provided to interpret the intention of the arrows in the context (content and purpose) of the diagram?				
Frame of reference				
14. Is the way that the arrows are used in the design of the diagram suited to the reader's learning level and culture?				
Modification				
Are modifications to the diagram or guidelines for the student, necessary? If so, select suggested modifications from guidelines (Chapter 8, Table 8.1).				

Application of the criteria (Table 5.1, page 95) to 614 diagrams also illustrated the suitability of the criteria for assessing the quality of diagrams in textbooks. The evaluations showed that the presentation of arrow symbolism might not always be appropriate, with potentially misleading or confusing aspects of presentation occurring in 30% of the diagrams. If it is assumed that the criteria focus on relevant problems, then it is reasonable to presume that inappropriate presentations could impact negatively on students' perceptual and reasoning processes of interpretation, thereby impacting on conceptual understanding and the successful formation of mental models. Given the frequency of diagrams employing arrow symbolism (Chapter 4), and the fact that almost one in three of these diagrams is potentially misleading, serious consequences for the interpretation of diagrams could be indicated. This reinforces the importance of presenting arrow symbolism according to sound graphical principles in order to minimise difficulties with the interpretation of arrow symbolism and the possible formation of alternative conceptions (e.g. Lowe, 1993b and 1996; Ametller & Pinto, 2002). In this regard, Lowe (1988a, page 35) stated that it is necessary 'for the diagram to have an inherent physical and scientific logic' - not just look 'good'.

To inform the process of improving diagrams with inappropriately presented arrow symbolism, I developed a broad set of guidelines presented as part of the remedial proposals for further study in Chapter 8, Table 8.1, page 193.

In conclusion, this investigation into the presentation of arrow symbolism in diagrams was done using criteria developed from the ideas of experts presented in the literature, although honed and validated by the input of a range of stakeholders including educators, graphic-design expert and students. The evaluation of the 614 diagrams, performed by experts using the set of criteria, revealed a range of inappropriately presented arrow symbolism. Although it would be convenient to assume that inappropriately presented symbolism as judged by experts, would definitely cause difficulties for students who are novices in the field, it would be presumptuous to do so. I therefore considered it crucial to include Criterion 10: Validity Check (Table 5.1) in the set of criteria to investigate how the design of arrow symbolism in diagrams influences student interpretations and difficulties. The application of Criterion 10: Validity Check is the major focus of Chapter 6 in which I shall discuss student difficulties that correspond to certain problems predicted by Criteria 1 – 9 in this chapter.

CHAPTER 6
THE INFLUENCE OF ARROW SYMBOLISM ON STUDENT INTERPRETATION AND DIFFICULTIES

6.1 INTRODUCTION

Many researchers (e.g. Hill, 1988; Wheeler & Hill, 1990; Sanger & Greenbowe, 1999; Ametller & Pinto, 2002) agree that all science teachers rely heavily on diagrams as teaching and learning tools to convey concepts and relationships to students. However, Constable *et al.* (1988) suggest that science teachers make too many assumptions about students' ability to cope with diagrams. In the words of Lowe (1996, page 395) 'While an elegantly simple diagram may be seen by teachers as capturing the essence of its subject matter, to their students it may appear as a de-contextualised assortment of graphic symbols that are difficult to combine into a meaningful whole.' (See also the expert /novice discussion, Chapter 3, Table 3.2, page 24). Therefore for students to derive meaning from a diagram, it should be appropriately presented at the relevant learning level (Chapter 5, Table 5.1, Criterion 8a) so that its purpose is effectively communicated and understood by them (Levin & Mayer, 1993). In order to achieve meaning, the student needs to integrate prior knowledge (see discussion of constructivism, Chapter 3, Section 3.1.2, page 22) with deductions drawn from the internal logic of the diagram (Barnard & Marcel, 1978). This highlights two possible lines of investigation. Firstly, is the student able to recognise, organise and reason with the relevant data contained in a diagram? And secondly, to what extent, if at all, does a lack of internal logic of the diagram (from inappropriately presented information) affect interpretation? Hegarty (2004) and Chandler (2004) note the importance of considering students' visualization abilities and cognitive processing respectively. This study would therefore be incomplete without these two aspects of study.

Sources in the literature (e.g. Barlex & Carre, 1985; Lowe, 1987b; Hill, 1988) have confirmed that diagrams in general, and arrow symbolism specifically, may cause difficulties for students as they are not always as straight-forward and as simple as they may seem, especially, as Wheeler & Hill (1990) note, they might use conventions that students may not be aware of. Furthermore, and in line with constructivist theory (Chapter 3, Section 3.1.2, page 22), students need topic-relevant (domain-specific) prior knowledge in order to extract the intended information (e.g. Levin & Mayer, 1993; Winn, 1993; Henderson, 1999; Lowe, 1999). If readers do not have a knowledge base and skills to draw from, they will rely on guidance from the diagram, which, as already shown from the evaluations of diagrams in

Chapter 5, and from studies conducted in the visual literacy field (e.g. Lowe, 1997), may be lacking.

Criterion 10: Validity Check was included in Chapter 5, Table 5.1 (page 95) specifically to apply questions designed to probe student understanding of arrow symbolism in diagrams, as ultimately it is student interpretation (assessed by Criterion 10: Validity Check) and not expert opinion (Criteria 1 – 9) that determines the usefulness of diagrams. A close correlation between student (novice) interpretations and the evaluations of experts would confirm which arrow symbolism, considered inappropriate by experts for the learning level of the student, may lead to student difficulties. In addition, verification of difficulties would further validate the set of criteria (Table 5.1) and inform the design of strategies for the appropriate presentation of arrow symbolism in diagrams. I therefore decided to determine whether expert opinions about the appropriateness of arrow presentations correlate well with student (novice) performance.

6.2 RESEARCH QUESTIONS

To address Research Question 3 (Chapter 1), namely: *To what extent does the design of arrow symbolism in diagrams influence students' interpretation and difficulties?*, I asked further questions:

a. How do expert opinions about the appropriateness of arrow presentations (using the criteria identified in Chapter 5) correlate with student performance? In this regard:

b. Do students, as novices, experience difficulties with the processing of inappropriately presented arrow symbolism in diagrams? If so: What is the nature of such difficulties?

c. Do students have difficulties with the processing of appropriately presented arrow symbolism? If so: What is the nature of such difficulties?

6.3 METHODS

The following procedure (outlined in Figure 6.1, page 120) was used to investigate student interpretation of arrow symbolism as required by the Criterion 10: Validity Check (Chapter 5, Table 5.1). Examples of a stylised diagram (Figure 6.2, page 121) and an abstract diagram (Figure 6.3, page 121) were selected and evaluated using the criteria developed in Chapter 5. The results of the evaluations of Figures 6.2 and 6.3 were used to inform the design of a series of probes for each diagram. The probes were administered to groups of students (see Chapter 3, Section 3.2.2.2, page 30). The responses to the probes were analysed and the emerging difficulties were described and classified. The difficulties were in turn correlated with the evaluations of the diagrams (Figures 6.2 and 6.3) and used to suggest remediation strategies (Chapter 8).

6.3.1 Selection of diagrams

As shown in Chapter 4 (Table 4.1, page 59) the biology textbooks analysed for this study primarily use stylised and abstract rather than realistic diagram types. Thus, based on this result, I selected an example of a stylised and an abstract diagram for the present study, namely:

- A stylised diagram (Figure 6.2) of the cardiac cycle (Wright, 1989) without its accompanying text, as adapted for use in the 1998 internal biology examination at St. Anne's Diocesan College, Hilton, South Africa. The original diagram was not labelled. However, labels were added for the multiple-choice and interview probes to facilitate focused answers.
- An abstract diagram of a flow chart (Figure 6.3) of the thermoregulation process used in the Independent Examinations Board of South Africa, Senior Certificate (1994) examination paper and circulated in 1999 by the I.E.B. to schools as a recommended resource material.

The selection of the above diagrams was also informed by the various graphic principles identified in Chapters 2 and 4 and the corresponding criteria developed in Chapter 5 (Table 5.1, page 95). In other words, I needed diagrams with the features that would enable me to thoroughly trial and test the criteria in Table 5.1 and to evaluate to what extent the student (novice) data (Criterion 10: Validity Check) correlated well with the expert data (Criteria 1 – 9). In this regard, the two diagrams selected for this study were unfamiliar to the students but typical of what South African educators expect Grade 11 and 12 students to be able to understand and use for learning (Criterion 8). Also, together they reflected a range of visual cues thereby allowing a comprehensive investigation of a range of criteria (Chapter 5, Table 5.1).

The visual cues included the following:

a. All arrows in both diagrams are suitably visible (Criterion 1 a – c);

b. Both have clearly presented linear or cyclic spatial organisations in a repetitive format suitable to the context of the diagram (Criterion 4);

c. They each possess several perceptual units placed in vertical, horizontal and opposite directions dependent on clearly defined boundaries (Criterion 2b);

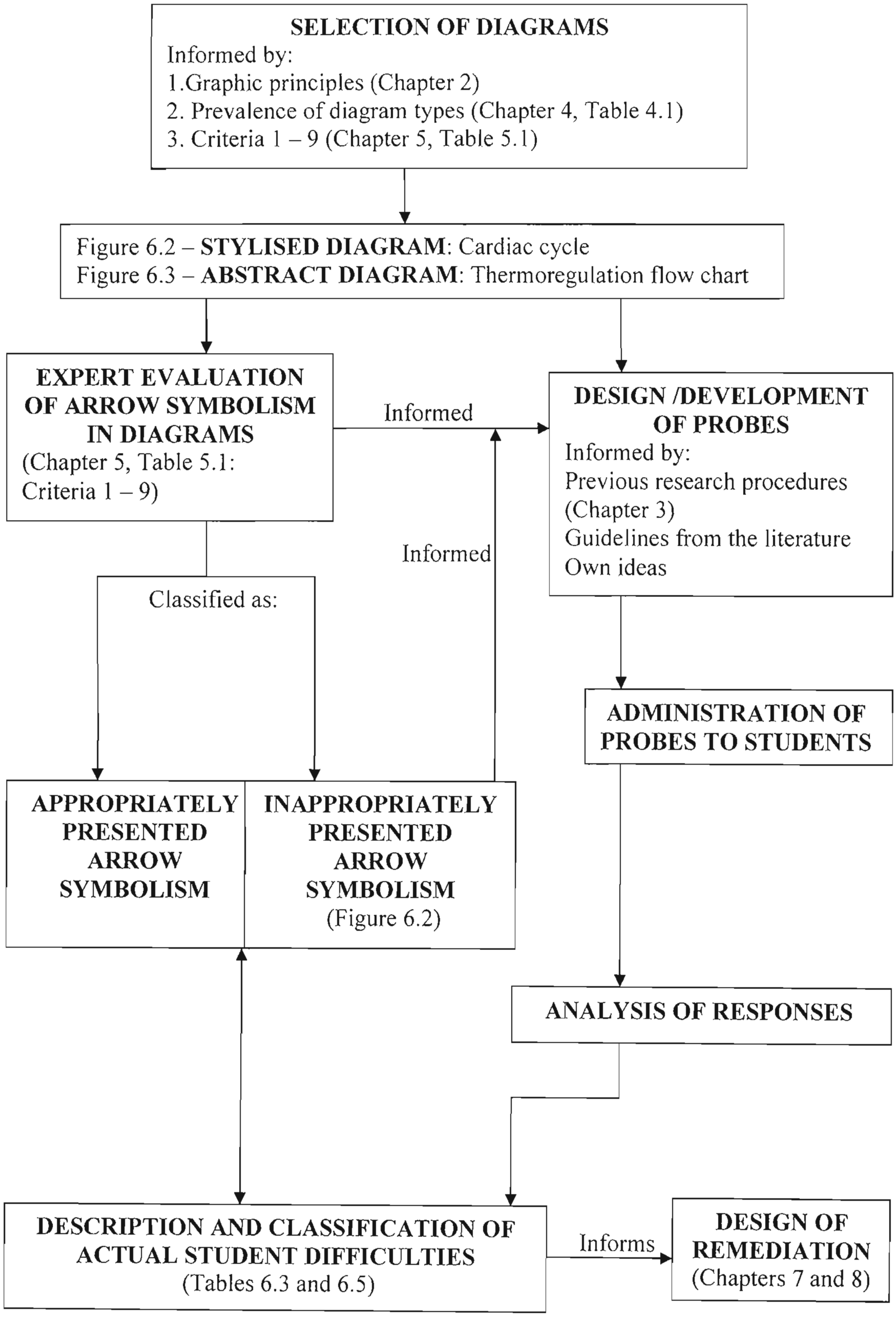


Figure 6.1 The design of the research protocol to investigate the effect of arrow symbolism on student interpretation and difficulties.

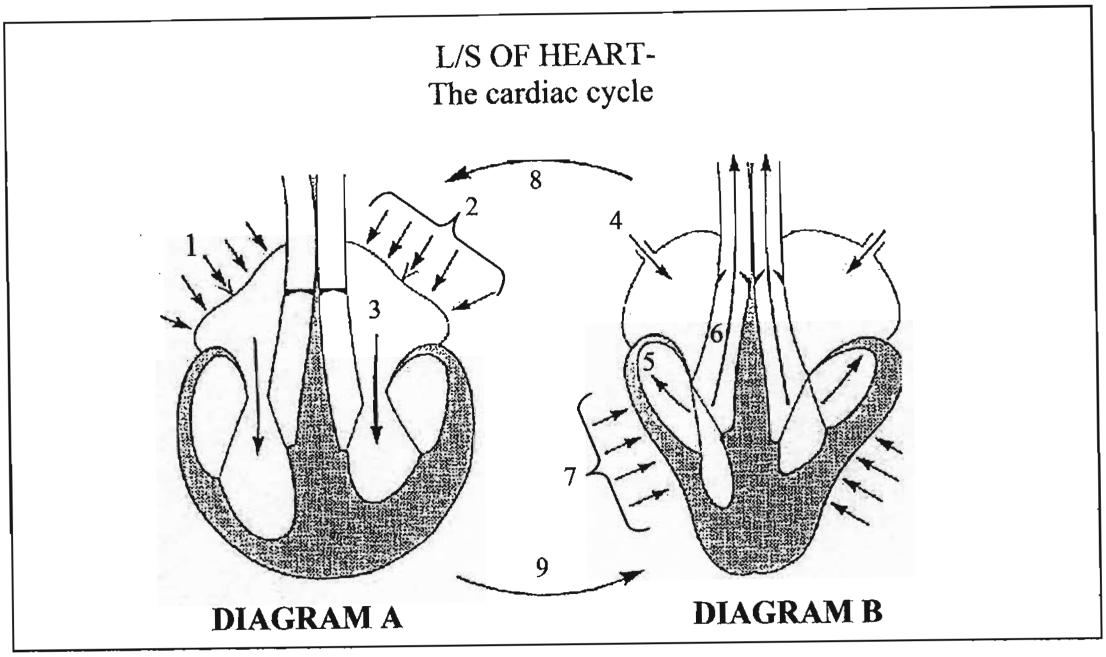


Figure 6.2 A stylised diagram of the cardiac cycle (adapted from Wright, 1989 page 55). The numbers, additional caption (L.S. HEART -) and labels (not shown above) were added to the diagram for the multiple-choice and interview probes to facilitate focused responses.

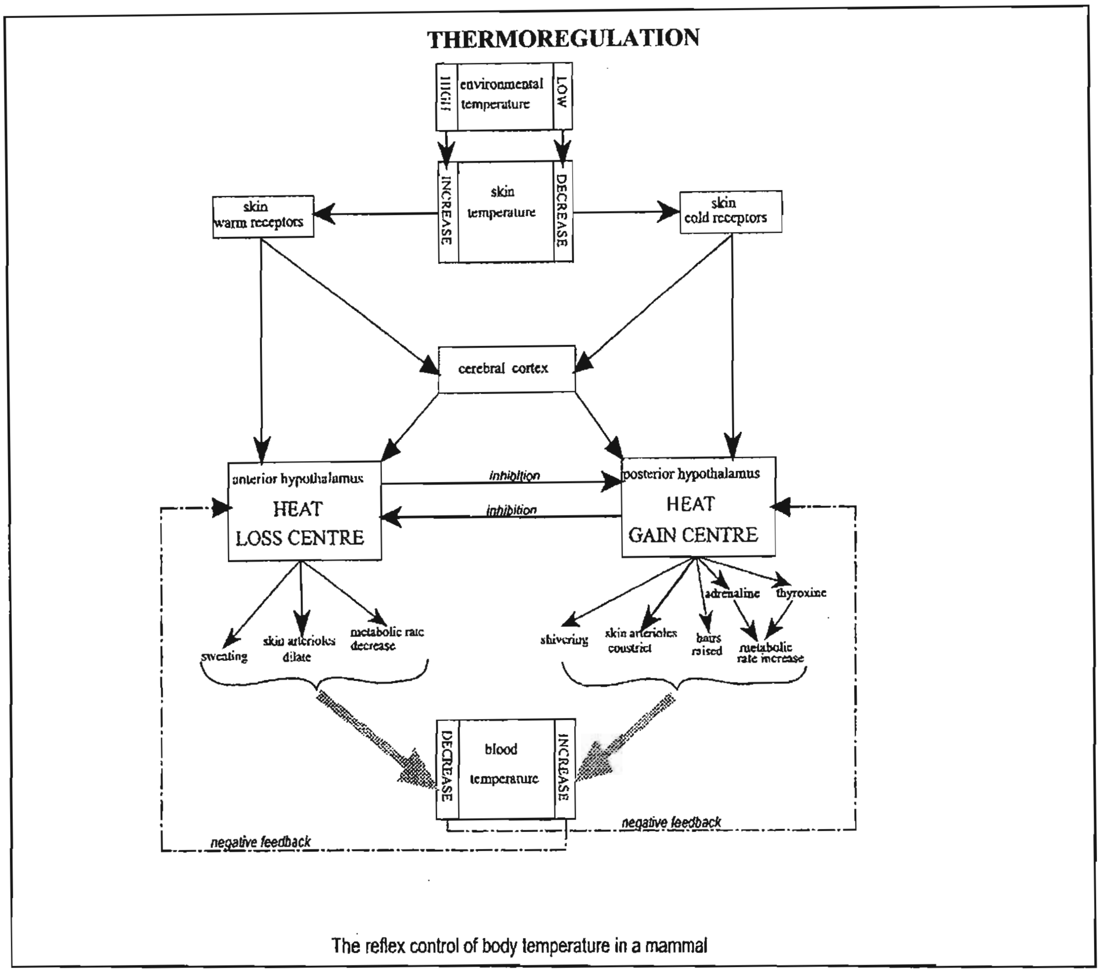


Figure 6.3 An abstract diagram of a flow chart showing the process of thermoregulation (Independent Examination Board, South Africa, Senior Certificate examination paper, 1994 and recommended resource material, 1999).

d. Both use a number of arrows (Criteria 2d; 3) in groupings for particular purposes (Criterion 2b), including for the purposes of continuity, proximity, similarity and, in Figure 5.2 (page 84 - 92), frequency effects (Criterion 2c), and grouped in various arrow patterns such as diverging, converging and sequential patterns;
e. Arrow style (Criterion 5): Figure 6.2, showing the cardiac cycle, has one style of arrow (Criterion 5b) and Figure 6.3 has several styles of arrow (Criterion 5b), including commonplace styles representing different purposes (Criterion 5a);
f. Arrows are variously used in different placements (Criterion 6a) and connecting positions (Criterion 6b);
g. Both diagrams have propositional guidelines (captions and labels) but no accompanying text (Criterion 7b).

6.3.2 Expert evaluation of diagrams for potential difficulties with arrow symbolism

To ensure that this research fully considered the design features of the selected diagrams (Figures 6.2 and 6.3), the following procedures were adopted:

a. Following the example of Pinto *et al.* (2000), the selected diagrams were described in respect to their graphical features and represented propositional knowledge.
b. The arrow symbolism used in the diagrams was evaluated objectively using the pre-determined criteria (Chapter 5, Criteria 1 – 9).
c. The evaluations were further validated by input from three qualified biology educators (Chapter 3, Section 3.2.3.1, page 46).
d. The results of the evaluations of the two diagrams (Figures 6.2 and 6.3) according to the nine criteria were used to inform the design and therefore the focus of the written probes and interviews for student understanding.
e. Difficulties emerging from the written probes and interviews into student interpretations of the diagrams (Section 6.3.3, page 122) were correlated with the potential difficulties arising from the evaluation.

6.3.3 Design and development of written probes and interviews

The process of designing and developing probes for investigating student interpretation of arrow symbolism and related difficulties, as well as the process of their development, administration, analysis and recording data, is outlined in Figure 6.1 (page 120) The design features of the written probes and interviews with Figures 6.2 and 6.3 were informed by previous research procedures explained in Chapter 3, Section 3.2, page 25, by guidelines from the literature (e.g. Posner & Gertzog, 1982; Treagust, 1988 and 1995; Tamir, 1989; Amir & Tamir, 1994; Duit *et al.*, 1996; Treagust *et al.*, 1996; Cohen *et al.*, 2000; White & Gunstone, 1993), as well as my own ideas. Probe design was further informed by the results of the expert evaluation of Figures 6.2 and 6.3 for potentially appropriate and inappropriate arrow symbolism in the diagram (Section 6.3.2 and Table 6.2, page 130). The design of these probes employed procedures traditionally used to probe conceptual understanding (e.g. Treagust, 1988; Cohen *et al.*, 2000; White & Gunstone, 1993) as well as questions focused on relationships, as suggested by van Dusen *et al.* (1999). In this way, the design of the probes addressed the three interacting factors affecting interpretation of diagrams as proposed by Schönborn and Anderson (Schönborn, 2005), namely the M (mode of representation), R (reasoning strategies) and C (conceptual understanding) factors, as well as the integrative factors of C-M, R-C and R-M. Probes were designed to specifically probe both potentially appropriate and inappropriate use of symbolism, as classified by Criteria 1 – 9 so as to establish whether:

a. Students do or do not have difficulty with arrow symbolism classified as inappropriately presented

b. Students do, or do not have difficulty with arrow symbolism classified as appropriately presented (see Figure 6.1, page 120).

Structure of the probing protocol

As explained in Chapter 3, a 3-step research protocol was used to probe students' visual processing with Figures 6.2 and 6.3. The protocol included the consecutive use of three types of probes (see Section 3.2.2.2, page 30):

1. Semi-guided probes to get students to reveal their understanding of the role of arrow symbolism in diagrams
2. Multiple-choice probes with justifications (Haslam & Treagust, 1987; Treagust, 1988 and 1995).
3. Clinical interviews (Posner & Gertzog, 1982; Cohen *et al.*, 2000; White & Gunstone, 1993; Schönborn, 2005).

Both steps 2 and 3 used a series of progressively more guided questions of a more selective and specific (and therefore more in-depth) nature to probe specific problem areas that had emerged at each of the previous steps of the process. During interviews, students were also encouraged to modify Figures 6.2 and 6.3 according to their thinking by drawing on the diagram (as explained in Chapter 3).

Addressing validity and reliability of the research protocol

Validity and reliability of the probes and probing process were addressed as explained in detail in Chapter 3, Section 3.2.3, page 46.

Examples of the sets of probes developed for Figures 6.2 and 6.3, and details of the propositional knowledge statements and explanatory notes, are provided in Appendices 1.1 – 1.6 (pages 233 – 248).

6.3.4 Administration of probes

In order to broaden the base of the investigation, the sets of probes were administered to different groups of Grade 11 or 12 students as detailed below and summarised in Table 6.1. In each case, all students had recently been instructed in, and tested on, the relevant content knowledge to ensure a thorough grounding in relevant concepts and terminology. Students were given the probes under my supervision and encouraged to respond freely and fully.

Administration of the probes on the Cardiac cycle (Figure 6.2)

The semi-guided sets of probes (Probe sets 1a, b and c in Appendix 1.1, page 233) were administered to 60 mixed ability Grade 11 students over a period of two weeks in October 2000. In November 2001, the multiple-choice probes (Probe set 2, Appendix 1.2, page 235) were administered to a new group of 49 Grade 11 students. This was followed in March 2002 by 10 interviews (Probe set 3, Appendix 1.3, page 242) with Grade 12 students, five of whom had answered the multiple-choice probes. For these five students, a profile was prepared in advance to facilitate probing of previously exposed difficulties.

Table 6.1 Student populations, data collection dates and the corresponding types of data collected from each group.

Number (*n*) in student groups	Data collection date	Grade of study	Responded to written probes	Semi-guided probes	Focused (two-level) probes	Participated in clinical interviews	Figure under study	Probe set number	Sample probes: Appendix
60	Oct 2000	11	Yes	Yes			6.2	1a – c	1.1
49	Nov 2001	11	Yes		Yes		6.2	2	1.2
10 (5 had completed the two level probe)	March 2002	12				Yes	6.2	3	1.3
25	Oct 2000	12	Yes	Yes			6.3	4	1.4
13	Sept /Oct 2001	12				Yes	6.3	5	1.5
47	May 2002	12	Yes		Yes		6.3	6	1.6

Administration of the probes on the Thermoregulation flow chart (Figure 6.3)

Probe set 4 (Appendix 1.4, page 245) was administered to 25 pupils in Grade 12 on the 7th October 2000. Over a two-week period in September and October 2001, I interviewed (Probe set 5, Appendix 1.5, page 246) a new group of 13, Grade 12 students. The multiple-choice probes (Probe set 6, parts 1 and 2 in Appendix 1.6, page 248) were administered to a third, heterogeneous population of 47 Grade 12 students over a period of a week in May 2002.

6.3.5 Analysis and recording of data

The format of analysis and recording of data explained in Chapter 3 (Section 3.2.2.2, page 30) was followed and is summarised below:

a. Transcripts were made of student interviews and correlated with student-modified diagrams and video-footage.

b. Inductive analysis was used to systematically synthesise the qualitative data from student responses to written and interview probes thereby allowing categories of difficulties to emerge.

c. The 4-level framework of Grayson *et al.* (2001) was used to guide the progressive and cyclical process of classification of the difficulties.

d. Incidences of difficulties emerging in response to the written probes (semi-guided and multiple-choice probes) were calculated and recorded.

e. As greater insight into the source and nature of each difficulty was gained, identifying descriptions of the difficulties were written.

f. Descriptions of the difficulties were then correlated with the expert evaluations of appropriate and inappropriate symbolism done according to Criteria 1 – 9 (Chapter 5, Table 5.1, page 95).

6.4 RESULTS AND DISCUSSION

In this section, I record and compare the experts' evaluations of the diagrams (Figures 6.2 and 6.3) using Criteria 1 - 9 (Chapter 5, Table 5.1) with the difficulties experienced by students with the same diagrams (Figures 6.2 and 6.3) that emerged from the application of Criterion 10: Validity Check (Chapter 5, Table 5.1).

6.4.1 Expert evaluation of Figures 6.2 and 6.3

Evaluation of the two diagrams (Figures 6.2 and 6.3) revealed several sources of inappropriately presented symbolism that could be confusing or misleading to students leading to difficulties with some aspects of interpretation of the diagrams. Descriptions of Figures 6.2 and 6.3 and evaluations of the arrow symbolism used in the diagrams, are discussed below and summarised in Table 6.2 (page 130).

Description of Figure 6.2 (Flip-out page 121 may be used to reference the diagram)

Analysis of the cardiac cycle diagram (Figure 6.2) revealed the following description of the design features and the process it represents. Figure 6.2 is an example of a stylised diagram of two stages, A and B, each highlighting different aspects of the cyclical process of blood circulation through the mammalian heart. In each diagram, groups of arrows (arrow groups numbered 2 and 7) are used to show which parts of the heart muscle are contracting, thereby reducing the size of the heart chambers and exerting pressure on the blood therein. Further arrows show the pathway of blood flow into the atrium (arrow 4), through open cuspid valves from atrium to ventricle (arrow 3) and from the heart through open semilunar valves (arrow 6). Arrow 5 in Diagram B shows blood pushing against and closing the cuspid valves. Arrow 1 in Diagram A (equivalent to the central arrow of the group labelled 2) points against the closed vessel indicating that blood cannot flow into the atrium. Curved arrows (arrows 8 and 9) link Diagrams A and B to show alternation of the stages shown in each diagram.

The diagram uses arrows or arrow groups as cues or links in at least nine distinct perceptual units. The perceptual units include the arrows or arrow groups, numbered 1 – 7, associated with their respective atria, ventricles and arteries, plus the two linking arrows (arrows 8 and 9) between Diagrams A and B. This diagram was therefore according to Criterion 3, classed as having medium complexity. However, the repetitive and cyclical spatial organisation (Criterion 4) encourages comparison of features and processes and should, if the cues are recognised, reduce the effects of complexity. The key question though (as per Criterion 8a) is whether students at Grade 11 and 12 levels are able to cope with this level of complexity.

Evaluation of arrow symbolism in Figure 6.2

Evaluation of Figure 6.2 using the nine criteria (Chapter 5), revealed the following details. The arrows in Figure 6.2 are drawn in the same style but represent several purposes (termed synonymy), including direction of flow (arrows 3, 4 and 6), direction of flow stopped by closed valves (arrows 1 and 5), alternating processes (arrows 8 and 9) and pressure (arrow groups 2 and 7). It is possible that arrow groups 2 and 7 may also suggest a process of contraction, a change in position of the heart wall or change in size of the heart chamber. According to Criterion 5bi, however, synonymy as presented in Figure 6.2 is an inappropriate design feature and therefore student difficulties could arise from this potential problem. Will students be confused by the same style of arrow used for different purposes (synonymy)? In addition, and according to the Principles of Similarity and Proximity (see Glossary), arrow 1 forms part of the perceptual unit of the arrows labelled 2. However, the supporting cues in the form of the 'V' shape of the closed vessel and the inclusion of arrow 4 in the same position on Diagram B, suggests that arrow 1 should be read as an individual arrow representing blood flow and not as part of the perceptual group (Criterion 2b). The purpose of arrow 1 is therefore not clearly presented and leads me to ponder whether students will separate arrow 1 from the group of arrows (numbered 2) based on its purpose and supporting diagram information (cued by the repetitive nature of the arrow symbolism in the diagram) rather than on arrow style? Arrows 8 and 9 successfully link the two diagrams to show alternation of the stages. However, in terms of the continuity effect (Criterion 2c), the curved shape of these arrows, in line with other similarly styled arrows form a distinctly circular pattern not only between but also through the heart. Thus another question that arises: Will students perceive arrows 8 and 9 as distinct arrows showing alternation of stages or will they see arrows 8 and 9 as part of a circular pattern linked with other similarly styled arrows? In the latter case, will students find the emergent pattern misleading?

The groups of arrows (five arrows in group 2 and four arrows in group 7) both show muscular contraction. However, the syntactic emphasis (Criterion 7a), suggested by the number of arrows in each group, implies that group 2 on the atrium has a stronger contraction than group 7 on the ventricle. This is contrary to scientific knowledge, as there is greater pressure, contraction and change in size associated with the ventricle than with the atrium. Thus this is an example where arrow presentation could be misleading and compromise the intended meaning of the symbolism and affect student conceptual understanding. Thus, an important question is whether students will be aware of the significance of the frequency effect implied by the number of arrows, when interpreting Figure 6.2, and if so how they will reconcile it with previous knowledge? All the above questions are summarised in Table 6.2 for further reference.

Description of Figure 6.3 (Flip-out page 121 may be used to reference the diagram)

The thermoregulation flowchart (Figure 6.3) is an example of an abstract diagram with, typically, referents placed in 'frames' and arrows used between the referents to show cause-effect relationships (Criterion 6a and 6b). The diagram shows the effects of both the environment (external) and blood (internal) on the process of thermoregulation in the mammalian body. The diagram (Figure 6.3) illustrates how a change in external temperature affects the temperature of the skin, which in turn stimulates either the cold or warm receptors in the skin. The receptors relay the information about skin temperature to the cerebral cortex (so that the person becomes aware of the external temperature), as well as to the respective heat centres in the hypothalamus. The hypothalamus initiates a range of responses to generate heat or lose heat from the body, including from the blood, as required. During a negative feedback process, the blood is monitored for resulting temperature changes and the actions initiated by the hypothalamus are either reinforced or inhibited.

The diagram is composed of a relatively high number of perceptual units (10) namely, the frames of environmental temperature, skin temperature (warm and cold), cerebral cortex, heat centres (gain and loss) and the blood temperature, as well as the various parts of the body affected by both heat centres. Thus according to Criterion 3, it is in the upper limit of the medium range of complexity. Thus it is important to check students' ability to cope with this level of complexity.

Evaluation of arrow symbolism used in Figure 6.3

The following evaluation of Figure 6.3 was performed using the nine criteria. The evaluation revealed several well-designed arrow features that should promote the correct interpretation of the diagram.

- Differently styled arrows were used to represent the various cause-effect relationships (Criterion 5bii).
- The various patterns of grouping (Criterion 2c) that were used, such as continuity (to show sequence), proximity and similarity (such as closely grouped, similarly styled arrows indicating the various effects of the heat centres) were suitable to the purpose of the diagram.
- Perceptual units (Criterion 2b) were clearly discernable and the spatial organisation (Criterion 4) distinctly repetitive, with 'opposite' processes shown in 'mirror image'.

However, the evaluation suggested that the design of several of the features in Figure 6.3 was potentially confusing. The spatial organisation of Figure 6.3 uses a prominent vertical axis (linear layout) and a less prominent cyclical pattern. Although not misleading to experts, to students as novices, the more salient vertical arrangement may promote unwarranted perceptual precedence (Criterion 2a). This problem may be exacerbated, as the top-down format is also the culturally accepted direction of reading (Criterion 8b) favoured by the student population. Thus the question that arises is: Will students favour the prominent vertical direction of read and in so doing neglect to interpret the cyclical pattern in the lower half of the diagram? The cyclical pattern describes the negative feedback process by means of successive arrows labelled 'negative feedback' and 'inhibition'. However, the 'negative feedback' arrows between the blood temperature and heat centre frames are shown in a commonplace broken-shaft style, whereas the inhibition arrows between the heat centres are drawn with solid shafts. A change in arrow style within purpose (Criterion 5bii) negatively affects the continuity effect and the formation of a cyclical perceptual unit. Students may not link the arrows in sequence, which in turn, may hamper interpretation of the full feedback cycle. Hence the question: Will a change in style within purpose confuse interpretation (Criterion 5bii)? Furthermore, as the diagram is graded at the upper limit of medium complexity (10 perceptual units), the question remains: Will students find the presentation too complex (Criterion 3)?

In conclusion, the above posed questions arising from the evaluation of the diagrams (see Table 6.2) will be matched against difficulties identified in student responses to the probes in order to establish whether difficulties were due to inappropriately presented arrow symbolism or to some other source, including arrow symbolism that may have been judged appropriate by the criteria.

Table 6.2 Potential sources of difficulty with inappropriately presented arrow symbolism in Figures 6.2 and 6.3 evaluated from an expert's point of view using Criteria 1 – 9 of Table 5.1, Chapter 5.

Questions raised from the evaluation and to be addressed by the application of Criterion 10: Validity Check are posed in Column 4. Column 5 specifies the section in which each question is addressed.

Diagram	Criterion Table 5.1	Potential source of difficulty with arrow symbolism from an expert's point of view (using Criteria 1 – 9).	Questions to be addressed by the application of Criterion 10: Validity Check.	Section in which question addressed
Heart diagram (Figure 6.2)	3	Medium complexity: The diagram has nine distinct perceptual units using arrows as cues or links.	Can students at Grade 11 and 12 levels (according to Criterion 8a) cope with this level of complexity?	6.4.2.1
	5bi	One style of arrow is used for several different purposes (synonymy).	Will similarly styled arrows used for different purposes (synonymy) confuse students?	6.4.2.2
	2b (5bi)	Arrow 1 is part of the perceptual unit labelled 2 but has a different purpose to the other similarly styled arrows (synonymy).	Will students separate arrow 1 from the group of arrows (numbered 2) based on its purpose and supporting diagram information rather than on arrow style?	6.4.2.2
	2c (5bi)	A possible unexpected emergent pattern shows a cyclical path of blood flow that is contrary to scientific knowledge.	Will students perceive a cyclical pattern and therefore find the emergent pattern misleading?	6.4.2.3
	7a	Syntactic emphasis cued by the frequency effect is presented contrary to scientific understanding.	Will students be aware of the significance of the frequency effect, and if so, how will they reconcile it with previous knowledge?	6.4.3.4.
Thermoregulation flowchart (Figure 6.3)	2a	A prominent (salient) vertical axis may eclipse the less prominent cyclical layout within the diagram.	Will students favour the prominent vertical direction of read and in so doing neglect to interpret the cyclical pattern in the lower half of the diagram?	6.4.2.5
	3	Medium complexity: The diagram has ten perceptual units using arrows or arrow groups as cues or links.	Will Grade 11 and 12 students (according to Criterion 8a) find the presentation too complex, despite facilitative features?	6.4.2.1
	5bii	A change of arrow style within the same purpose (polysemy) in the sequence showing negative feedback may disrupt the continuity effect.	Will students perceive and understand the common purpose of different styles of arrows?	6.4.2.6

6.4.2 Difficulties with arrow symbolism (Figures 6.2 and 6.3)

Analysis of student responses to the various probes revealed at least 26 different perceptual or surface-level reasoning (S-L) difficulties and integration or deeper-level reasoning (D-L) difficulties with various features of Figures 6.2 and 6.3. By matching the evaluations of Figures 6.2 and 6.3 (Table 6.2, page 130) with the student difficulties that emerged, I identified a range of difficulties that may have been initiated or aggravated by the potentially misleading or confusing presentations of arrow symbolism in Figures 6.2 and 6.3. According to expert evaluations, these difficulties could be viewed as anticipated. On the other hand, difficulties not directly attributable to the design of arrows used in the diagrams, and therefore not predicted by the evaluation of the diagrams, also emerged. Both categories of difficulty, classified at level 3 on the 4-level framework (Grayson *et al.*, 2000) are summarised (Table 6.3, page 132 and Table 6.5, page 146) and discussed below. As explained in Chapter 3, Section 3.2.2.2, page 30, Level 3 difficulties are difficulties that carry a stable description but were researched in a limited context as in this research and are therefore classified as partially established.

6.4.2.1 Anticipated difficulties with arrow symbolism

Students showed difficulties with all of the aspects of arrow symbolism that were predicted as potential difficulties by the expert evaluations of Figures 6.2 and 6.3 (page 121). This is very important as it confirms that the criteria used to evaluate diagrams are good indicators of potential difficulties. The student difficulties that emerged are described and summarised in Table 6.3 (page 132), discussed below and endorsed with qualitative and quantitative evidence. Table 6.3 specifies the relevant diagram, Figure 6.2 or 6.3, (Column 1) and in Column 2, summarises the criterion (Table 5.1, Chapter 5) used to evaluate the diagram to expose the inappropriate presentation. The student difficulties are described in Column 5, coded numerically (Column 3) and with a descriptive code (Column 4). The incidence of each difficulty is supplied in the last column (Column 6).

Table 6.3 Student difficulties with the interpretation of inappropriately presented arrow symbolism in Figures 6.2 and 6.3.

The codes (Column 4) and descriptions of student difficulties (Column 5) with the interpretation of inappropriately presented arrow symbolism (as per Table 6.2) in Figures 6.2 and 6.3 (Column 1) that are classified at level 3 on the 4-level framework (Grayson *et al.,* 2001). Where possible, incidence of difficulties (Column 6) is presented as the % of students showing the difficulty over a series of related questions in the multiple-choice probes.

= Incidence not given in case of interview evidence only. Column 2 refers to the related criterion (Chapter 5, Table 5.1).

For the difficulty code, (S-L) = Surface-level reasoning, (D-L) = Deeper-level reasoning difficulties.

Figure number	Inappropriately presented arrows as per criterion no.:	Difficulty number	Difficulty code	DESCRIPTION OF DIFFICULTY	Incidence of difficulty (%)
6.2, 6.3	3	1	COMP (S-L)	Some students view the diagram (during surface-level reasoning) and indicate that they find diagrams with a large number of arrows (medium to high level of complexity) confusing. This may negatively influence aspects of perceptual processing including detection, selection and organisation of arrows.	#
6.2, 6.3	3	2	COMP (D-L)	After looking carefully at the diagram and trying to interpret it, some students have difficulty integrating information in diagrams with a large number of arrows (medium to high level of complexity).	#
6.2	5bi, 2b	3	SYN (S-L)	During surface-level reasoning, some students, by overlooking supporting cues, may have difficulty selecting and separating arrows intended for different purposes from a perceptual unit composed of similarly styled arrows (synonymy).	48
6.2	5bi, 2b	4	SYN (D-L)	The arrangement of similarly styled arrows in a diagram may cause some students to group arrows into a perceptual unit. Students who do not select and separate arrows of similar style intended for different purposes (Difficulty SYN (S-L)), may have difficulty understanding the purpose of arrows in the context of the diagram during deeper-level reasoning (Difficulty SYN (D-L)).	59
6.2	5bi, 2c	5	EMT (S-L)	The arrangement of similarly styled arrows in a diagram may cause some students to perceive unexpected perceptual spatial organisations (patterns) during surface-level reasoning. The spatial organisation will consequently be incorrectly identified.	18
6.2	5bi, 2c	6	EMT (D-L)	Some students who perceive an incorrect emergent pattern may interpret the scientific content of the diagram incorrectly.	18
6.2	2c	7	FREQ, (S-L)	Some students do not appear to notice the number of arrows in a group (frequency effect).	#
6.2	2c	8	FREQ1 (D-L)	Some students do not consider the number of arrows in a group significant for syntactic emphasis during deeper-level reasoning.	77
6.2	7a	9	FREQ2 (D-L)	If different size groups of arrows intended to show the frequency effect are presented contrary to accepted scientific understanding (content), some students may be confused about the purpose of arrows relative to the represented scientific content.	20
6.3	2a	10	SAL (S-L)	During surface-level reasoning, salient (prominently presented) patterns or axes may cause some students to identify only part of the spatial organisation.	50
6.3	2a	11	SAL (D-L)	Students who perceive an incomplete spatial organisation may not fully interpret the scientific content represented by the diagram.	#
6.3	5bii	12	POLY (S-L)	During surface-level reasoning, some students may not group arrows presented in different styles intended for similar or related purposes (polysemy) and therefore not identify common purpose.	39

Difficulties 1 and 2: The issues of many arrows and the consequent level of complexity

Difficulty 1. COMP (S-L): Some students view the diagram (during surface-level reasoning) and indicate that they find diagrams with a large number of arrows (medium to high level of complexity) confusing. This may negatively influence aspects of perceptual processing including detection, selection and organisation of arrows.

Difficulty 2. COMP (D-L): After looking carefully at the diagram and trying to interpret it, some students have difficulty integrating information in diagrams with a large number of arrows (medium to high level of complexity).

As explained in Section 6.4.1 (page 126), both diagrams (Figures 6.2 and 6.3) were evaluated according to Criterion 3 (Table 5.1, Chapter 5, page 95) at a level of medium complexity. In the quotations S1 and S2 below, students expressed confusion about the large number of arrows, which they perceived as pointing in different directions, negatively influencing the selection and organisation of arrows into perceptual units (*Difficulty 1.)*. Such perceptual or surface-level difficulties may in turn give rise to deeper-level reasoning difficulties (*Difficulty 2.*). For example, response (S3) showed that the student experienced some degree of difficulty trying to make sense of the various features of Figure 6.3 during the free-response stage of the interview.

Figure 6.2

S1: Because there [are] so many [arrows] and they all pointing in different directions.
(Appendix 1.3, Cardiac cycle interview)

Figure 6.3

S2: I think text would be better, it's quite bunched up and there's lots of arrows just pointing all over the place. And.............um , sometimes it's a little bit hard to follow exactly where it's going.
(Appendix 1.5, Thermoregulation interview)

S3:........... you really need to take a lot of time to look at it and try to understand it.
(Appendix 1.5, Thermoregulation interviews)

However, other students (S4, S5) preferred the format of the diagrams. Still others favoured the format after having engaged with the diagram during the interview process (S6). This is illustrated by the following student quotations.

Figure 6.3

S4: Because the arrows point to exactly what happens and what we should be looking at next.
S5: ....if the arrows weren't there it would be a lot harder to understand.
(Appendix 1.5, Thermoregulation interviews)

Figure 6.2

S6: Looking at it now, comparing it to what you're asking me, ...fine. It was quite confusing when I saw it by myself, cause I didn't notice those kind of things, like that closed, you know there [points to arrows numbered 1and 4]
(Appendix 1.3, Cardiac cycle interviews)

The problem of complexity, judged by the number of perceptual units using arrows or arrow groups as cues or links (Criterion 3) may make the diagrams appear complicated and difficult to understand and in turn influence students' abilities to integrate information in the diagram, during the stage of deeper-level reasoning (*Difficulty 2.).* However, comments made by students during the interviews showed that with guidance provided by the progressive nature of the interview process, all ten students interviewed were later able to interpret the diagram. Based on this finding, I considered that, although students may initially have difficulty with the number of arrows and arrow groups (described as the degree of complexity of the diagram) Grade 11 and 12 students were able to interpret the diagram. I was therefore confident that the evaluation of arrow use in the diagram was of medium complexity (neither easy, nor too difficult), as predicted by Criterion 3 (see Section 6.4.1, page 126).

Difficulties 3 and 4: The issue of synonymy particularly within perceptual units

Difficulty 3. SYN (S-L): During surface-level reasoning, some students, by overlooking supporting cues, may have difficulty selecting and separating arrows intended for different purposes from a perceptual unit composed of similarly styled arrows (synonymy).

Difficulty 4. SYN (D-L): The arrangement of similarly styled arrows in a diagram may cause some students to group arrows into a perceptual unit. Students who do not select and separate arrows of similar style intended for different purposes (Difficulty SYN (S-L)), may have difficulty understanding the purpose of arrows in the context of the diagram during deeper-level reasoning (Difficulty SYN (D-L)).

During the evaluation of the cardiac cycle diagram (Figure 6.2) using Criterion 5bi (Table 5.1, Chapter 5, page 95) described in Section 6.4.1, I noted that arrows 1, 2, 4 and 7 are presented in similar style but code for different purposes i.e. synonymy is a problem. For example, in Figure 6.2, the close proximity of the group of five same-styled arrows in Group 2 forms a perceptual unit (Criterion 2b, Table 5.1). However, based on supporting cues in the diagram, the central arrow, labelled as arrow 1, has a different intention to the other four. Therefore the group of arrows together with arrow 1 are not intended to be a perceptual unit. Students who overlooked the supporting cues did not select and separate same-styled arrows that are cueing for different purposes (synonymy) as described in Table 6.3 (page 132), leading to the identification of perceptual difficulties (*Difficulty 3.)* and deeper-level reasoning difficulties (*Difficulty 4.*).

Despite various supporting cues (the 'V' shape of the closed valve, the position of arrow 4 and different labelling techniques described in Section 6.4.1), 48% of students responding to questions 1, 2, 7, 8 and 9 of the multiple-choice probes (Probe set 2, Appendix 1.2) and in interviews (Probe set 3, Appendix 1.3) did not separate arrow 1 from the group of arrows.

This is illustrated by the following typical quotation in which the student assumed that label 1 labelled the group of arrows (not one single arrow) and was therefore no different from label 2. In other words, by disregarding the difference in labelling and associated cues, the student did not separate arrow 1 from the group of arrows labelled 2.

S2: I: Arrows number 1 and 2. Explain what they mean to you.
S: Number 2 and number 1 look the same to me.
I: Why do they look the same?
S: Because they're both on the atria (hm mm)...... and they both facing the same way. (hm mm)... and they're a group of five in each.
(probing omitted) ------------
I would have just taken them as the same. (Appendix 1.3, Cardiac cycle interviews)

This evidence demonstrated the strength of the perceptual unit and explained why students had difficulty separating the single arrow from the group of similarly styled arrows.

It stands to reason that students who are not able to do this may have difficulty with deeper levels of reasoning, such as identifying the different purposes of the arrows. In this regard, the results of this investigation into students' interpretation of arrows 1, 2, 4 and 7 (Figure 6.2) revealed that 58% of students in Probe set 1c, Appendix 1.1, page 233 (Q: What do each of the arrows 1 – 9 represent?), 59% of students in the multiple-choice probe (Q 1 – 3, 6 – 11, Appendix 1.2, page 235) as well as certain students who were interviewed, were unable to determine the different purposes of these arrows during deeper-level reasoning (*Difficulty 4.*). This difficulty is supported by the following quotations in which students attribute the same purpose to the group of arrows (labelled 2) as to the similarly styled single arrow (1). Student 1 referred to the relative strength of contraction and Student 2 to the relative portion of muscle that was contracting:

S1: I: Okay. Um.. What does number, arrow number 1 refer to?
S: Contraction of the right atrium.
I: And arrow number 2?
S: Contraction of the left.
I: Is there any difference in the labelling between arrow number 1 and arrow number 2?
S: Yes there's a bracket over 2.
I: Do you think that's got any significance?
S: They work together, the..these ones on the left. [referring to arrows 2]
I: And arrow number one?
S: Maybe not as strong..as that side.

S2: I: Hmm mm So number 1 represents muscle contraction in the atrium.
S: Yes.
I: Okay. Number 2?
S: Number 2. In Oh ja. It's the same thing...but with the entire muscle. well no, ja, Number 2 is all those, ja, okay.
I: So number 2 is the entire muscle, (ja) What's number 1 then?
S: A portion of the muscle. (Appendix 1.3, Cardiac cycle interviews)

In both the above quotations, the intended purpose of arrow 1 (path of blood) was not distinguished from the purpose of the other arrows in the group of arrows indicating muscle contraction. Further evidence of this difficulty is provided by the many responses to the function of arrow 1 in Figure 6.2 such as:

> 'Right atrium contracting' (Appendix 1.1, Probe set 1c, Cardiac cycle probe)

The following quotation (and others like it), suggests that the intention of arrow 1 would be clear had it been distinguished as a separate perceptual unit:

> I: Okay. If it was referring to only one arrow, what would it be showing?
> S: Then it would be like number 4, it would be the flow from, of blood.
> (Appendix 1.3, Cardiac cycle interview)

This information further confirms my prediction that students may have difficulty with arrows presented in similar style but intending different purposes (Criterion 5bi) and therefore supports the inclusion of Criterion 5bi in the set of criteria (Table 5.1, page 95). In addition, this evidence suggests that perceptual (or surface-level reasoning) difficulties such as *Difficulty 3.* can affect deeper-levels of reasoning – in this case, *Difficulty 4.*, when attributing purpose to arrow symbolism in the context of the diagram.

Difficulties 5 and 6: The issue of unexpected emergent properties

Difficulty 5. EMT (S-L): The arrangement of similarly styled arrows in a diagram may cause some students to perceive unexpected perceptual spatial organisations (patterns) during surface-level reasoning. The spatial organisation will consequently be incorrectly identified.

Difficulty 6. EMT (D-L): Some students who perceive an incorrect emergent pattern may interpret the scientific content of the diagram incorrectly.

The evaluation (Table 6.2, page 130) of Figure 6.2 according to Criterion 2c (Table 5.1, Chapter 5, page 95), suggested a circular continuity effect emerging from the positions of the curved arrows 8 and 9 in linear sequence with other arrows of similar style (Criterion 5bi, Table 5.1, Chapter 5). The results of this investigation revealed that 38% of students in response to the Cardiac cycle Probe set 1c (Q. 8 and 9, Appendix 1.1) and 14% of students in response to the multiple-choice probe (Q. 22 and 23, Probe set 2, Appendix 1.2) thought that arrows 8 and 9 represented a cyclical pattern of blood flow (*Difficulty 5.*), rather than showing an alternation of the stages A and B. Further evidence for *Difficulty 5.*, is provided by the following quotations (Students 1, 2) that explain arrows 8 and 9 as blood flow instead of cues to indicate alternating phases:

> S1: 8. Blood passing outside heart through various organs then back to the heart
> (Appendix 1.1, Cardiac cycle probe set 1c Q.8)
> S2: Blood entering the lungs (8)/body (9) (Appendix 1.2, Cardiac cycle M/C probes)

In addition, 18% of students in Question 7 of the multiple-choice probes (Probe set 2, Appendix 1.2), as well as in interviews (Probe set 3, Appendix 1.3), explained the path of blood as being represented in the diagram by the sequence of arrows from 1 and 2 through 3, 9, 7 and 6 to 8. The following quotation and accompanying student-modified arrow pattern (Figure 6.4, page 137), typical of other student responses, provide evidence for the existence of this difficulty (*Difficulty 5.*):

> I: Trace the flow of blood through the heart. Show me how the blood goes through the heart during the cardiac cycle.
> S: Must I draw?
> I: Alright.
> S: Okay, it goes through here......... [chatter omitted]
> I: Alright... into the ventricle
> S: Then it follows this arrow, your number 9 (hm mm) and it goes from the ventricle up to the aorta and follows arrow 8, and then, and then back into actually ja, it will go back into here.
> Okay. (Appendix 1.3, Cardiac cycle interview)

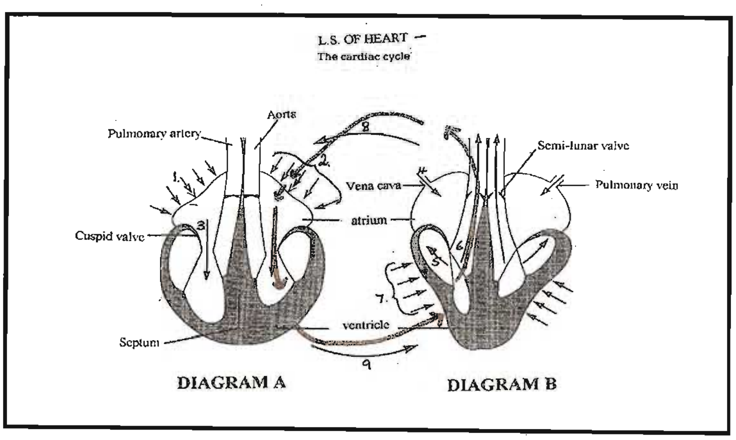


Figure 6.4 Student modified diagram showing the unexpected emergent pattern of blood flow during the cardiac cycle.

This evidence clearly shows that the arrangement of similarly styled arrows in the diagram may cause students to perceive an unexpected emergent pattern, thereby incorrectly identifying spatial organisation (*Difficulty 5.*). This evidence also confirms that Criterion 2c and 5bi are important predictors of the source of this difficulty.

In addition to incorrectly identifying the role of arrows 8 and 9 as showing blood or blood flow instead of indicating an alternation of phases, students also perceived a single cycle of circulation instead of the intended scientific concept of a double circulation - the purpose of a diagram about the cardiac cycle. In other words, the incorrect emergent pattern may precipitate interpretation of scientifically incorrect content (*Difficulty 6.*). This again demonstrates how a surface-level difficulty (*Difficulty 5.*) can influence deeper-level reasoning (*Difficulty 6.*).

Difficulties 7, 8 and 9: The issue of the frequency effect and its presentation contrary to accepted scientific understanding (content) of the diagram

Difficulty 7. FREQ (S-L): Some students do not appear to notice the number of arrows in a group (frequency effect).

Difficulty 8. FREQ1 (D-L) Some students do not consider the number of arrows in a group significant for syntactic emphasis during deeper-level reasoning.

Difficulty 9. FREQ2 (D-L) If different size groups of arrows intended to show the frequency effect are presented contrary to accepted scientific understanding (content), some students may be confused about the purpose of arrows relative to the represented scientific content.

According to the evaluation of Figure 6.2, using Criterion 7a (Chapter 5, Table 5.1) I predicted that students may see the five arrows in group 2 (or four if arrow 1 is perceived as a separate entity) cueing for contraction of the atrium, as indicating a stronger (or similar) contraction compared to the four arrows in group 7 showing ventricular contraction. In either case, this would be contrary to accepted scientific understanding as there is a stronger contraction of the ventricle than the atrium. I questioned whether students would perceive the number of arrows in groups and whether they would be aware that the size of groups of arrows can be significant for interpreting meaning. In this regard, my studies led to the identification of perceptual Difficulty FREQ (S-L) (Table 6.3, page 132) in which students did not perceive the difference in number of arrows in a group (frequency effect). This difficulty in turn, influenced students' reasoning, resulting in deeper-level reasoning difficulties (Difficulties FREQ1 (D-L) and (FREQ2 (D-L)).

No student responding to the probes on the cardiac cycle (Figure 6.2) referred to the number of arrows in groups 2 and 7 during the comparison of Diagrams A and B in Probe set 1b (Appendix 1.1, page 233). In fact, some students did not consider the number of arrows (Difficulty FREQ (S-L)) in each group until prompted, as shown by the following typical quotation from an interview:

I: Okay. Is there is any difference in the way that number 2 are, arrows numbered 2 are drawn and arrows numbered 7 are drawn?
S: No.
I: Are they identical in the way they are drawn?
S: Yes.

And after prompting:

I: Okay. How many arrows are in the group number 2?
S: 5, oh, and there're 4 here. [The difference in the number of arrows is only recognised at this point.]
(Appendix 1.3, Cardiac cycle interviews)

On the other hand, students (e.g. S1, S2) may have perceived the number of arrows, but did not, during deeper-level reasoning, appreciate its value for expressing the frequency effect (FREQ1 (D-L)), for example:

S1: I: Is there any significance in the difference in the number of arrows?
S: No I shouldn't think so.

S2: I: Okay Number 2 's got five arrows, number 7's got four. Is there any significance in that?
S: Um........ no. But I've...If I think about it, I think maybe um.the extra arrow would show me like greater contraction than here. Than the four arrows here, but I don't think that there is a difference. I don't. No I won't interpret it as a difference. (Appendix 1.3, Cardiac cycle interviews)

The majority of responses to similar questions suggested that students do not consider the number of arrows in a group important and are therefore not aware of possible syntactic emphasis implied by the frequency effect (Difficulty FREQ1 (D-L)). In fact, 77% of students responding to the multiple-choice probes for Figure 6.2 (Q. 10 & 11, Probe set 2, Appendix 1.2, page 235), and other students during interviews, used features other than the number of arrows to justify their conceptual understanding of muscular contraction of the heart. The features that were used included size or shape of the ventricles, spread of arrows, surface area or portion of muscle involved, the relative angle of impact of arrows or the power of contraction. Interview quotations supporting the use of these alternative explanations included:

S1: I: "Any significance in that?" [the four arrows in the group labelled 7 and 5 in group 2]
S: "Maybe a larger surface area in 5, er in 2"

S2: I: What is the significance of there being many of them [arrows in group number 2]?
S: The whole muscle maybe. (Appendix 1.3, Cardiac cycle interviews)

This evidence suggested another difficulty, namely that many students do not have the required graphical knowledge (which will be referred to in Table 6.5, page 146) to understand the implications of the frequency effect. The use of this design technique is therefore not suitable for students in Grade 11 and 12 (Criterion 8a, Table 5.1). In the case of Figure 6.2, it is just as well that the majority of students did not consider the frequency effect implied by arrow groups 2 and 7 as it is, according to the evaluation (Table 6.2, page 130), scientifically misleading. However, a few students did understand the implications of the frequency effect

(Criterion 2c) and were, as predicted in Table 6.2, confused by the incorrectly presented symbolism, as discussed further below.

A few students in interviews and 20% of students in the two-level multiple-choice probes (Q. 10 and 11, Probe set 2, Appendix 1.2, page 235) understood the significance of the frequency effect and realised that syntactic emphasis cued by the number of arrows in Figure 6.2 was contrary to scientific knowledge. They were then confused by the incorrect arrow messages. This difficulty, coded as FREQ2 (D-L) (Table 6.3) is supported by the following quotations from interviews that show that some students realised that a stronger contraction should be cued by a larger group of arrows. As this was not the case, Student 1 (S1) dismissed arrow number as insignificant, whereas Student 2 (S2) was confused by the unexpected size of the groups cueing differently to her prior knowledge:

S1: I: Okay. Do you think there's any significance in the number of arrows pointing at 2 and 7?
S: No I don't. If it was the other way round I might have.

S2: I: Is there any significance in that? [referring to the difference in number of arrows]
S: That makes me a bit confused because the ven, the ventricles um systole should be much stronger than atricular systole. (okay) It is confusing. (Appendix 1.3, Cardiac cycle interviews)

This information clearly shows the importance of including Criterion 7a to evaluate for harmony of meaning between all aspects of the diagram as 'mixed' messages, in this instance between mode of presentation of arrow symbolism and the scientific content of the diagram, could result in difficulties with interpretation of the diagram.

Thus the above students' responses have shown that the problems associated with using the frequency effect for syntactic emphasis could result in several difficulties. Students may not associate the number of arrows in a group with syntactic emphasis, either because they do not detect the difference in number (Difficulty FREQ (S-L)) or because they do not consider the difference in number significant (Difficulty FREQ1 (D-L)). Students may also be confused if the size of the groups of arrows intended to show the frequency effect are presented contrary to their prior conceptual knowledge (Difficulty FREQ2 (D-L)). Whatever the cause, interpretation of the scientific content of the diagram, and the formation of a scientifically acceptable mental model may be adversely affected. This evidence confirms my prediction (Table 6.2) that the presentation of the frequency effect evaluated according to Criterion 7a, may cause difficulties for students using Figure 6.2.

Difficulties 10 and 11: The issue of salience of spatial organisation

***Difficulty 10. SAL (S-L)*:** During surface-level reasoning, salient (prominently presented) patterns or axes may cause some students to identify only part of the spatial organisation.

***Difficulty 11. SAL (D-L)*:** Students who perceive an incomplete spatial organisation may not fully interpret the scientific content represented by the diagram.

Our evaluation of Figure 6.3 (summarised in Table 6.2) using Criterion 2a (Table 5.1, Chapter 5, page 95), revealed a strongly vertical spatial organisation, which I suspected might cause perceptual precedence at the expense of other features, arranged contrary to this line. As explained below, an analysis of search patterns used by students during the free response sections at the beginning of the interviews on Figure 6.3, as well as supporting quotations from interviews, showed that this was in fact the case. The sequence of reading of the diagram is shown by the sequence of numbers in Table 6.4. Dashes (-) indicate the perceptual units of the diagram that were not accessed during interpretation.

Table 6.4 Students' sequences of reading during free response probing in interviews about Figure 6.3.
The numbers represent the order in which students accessed elements of the diagram. The dash (-) indicates that the student did not note the perceptual unit.

	Perceptual units in order of vertical read (from left to right)								
Student Code	Environmental temperature	Skin temperature	Receptors	Cerebral cortex	Heat centres	Heat centre responses	Blood temperature	Negative feedback	Inhibition
AC	2	1	-	-	3	-	-	-	-
BH	1	2	3	-	4	-	-	-	-
CD	-	-	-	-	1	2	3	-	-
DR	1	2	3	5	4	6	7	8	-
KP	1	2	3	5	4	6	7	8	-
LS	2	3	1, 4	5	6	7	8	9	-
MN	1	2	3	5	4	6	7	8	-
RA	1	-	-	-	-	-	-	-	-
RS	4	5	6	2	1	3	7	8	-
SB	1	2	3	4	5	6	7	8	-
SF	1	-	-	-	-	-	-	-	-
SM	1	-	-	-	2	-	-	-	-
TW	1	2	3	4	5	6	7	8	-

As can be seen from Table 6.4, nine of the thirteen students interviewed looked first at the top of the diagram before proceeding sequentially. Two students however, for no apparent reason, started their explanations at the skin temperature (Student AC) or skin receptor (Student LS) frames. Furthermore, Table 6.4 shows that two other students (CD and RS) considered presentation techniques of the heat centres, such as the size of text (S1, S2) or text frame (S2), more salient and started interpreting the diagram at that point. This is supported by the following quotations:

S1(CD): I: Okay, you started interpreting the diagram at heat gain centre. Why did you start there?
S: Because the letters are so big that they emphasised upon you and you picked that up first.
I: You think there's a significance in that - that they've written them so big?
S: Yes because I think that's what the whole well mainly what the diagram is aiming at; that's the message it's trying to convey.

S2 (RS): I: Why did you start there? [referring to heat centres]
S: They are the big boxes. (laughs) with capital letters..........[words omitted] before I looked at the diagram properly, I just, got drawn to them. (Appendix 1.5, Thermoregulation interviews)

By focussing their attention on the prominently presented heat centre frames, one student (S1 (CD)) only interpreted the lower part of the diagram (see Table 6.4). Student S2 (RS) did not interpret the diagram in the linear sequence necessary to understand the sequential cause-effect relationships intended by the flow chart format. Thus both students showed perceptual difficulties, *(Difficulty 10.)*, namely that the prominently presented patterns or axes (such as the prominently vertical axis of Figure 6.3, might cause students to identify only part of the spatial organisation. Some clues provided by the mode of presentation in support of the scientific content or of the purpose of the diagram may therefore be missed, possibly causing subsequent deeper-level reasoning difficulties such as *Difficulty 11.* This evidence clearly indicates the importance of considering the influence of salient features on students' interpretations of diagrams and therefore for including Criterion 2a in the set (Chapter 5, Table 5.1).

Sixty-nine percent of students (9 of 13) interviewed started interpreting the diagram at the top of the page as expected from their cultural background. The following typical quotation illustrates this tendency and confirms the importance of Criterion 8b (Chapter 5, Table 5.1):

I: Ok, where did you start interpreting that diagram?
S: Like where I first looked?
I: Mmm
S: At the top
I: Why?
S: Because things usually run from the top down. (Appendix 1.5, Thermoregulation interview)

This tendency (shown in the student group interviewed) could account for students' choice of starting point and direction of reading when interpreting the diagram, but it does not necessarily account for cues being overlooked. I have already shown that salient features may override students' tendency to start at the top of a diagram. In this case (Figure 6.3), the prominent vertical axis of the diagram could be considered salient. Students may therefore read the diagram from top to bottom, possibly missing cues that are presented in another plane e.g. horizontally. The results showed this tendency as students missed the centrally positioned cerebral cortex and blood temperature frames and the horizontally placed cyclical format of the feedback mechanism. As a result of not perceiving this information, the diagram was only partially interpreted (*Difficulty 10.*). For example, for Figure 6.3, five (AC, BH, RA, SF, SM) of the thirteen students interviewed (see Table 6.4), and 48% of students who responded to the multiple-choice probes (Q.1, Part 2, Probe set 6, Appendix 1.6), stopped short of the centrally situated frame representing blood temperature. This may have been because of the inward slant of the layout at that point (S1) or that the bottom of the diagram meant 'end' to those students (e.g. S1). In such examples, the arrows indicating the negative feedback cycle, an integral part of the thermoregulation process, was overlooked.

Furthermore, some students (e.g. S2) described the relationship between the external temperature and the heat centres as a cyclical process. Their explanations implied that the external temperature affected the heat centres, which in turn affected the external environment. Not only was this explanation of the upper portion of the diagram scientifically unacceptable, but also the information about the negative feedback mechanism in the lower half of the diagram was ignored. In both cases, the intended scientific content of the diagram will not be established. The following quotations constitute further evidence for the partial descriptions of the thermoregulation process (*Difficulty 10.*) and illustrate how this difficulty, by omitting part of the diagram, could lead to scientifically incorrect interpretations of the represented scientific content (*Difficulty 11.*).

S1: I: The layout of the diagram, is it arranged in a suitable way?....
S: Like everything else goes straight down except the blood temperature, but that's obviously, the most obvious because that's where it ends, where the whole diagram ends.
[The negative feedback mechanism, an integral part of the thermoregulation process, is not considered.]

S2: I: What does the diagram tell you?
S: Okay, the diagram says that the environmental temperature umm... whether its higher or lower will affect umm..., will affect the skin temperature which will in turn either increase or decrease, and...the skin might umm, the skin receptors will either warm or cool and then... - - - - - - - -
The ..the skin receptors will umm warm up...and ummm heat...heat will be lost... ---(omitted prompts)
Ja, and then the heat's lost umm umm it just goes round in circles... On to heat gain centre.
I: Alright (encouraging)
S: And ummmm and then ummm then you go back to environmental temperature, if the skin temperature dec, decreases........................ [This is a scientifically incorrect interpretation].
(Appendix 1.5, Thermoregulation interviews)

The analysis of student reading patterns (Table 6.4) in the interviews showed further evidence of partial interpretation. Seven of the students interviewed (DR, KP, LS, MN, RS, SB and TW) included the upward-facing negative feedback mechanism in their response, but all of these students stopped short of the horizontally placed inhibition arrows (see data in Table 6.4, Column 10) and therefore did not appreciate the cyclical nature of the lower part of the diagram. The following typical student quotation refers:

> S: Its the end process, the negative feedback. (Appendix 1.5, Thermoregulation interview)

All of these findings show that the prominent vertical axis possibly influenced by students' preference for reading from the top, downward, may have eclipsed the less obvious cyclical layout of the feedback mechanism resulting in partial access (*Difficulty 10.*) to the spatial organisation. As the diagram will consequently be partially interpreted, understanding of the purpose of the arrow symbolism and the scientific content may be compromised (*Difficulty 11.)*. When I evaluated Figure 6.3 using Criterion 2a, I predicted that the prominent vertical axis might be a difficulty (Table 6.2, page 130). This evidence therefore confirms the suitability of the criteria for predicting student difficulties with arrow symbolism in diagrams.

Difficulty 12: The issue of Polysemy

Difficulty 12. POLY (S-L): During surface-level reasoning, some students may not group arrows presented in different styles intended for similar or related purposes (polysemy) and therefore not identify common purpose.

Evaluation (Table 6.3, page 132) of Figure 6.3 according to Criterion 5bii suggested that a change of arrow style within the same purpose in the sequence showing the negative feedback mechanism, might disrupt the continuity effect. Analysis of the responses to the probes showed that this proved to be a difficulty for 39% of students in the two-level multiple-choice probes (Q. 2 & 4, Part 2, Probe set 6, Appendix 1.6, page 248). As illustrated in the following quotation from an interview, some students did not notice the arrows:

> I: Just now when you described the [feedback] process to me you didn't actually mention those two arrows [the inhibition arrows]. Can you give me a reason for that?
> S: Umm.......No, I just sort of really noticed them now talking about these two – it just then struck me.
> (Appendix 1,5, Thermoregulation interview)

Other students may have noticed the arrows but not combined them to form a perceptual unit. In either case, students experienced perceptual difficulty (Difficulty POLY (S-L)) as they did not group arrows presented in different style but intended for similar or related purposes (polysemy). This evidence also confirms my prediction (Table 6.2) that polysemy (Criterion 5bii) may cause difficulties with the identification of the spatial arrangement and therefore purpose of the arrow symbolism. As a result, interpretation of the diagram will be compromised.

To sum up, students experienced problems with all aspects of inappropriately presented arrow symbolism revealed during the expert evaluations of Figures 6.2 and 6.3 using Criteria 1 – 9 (Chapter 5, Table 5.1), as presented in Table 6.2. These findings reinforce my contention that the criteria are excellent predictors of potential sources of difficulty with the use of arrow symbolism. Furthermore, these findings suggest the value of including Criterion 10: Validity Check in Table 5.1, Chapter 5 to design questions to investigate whether potential difficulties, predicted by experts using Criteria 1 – 9, will actually occur when students interpret arrow symbolism. In turn, these findings confirm my evaluations of Figures 6.2 and 6.3 using the criteria, and therefore further validate them.

The difficulties (in Table 6.3) resulting from inappropriately presented features of arrow symbolism show that arrow design may jeopardise students' perceptual (using surface-level reasoning) and integrative processing (during deeper-level reasoning) and therefore impact negatively on the interpretation of the diagram, possibly resulting in alternative or scientifically unacceptable interpretations. These findings suggest the importance of ensuring that arrow symbolism used in diagrams is appropriately designed.

6.4.2.2 Unanticipated difficulties with the interpretation of Figures 6.2 and 6.3

In addition to the anticipated difficulties described above, a range of other surface-level reasoning (S-L) and deeper-level reasoning (D-L) difficulties (see Table 6.5, page 146) that had not been predicted by Criteria 1 – 9 (Table 5.1, Chapter 5, page 95) also emerged during probing. These difficulties, therefore, were not directly attributable to inappropriately presented symbolism, as predicted by the analysis in Table 6.2 (page 130), but rather to the way that students interpret arrows.

Table 6.5 The codes and descriptions of student difficulties with the interpretation of arrows evaluated as appropriately presented in Figures 6.2 and 6.3.

The difficulties are classified at level 3 on the 4-level framework (Grayson *et al.*, 2001). Where possible, incidence of difficulties is presented as the % of students showing the difficulty over a series of related questions in the multiple-choice probes. # = Incidence not given in the case of interview evidence only. Column 1 refers to the corresponding criterion (Chapter 5, Table 5.1) used to evaluate the arrow symbolism and which did not reveal any potential difficulty. Column 6 refers to the possible source of difficulty: The letters in brackets in Column 2 refer:
S-L = surface-level reasoning (perceptual) difficulties; D-L = deeper-level reasoning (integration) difficulties.
G = graphical schemata; T = cognitive schemata; K = conceptual schemata

Appropriately presented criterion (Table 5.1)	Difficulty number	Difficulty Code	DESCRIPTION OF DIFFICULTY	Figure number	Incidence of difficulty (%)	Difficulty source
2b	13	PU, OV (S-L)	Some students explain the overall layout of the diagram, instead of searching for, selecting and grouping relevant arrows to form perceptual units.	6.2, 6.3	#	G
2b	14	PU, REL (S-L)	Some students do not select the relevant referents linked by arrows, and may therefore have difficulty forming perceptual units. Either only one referent is referred to (Difficulty PU, REL1 (S-L)) or subsequent information is named (Difficulty PU, REL2 (S-L)).	6.2 6.3	16	G
2b	15	PU, EXC (S-L)	Some students have difficulty forming a perceptual unit if they exclude arrows from groups of arrows related to particular referents.	6.3	36	G
2b	16	PU, SEQ (S-L)	Some students have difficulty forming perceptual units if they do not use the presentation technique of continuity to group arrows into a sequence.	6.3	11	G
6a	17	PLACE (S-L)	If students do not identify the placement of arrows relative to supporting information including other arrows, they may not establish the relationship between the arrow and its referent/s.	6.2	24	G
6b	18	POS (S-L)	Some students may identify the placement of an arrow relative to its referent/s. However, if they do not identify the precise positions of the arrowhead and shaft origin relative to supporting information including other arrows, they may not resolve the purpose of the relationship between the referents.	6.2	39	G
6a,b	19	C-E, (S-L)	Some students may perceive the referents in a perceptual unit, but reverse the relationship.	6.3	11	G
	20	CUE (S-L)	Some students do not (or do not adequately) use arrows in diagrams as cues because they do not understand the relevance of arrows (Difficulty CUE1 (S-L). Instead, they may rely on prior knowledge to interpret the scientific content of the diagram (Difficulty CUE2 (S-L).	6.2 6.3	33	G
5a	21	STYLE (S-L)	Some students may place undue syntactic emphasis on the style of the arrow by interpreting the style of the arrow literally.	6.3	14	G
5a	22	STYLE (D-L)	Some students may not consider the purpose of the style of the arrow, including of commonplace presentations, in the context of the diagram.	6.3	14	G, T
6a,b	23	C-E (D-L)	Some students may not integrate the various data relative to the cause-effect relationships.	6.2	32	T
4	24	CORR (D-L)	Some students, by not consciously matching (by means of bottom-up processing) and correlating complementary arrows, may miss supporting or repetitive cues that would facilitate interpretation during deeper-level reasoning.	6.2	#	T
7a	25	MEAN (D-L)	Some students have difficulty assigning meaning (words) to arrows. (They do not link the purpose of arrows (P) with the represented scientific content (C).)	6.3	13	T
8a	26	KNOW (D-L)	Some students who do not understand aspects of the scientific content (including terminology) represented in the diagram may not interpret the purpose of arrow symbolism effectively.	6.2 6.3	17	K

Possible sources of these difficulties were attributed to students' inadequate conceptual, graphical, or cognitive schemata (see Glossary), rather than with the presentation of the diagram. In terms of Schönborn and Anderson's model (Schönborn, 2005), these difficulties are attributable to the C (conceptual and graphical knowledge), R-C (reasoning with own conceptual knowledge) and R-M (reasoning with the mode of presentation) factors, rather than to the M (mode of presentation) factors. Descriptions of the difficulties (Column 4) and their incidence (Column 6), calculated from the responses to the multiple-choice probes for Figures 6.2 and 6.3 are presented in Table 6.5. Each difficulty is coded both numerically and by a descriptive code (Columns 2 and 3). Table 6.5 also includes the corresponding criterion (Column 1) which, when used in the expert evaluation, did not support any potential problems that would lead to the listed difficulties. Examples of evidence for the graphical, cognitive and conceptual difficulties are discussed below.

Difficulties associated with poor graphical schemata

A range of difficulties (Difficulties 13 – 22, Table 6.5) was attributed to students' inadequate graphical schemata and therefore poor understanding of the relevance of the syntactic features of arrow symbolism in diagrams. As these graphical difficulties are all associated with how students perceive the syntactic features of arrow symbolism and recognise arrow units and patterns, they are classed as surface-level difficulties (see Glossary). Various categories of graphical difficulties (coded by the letter G in column 7 of Table 6.5) are described below:

Difficulties 13 - 16: Difficulties with the formation of perceptual units at surface-level reasoning

Difficulty 13. PU, OV (S-L): Some students explain the overall layout of the diagram, instead of searching for, selecting and grouping relevant arrows to form perceptual units.

Difficulty 14. PU, REL (S-L): Some students do not select the relevant referents linked by arrows, and may therefore have difficulty forming perceptual units. Either only one referent is referred to or subsequent information is named.

Difficulty 15. PU, EXC (S-L): Some students have difficulty forming a perceptual unit if they exclude arrows from groups of arrows related to particular referents.

Difficulty 16. PU, SEQ (S-L): Some students have difficulty forming perceptual units if they do not use the presentation technique of continuity to group arrows into a sequence.

As far as the appropriately presented features including arrow symbolism were concerned, the expert evaluation of Figures 6.2 and 6.3, using Criterion 2b (Table 5.1, Chapter 5, page 95), did not predict that students might have difficulties associating information into perceptual units. However, students experienced a range of such difficulties, broadly coded as *Difficulties 13 – 16. PU, (S-L): Difficulties with the formation of perceptual units at surface-level reasoning*). The findings suggest that students may not have used effective perceptual (graphical) strategies to select and group information into appropriate spatial organisations or perceptual units. From the evidence, I infer that students do not appreciate the importance of the role of arrows as links between referents thereby forming relationships, including cause-effect relationships. In other words, students do not have the graphical knowledge to know that perceptual units are important for communicating ideas in diagrams. To illustrate how important perceptual unit knowledge is as an essential aspect of visualization theory, Difficulties 13 – 16 are each briefly discussed below.

Difficulty 13. PU, OV (S-L): Some students explain the overall layout of the diagram, instead of searching for, selecting and grouping relevant arrows to form perceptual units.

Instead of selecting relevant information, students gave universal answers by focussing globally rather than on the relevant cues (arrows) needed to form pertinent perceptual units within the diagram. This particular perceptual difficulty (Difficulty PU, OV (S-L), Table 6.5) was apparent in interviews and free-response questions about both Figures 6.2 and 6.3, but the more focussed nature of the multiple-choice answers precluded it. Incidence was therefore not calculated. This type of usually long and unfocussed answer (Difficulty PU, OV (S-L)) suggests that students may not employ effective search strategies when interpreting arrow symbolism in diagrams, possibly as they do not understand the importance of arrows, let alone arrows forming perceptual units, for specifying relationships in the diagram. This in turn suggests that students may have poor graphical schemata, a crucial part of visual literacy.

Analysis of responses also showed that students referred to other features of the diagram, such as subsequent effects, instead of to the relevant referents. For example, analysis of the responses to Question 1b of Probe set 4, Appendix 1.4 (Figure 6.3), revealed that 12% of students, when asked to name the effects of the skin cold receptors, did not name the associated referents, namely the cerebral cortex and heat gain centre (both of which are linked to the skin cold receptor frame by arrows), but rather named subsequent effects such as the functions of the heat gain centre. Therefore, perceptual units relative to the skin cold receptors were not formed. This difficulty (Difficulty PU, REL2 (S-L), Table 6.3, page 132) is further illustrated by the following student quotations (S1 and S2):

> S1: The [skin cold] receptors also cause skin arterioles to constrict and makes you shiver.
> S2: [The skin cold receptors] increase blood temperature.
> (Appendix 1.4, Thermoregulation Probe set 4, Q1 b)

Similar difficulties were experienced by 20% of the students responding to the multiple-choice probes using Figure 6.3 (Q. 2, Part 2, Probe set 6, Appendix 1.6, page 248).

Difficulty 14. PU, REL (S-L): Some students do not select the relevant referents linked by arrows, and may therefore have difficulty forming perceptual units. Either only one referent is referred to or subsequent information is named.

An arrow, by forming a link between two referents, specifies a relationship (often a cause-effect relationship) as a unit of information or perceptual unit. However, numerous responses to various probes on Figure 6.2 such as Probe set 1c (Appendix 1.1, page 233), the multiple-choice probes (e.g. 17% in Qs. 5, 12 and 13, Probe set 2, Appendix 1.2, page 235) and interviews (Probe set 3, Appendix 1.3, page 242) showed that on average 16% of students may note only one of the two referents (or groups of referents) associated with an arrow and therefore do not form an entire perceptual unit (*Difficulty 14.*). In the following typical quotations, students (S1 – S3) refer either to the origin, or destination of the blood, not both:

> S1: [Arrow 3 shows] Blood entering the left ventricle
> S2: [Arrow 6 shows] Blood leaving the heart
> S3: [Arrow 6 shows] Blood flowing to body (Appendix 1.3, Cardiac cycle interview)

Failure to name both referents and therefore form entire perceptual units has serious consequences for correctly interpreting intended relationships such as cause and effect relationships. Possibly as a consequence of this difficulty, students experienced *Difficulty 16. PU, SEQ (S-L): Difficulty forming perceptual units if the presentation technique of continuity is not used to group arrows into a sequence.*

Difficulty 15. PU, EXC (S-L): Some students have difficulty forming a perceptual unit if they exclude arrows from groups of arrows related to particular referents.

On average, 36% of students responding to Question 1c and d, Probe set 4, Appendix 1.4 and the multiple-choice Questions 2 and 4, Part 2, Probe set 6, Appendix 1.6 for Figure 6.3, omitted at least one arrow from a group of arrows forming a perceptual unit. For example, 41% of students failed to select at least one of the four arrows associated with the heat gain and heat loss centres and 32% of students did not consider at least one of the three arrows associated with the skin cold receptor 'frames'. *Difficulty 15.* precluded the formation of entire perceptual units. This in turn, may have resulted in partial interpretation of the diagram. Probing for possible sources of this difficulty (*Difficulty 15.*) in Question 3, Part 1, Probe set 6, Appendix 1.6 (page 248) and during interviews (Probe set 5, Appendix 1.5, page 246) revealed that students often did not fully understand the implications of grouped or branching arrows. For example student responses in interviews suggest that the 'choice' of pathway depends on the outcome required (S1); that there is no necessity to have more than one arrow as either the alternate pathway (e.g. to the cerebral cortex) is unnecessary and may be omitted in favour of a direct route (S2) or the alternate referent may be bypassed (S3, S4); that the 'direct' arrow implies a shorter and therefore quicker route (S5); and that the 'direct' (vertical) arrow is the more obvious (S6).

S1: It goes specific ways depending on how heat needs to be lost.

S2: ....but it doesn't seem like it needs to [go to the cerebral cortex] because it goes straight there [to the heat gain centre] any way, so it doesn't look like it gains anything... maybe it does or drops something off ....And the cerebral cortex is just drawn with arrows just pointing off then pointing back so it looks like its not that important.

S3: Because no reaction takes place, because its just something it bypasses.............

S4: Um...well it just goes straight to the posterior hypothalamus. It doesn't have to go to the ..cerebral cortex.

S5: Ummm...ja well, I think the skin cold receptors obviously have an effect on the cerebral cortex which in turn has an effect on the heat and gain receptors, but......ummm.......I think that's just a long way round. So I took the short way. Straight to the heat gain centres.

S6: I: Right. Umm.. Why did you move just now when you were explaining the diagram from skin cold receptors to the heat gain centre?
S: Because I followed the arrow that went straight down because the.. the label in the middle didn't really come out at me and I hadn't heard that word before. [Students had been exposed to the definitions of all words in the diagram in the pre-test.]

(Appendix 1.5, Thermoregulation interviews)

***Difficulty 16. PU, SEQ (S-L):* Some students have difficulty forming perceptual units if they do not use the presentation technique of continuity to group arrows into a sequence.**

In addition to the above difficulties with the formation of perceptual units, 11% of students responding to Question 1, Part 2, Probe set 6, Appendix 1.6 (page 248), and several students in interviews (Probe set 5, Appendix 1.5, page 246), found it difficult to group arrows into a sequence using the graphic design principle of continuity. For example, the following student linked low temperature with data (heat loss and decrease in blood temperature) in frames that are on the opposite side of the diagram, instead of following the sequence of arrows to guide the response:

> I: Right. Let's look at some of the features you have used. Again, remember to point when you are referring to them. Firstly, what effect does a low temperature have on skin temperature? (Interviewer points to low environmental box.)
> S: Ummm..(Student points to heat loss centre.) It decreases the blood temperature… and ………………..ja, no, decreases the blood temperature.
> I: Where are you pointing?..(S. points to the blood temperature box)
> I: confirms: To the blood temperature,
> S: Ja.
> I: And what makes you decide that it decreases the blood temperature?
> S: Because the heat loss causes the sweating and the metabolic rate to decrease and umm …then there's an arrow pointing to the blood temperature, but on the side where it says decrease.
> (Appendix 1.5, Thermoregulation interview)

The above information confirms that students may not use the presentation technique of continuity to group arrows into a sequence (Difficulty PU, SEQ (S-L), Table 6.5) and constitutes further evidence that students may not have the appropriate graphical schemata to understand the relevance of a sequence of arrows.

Difficulties 17 and 18: Difficulties with the observation of arrow placement (Difficulty 17) and positioning of arrow origin and arrowhead relative to other features of the diagram (Difficulty 18)

Difficulty 17. PLACE (S-L): If students do not identify the placement of arrows relative to supporting information including other arrows, they may not establish the relationship between the arrow and its referent/s.

Difficulty 18. POS (S-L): Some students may identify the placement of an arrow relative to its referent/s. However, if they do not identify the precise positions of the arrowhead and shaft origin relative to supporting information including other arrows, they may not resolve the purpose of the relationship between the referents.

During evaluation of Figures 6.2 and 6.3, using the criteria (Chapter 5, Table 5.1), the experts considered the placement of arrows (Criterion 6a) and the positioning of arrow origins and arrowheads relative to surrounding data (Criterion 6b) appropriate to the interpretation of the cause-effect relationships in the diagram. However, some students (as illustrated below) experienced difficulty on both counts.

Despite arrow 5 in Figure 6.2 being drawn entirely within the ventricle, 24% students responding to Qs. 4 & 15, Probe set 2, Appendix 1.2 (page 235), and in interviews, implied that the arrow was placed in a position to show blood flowing out of the heart (*Difficulty 17.*). This difficulty is illustrated by the following typical student quotation about the purpose of arrow 5:

S: Blood moving up and out (Appendix 1.1, Cardiac cycle Probe set, 1c)

Similarly, 39% of students did not consider the precise positions of the arrowhead (e.g. arrows 1, 2 and 7, Qs. 1, 6, and 24, Probe set 2, Appendix 1.2) in relation to supporting features (*Difficulty 18.*). In these instances, blood was identified as flowing into the heart, despite the arrows being placed entirely outside the heart with the position of the arrowhead pointing to the line indicating the outer perimeter of the atrium and not through it into the atrium. The following quotation epitomises many similar answers occurring in all probes conducted on Figure 6.2 (Appendices 1.1 – 1.3):

S4: I: What does it mean? [arrow 1]
S: (laughs) It means blood going into the atrium.
I: Okay. Is blood going into the atrium at that point?
S: Yes.
I: Okay, what tells you that?
S: The arrow point, pointing down into the atria. (Appendix 1.3, Cardiac cycle interview)

These, and other similar examples showed that students, by not considering the placement of arrows and the position of the features of the arrows (arrowheads, shafts and origins) within the spatial organisation, might not establish the intended relationship between the arrow and its referents. In such cases, students may not fully realise the implications of arrow symbolism relative to supporting data. Interpretation of the diagram could, at very least be partial, if not incorrect. Such difficulties could arise if students do not have adequate graphical knowledge about the design features of arrows to seek out the relevant characteristics such as the placement of arrows and of arrow features relative to other diagram features.

Difficulty 19. C-E (S-L): Some students may perceive the referents in a perceptual unit, but reverse the relationship.

In the opinion of the experts during evaluation of Figures 6.2 and 6.3, no cause-effect relationships (Criteria 6a and b) were inappropriately presented. However, despite correctly identifying perceptual units and specifying cause-effect relationships, an average of 11% of students reversed the cause-effect relationship (Difficulty C-E (S-L)). For example, in the multiple-choice questions 2, 3 and 4, Part 2 of Appendix 1.6 on Figure 6.3 (page 121), 13% of students suggested that sweating or dilated arterioles affected the heat loss centre and 6% of students reversed the intentioned cause-effect direction between skin temperature and skin warm receptors. This difficulty is illustrated by the following typical quotation:

> S 1: Skin warm receptors increases the skin temperature.
> (Appendix 1.2, Cardiac cycle multiple-choice probe)

Clearly, some students either do not perceive the position of the arrowhead in the relationship, or they are not using the conventional linear arrangement of cause at the origin of the arrow and the effect at the arrowhead. In either case, this suggests inadequate graphical schemata or knowledge of the significance of arrow symbolism.

Difficulty 20: Difficulty using arrows as cues during interpretation of the diagram

Difficulty 20. CUE (S-L): Some students do not (or do not adequately) use arrows in diagrams as cues because they do not understand the relevance of arrows (Difficulty CUE1 (S-L). Instead, they may rely on prior knowledge to interpret the scientific content of the diagram (Difficulty CUE2 (S-L).

Despite arrows in both Figures 6.2 and 6.3 being clearly visible (Chapter 5, Table 5.1, Criteria 1a – c), there are many examples to show that students did not use arrow cues in the diagram to aid interpretation of the diagram (Difficulty CUE1 (S-L)). For example, 22% of students did not note that blood enters the atria in Diagram B of Figure 6.2 (Appendix 1.1, Probe set 1a, Q. 2, page 233), despite an arrow (arrow 4) placed at that point. Conversely, when explaining the pathway of blood in Figure 6.2 (Appendix 1.1, Probe set 1b, Q.2, page 233), 27% of students noted the flow of blood from the atria to the ventricles in diagram B, despite no arrow in that position and the cuspid valves drawn in a closed position.

Instead of using arrow cues, some students relied to some extent at least, on their prior knowledge to interpret the diagram. This subcategory of Difficulty CUE (S-L) is described and coded as Difficulty CUE2 (S-L) in Table 6.5. Examples of this difficulty emerged from responses to the thermoregulation flowchart (Figure 6.3) in Appendix 1.4 (page 245), Probe set 4, Qs. 1b (12%) and 1d (13%), and from responses to the cardiac cycle diagram (Figure 6.2) in Appendix 1.1 (page 233), Probe set 1a, Q.1; Probe set 2, Appendix 1.2, Q. 10 (49%), Q. 11 (20%), Q. 22 (41%), Q. 23 (24%), as well as in interviews about both diagrams (see Appendices 1.3 (Probe set 3) and 1.5 (Probe set 5) on pages 242 and 246. The following quotations illustrate that students did not use arrows as cues (S1), instead using information not on the diagram (S2) to interpret the diagram:

S1: [referring to the role of the arrows labelled 1 and 2]
S: There'll be more, more pressure in t..no there'll be more pressure on 1 than there will on two.
I: Alright.
S: Because um..the one side only has to pump the blood to the lungs and the other side has to pump it round the whole body...so it needs more pressure to..pump it around the whole body.
I: Okay, does the diagram tell you that?
S: No
I: Has it got any reference to the amount of pressure?
S: No (Appendix 1.3, Cardiac cycle interview)

S2: [referring to the role of the arrow between the cold receptors and heat gain centre]
This is to stop the amount of blood going to the skin to cool down. It causes the body to send less blood to the skin so that the body can stay warm.'
(Appendix 1.4, Thermoregulation probe set 4, Q 2b)

Both subcategories CUE1 and CUE2 of Difficulty CUE (S-L) suggest that students might not have the graphical knowledge about arrows to fully understand their importance as cues to interpretation. In consequence, the intended purpose of the arrow symbolism and its relevance to the scientific content of the diagram will not be realised.

Difficulty 21 and 22. Difficulty understanding the relevance of arrow style

Difficulty 21. STYLE (S-L): Some students may place undue syntactic emphasis on the style of the arrow by interpreting the style of the arrow literally.

Difficulty 22. STYLE (D-L): Some students may not consider the purpose of the style of the arrow, including of commonplace presentations, in the context of the diagram.

In Figure 6.3, arrows for different purposes are drawn in different styles, including the commonplace presentation of a dashed arrow to represent negative feedback. The styles of the arrows were not considered inappropriate in the evaluation (using Criterion 5a, Table 5.1). However, 14% of students when interpreting the purpose of the arrows in the multiple-choice probes for Figure 6.3 (e.g. Q. 6, Part 1, Probe set 6, Appendix 1.6, page 248) gave an explanation commensurate with the syntactic features of the arrow style, rather than considering its semantic intentions. For example, during interviews (Probe set 5, Appendix 1.5, page 246), interpretations of the dashed-style of the negative feedback arrow included:

S1: not permanent or they don't always happen.
S2: because its not going anywhere as such its just umm......
S3: maybe because their function is prolonged ..umm......ja.
S4: ummm... well the part here with the blood temperature and the negative feedback mechanism, the line was dotted so makes you think that its not umm very clear or important.
S5: S: Um......they (negative feedback arrows) don't have to be there whereas these are the ones (refers to vertical pattern of arrows) that you know. Because if you wanted to write an essay, I think this, these (vertical pattern of arrows) would be more important. And those are just saying, it, it can be the reversable as well.. but it's not really part of the process.
(Appendix 1.5, Thermoregulation interviews)

These quotations suggest that if students do not understand the intention of commonplace presentations, such as the dashed arrow for showing the negative feedback process, they may place undue emphasis on the style of the arrow without considering the role of the arrows in the context of the diagram. In other words, instead of reasoning with the arrow symbolism in a scientifically acceptable way, students may explain the purpose of the arrow symbolism literally expressed in concrete rather than abstract terminology (Sandmann *et al.*, 2002), or in terms of everyday knowledge (Lowe, 1999), according to its syntactic features (*Difficulty 21. STYLE (S-L):* Some students may place undue syntactic emphasis on the style of the arrow by interpreting the style of the arrow literally). This evidence not only points to the importance of well-developed graphical schemata, but also indicates the significance of well-developed cognitive strategies (see also next section on cognitive schemata) for integrating the cue-value of arrows in association with other data in of the diagram *(Difficulty 22. STYLE (D-L):* Some students may not consider the purpose of the style of arrow, including of commonplace presentations, in the context of the diagram (D-L).

To sum up, students may not understand the purpose, meaning and importance of the role of arrow symbolism in diagrams or may not have the required training to interpret the symbolism. In either case, students' poor graphical schemata may cause a range of difficulties when interpreting arrow symbolism.

Difficulties associated with poor cognitive schemata

In order to understand the purposes of, and attribute meaning to, arrow symbolism used in diagrams, students need to integrate information about the arrows with the relevant referents in the diagram using graphical schemata, as well as with previous knowledge (conceptual schemata) using reasoning and problem-solving skills (cognitive schemata), during deeper-levels of reasoning (D-L). However, some students had difficulty using deeper-reasoning skills when interpreting cause-effect relationships (see Difficulties 22 - 25, Table 6.5), suggesting problems with their cognitive schemata. Difficulties 23 - 25 are briefly discussed below (Difficulty 22 was noted in the discussion in the above paragraph, about difficulty with the understanding of the relevance of arrow style).

Difficulty 23. Difficulty with cause-effect relationships

Difficulty 23. C-E (D-L): Some students may not integrate the various data relative to the cause-effect relationships.

As already stated, the cause-effect relationships in both Figures 6.2 and 6.3 were evaluated (as explained in Section 6.4.1) as appropriately presented. However, in questions specifically designed to probe students' integration of information and therefore understanding of the cause-effect relationships in Figure 6.2 (Probe set 2, Appendix 1.2, page 235), 35% of students could not identify the effects (Qs. 16 and 17) and 29% of students had difficulty with the cause of blood flow (Qs. 18 - 20). Similar difficulties were experienced in interviews. For example, student (S1) provided a non-specific answer for the cause of blood flow (Figure 6.2).

S1: I: What is the cause of the blood flowing through the arteries?
S: The cause? It's oxygenated by the lungs. [This occurs as a consequence of blood flowing through arteries to the lungs.] (Cardiac cycle interview)

In addition, some students did not interpret the arrow as a functional connector between referents but rather as an entity or structure, such as the actual cause or effect, a process, method of transfer or other noun (e.g. a structure). A few examples of typical terms used in place of arrows in Figure 6.2 (Probe sets 1 and 2, Appendices 1.1 and 1.2, pages 233 and 235) include:

product (end result);
reaction;
results - the overall results of all the functions functioning together;
superior vena cava;
blood. (Appendices 1.1 and 1.2, Cardiac cycle probes 1 and 2)

These examples again indicate that students may not use arrows as links in cause-effect relationships and may therefore not be able to effectively integrate the arrows with their referents (*Difficulty 23.*) during the deeper-level reasoning stages (D-L) of interpretation. This difficulty has further serious repercussions for successfully integrating information and may lead to the development of misconceptions.

Analysis of the results obtained from these investigations indicated that on average 32% of students have difficulty integrating the various cues in the diagram in order to determine cause-effect relationships. Some difficulties with interpretation of cause-effect relationships have already been noted in Table 6.3 for:

Difficulty 14. PU, REL (S-L): Some students do not select the relevant referents linked by arrows, and may therefore have difficulty forming perceptual units; (16%) and,

Difficulty 19. C-E (S-L): Some students may perceive the referents in a perceptual unit, but reverse the relationship (11%).

The higher incidence of 32% for *Difficulty 23,* possibly indicates that difficulties with cause-effect relationships occur at both the surface- and deeper-levels of interpretation. This in turn presupposes that difficulties with cause-effect relationships are not only attributable to poor graphical schemata, but also to poorly developed cognitive strategies.

Difficulty 24. CORR (D-L): Some students, by not consciously matching (by means of bottom-up processing) and correlating complementary arrows, may miss supporting or repetitive cues that would facilitate interpretation during deeper-level reasoning.

The repetitive nature of both Figures 6.2 and 6.3 was evaluated as suitable to the context of the diagram (Criterion 4), facilitative, and an aid to reducing complexity (Criterion 3). However, during interpretation of Figure 6.2, students did not make use of the repetitive nature of the diagram. Although arrows 1 and 4 were drawn in similar style and repeated in corresponding positions on Diagrams A and B (Figure 6.2), students did not compare arrow placements and therefore missed cues that may have facilitated interpretation of the arrow symbolism used in the diagram, resulting in Difficulty CORR (D-L). For example, 36% of students (Q.1, Probe set 1a, Appendix 1.1, page 233), 36% of students (Probe set 1b, Appendix 1.1, page 233) and several students in interviews (Probe set 3, Appendix 1.3, page 242) did not use arrow 4 (showing the pathway of blood into the heart) to either substantiate the function of arrow 1, as blood flowing to, but not into, the heart, or to separate the single arrow from its perceptual unit of similarly styled arrows as shown for Difficulty SYN (S-L). The following quotation, typical of several during interviews further supports this tendency:

S1: I: Is there any difference between arrow 1 and arrow 4?
S: No.
I: Do they show the same thing?
S: Yes.
I: You said arrow 1 was showing you blood flowing into the atrium; arrow 4? .....
S: Also. (Appendix 1.3, Cardiac cycle interviews)

This evidence suggests that students, by not consciously searching for complementary data (by means of bottom-up processing) or by not correlating relevant information during deeper-levels of reasoning, may miss supporting or repetitive arrow cues to interpretation of the diagram (Difficulty CORR (D-L)). In either scenario, poor cognitive schemata may compromise effective interpretation of the arrow symbolism specifically and consequently interpretation of the diagram.

Difficulty 25. MEAN (D-L): Some students have difficulty assigning meaning (words) to arrows. (They do not link the purpose of arrows (P) with the represented scientific content.)

Based on Criterion 7a (Chapter 5, Table 5.1), the expert evaluations of Figures 6.2 and 6.3 did not anticipate difficulties with the application of meaning to arrows used in the diagrams. However, data emerging from Probe set 4 on Figure 6.3 (Q. 2, Appendix 1.4, page 245) detailed in Table 6.6 below shows that 55% of students either did not try to interpret the meanings of arrows (21%) or interpreted the meanings of arrows inappropriately (34%).

Table 6.6 Summary of responses to Question 3, Probe set 1, Figure 6.3 (the thermoregulation flowchart) showing the incidence of scientifically acceptable and unacceptable answers.

including poor grammar and expression
Students claimed they were unable to reason a meaning

Arrow number	No. acceptable /25	No. unacceptable /25	No. unanswered /25
1	5	16	4
2	7	12	6
3	16	4	5
4	17	2	6
5	11	9	5
TOTAL /125	56 (45%) #	43 (34%)	26 (21%) ##

This trend continued during more specific probing in the multiple-choice probes on Figure 6.3 (Qs. 5 - 7, Part 2, Probe set 6, Appendix 1.6, page 248), where 13% of students had difficulty attributing meaning to arrows. For example, the student quotation (S1) below, justified her unsuitable selection of the word 'heat' for arrow 3 (between the warm receptor and heat loss centre frames). Similar difficulties persisted in interviews for both Figures 6.2 and 6.3 (Probe set 3, Appendix 1.3, page 242 and Probe set 5, Appendix 1.5, page 246) as illustrated by the quotation below from a student (S2):

S1: It could say this because it goes to the heat centre (temperature increase).
(Appendix 1.2, Cardiac cycle multiple choice)

S2: I: See if you can find a word to replace any of those [arrows].
S: Umm The skin the neurons would pick up that um the skin warm receptor the um the message of the skin warm receptor which means that the skin is warm
I: Ok, so what words are you going to put into that particular position?
S: Umm............... Umm.............. I don't know.
(Appendix 1.5, Thermoregulation interview)

These quotations show that students were unable to adequately integrate the purpose of the arrow with the scientific content represented in the diagrams in order to attribute meaning to the arrow symbolism. If such meaning is not assigned, the diagram will not be fully understood. This deeper-level reasoning difficulty was coded as Difficulty MEAN (D-L).

From these examples, it is apparent that some students due to their poor cognitive schemata are not able to effectively integrate arrows with referents and supporting data in the diagram in order to effectively interpret the diagram.

Difficulties associated with poor conceptual schemata

Students were pre-tested to ensure that they possessed at least a basic understanding of the circulatory system (Figure 6.2) and thermoregulation process (Figure 6.3) prior to application of the probes. In addition, Figure 6.2 was labelled to reduce the emphasis on prior content knowledge. Difficulties with conceptual understanding were therefore not the focus of this investigation. However, several conceptual difficulties (collectively described as Difficulty KNOW (D-L); Table 6.5) emerged during the investigation, one category of which is presented below.

Difficulty 26. KNOW (D-L): Some students who do not understand aspects of the scientific content (including terminology) represented in the diagram may not interpret the purpose of arrow symbolism effectively.

The following examples illustrate difficulties with conceptual understanding. In Figure 6.2, the functioning of the chordae tendinae was poorly understood (Q. 21, Probe set 2, Appendix 1.2, Figure 6.2) by 28% of students. In addition, students (41%) who chose the alternative:

'Pressure causes contraction' (Appendix 1.2, Cardiac cycle, Probe set 2) for the function of arrow 1 in the two-level multiple-choice probes using Figure 6.2 (Q.1, Probe set 2, Appendix 1.2, page 235), clearly did not understand the concept that heart muscle contracts and presses on to (contraction causes pressure) the blood contained within the heart. This difficulty with arrows 1 and 2 is also illustrated by a student response to Probe set 1c, Appendix 1.1, Figure 6.2:

> S1: Pressure is applied on to the right atrium causing it to contract (systole)
> (Appendix 1.1, Cardiac cycle Probe set 1c for arrow 1)

Several students in interviews about Figure 6.3, (Probe set 5, Appendix 1.5, page 246) and 42% of students in the two-level multiple-choice probes (Q. 8, Part 1, Probe set 6, Appendix 1.6, page 248) did not understand the meaning of the word 'inhibition' as illustrated by the following typical quotation:

> S: .....actually no....I don't know.....mm....I don't know what these are doing cause I don't know what inhibition means. (Appendix 1.5, Thermoregulation interview)

Conceptual difficulties were also experienced in interviews with students preferring the term 'cerebrum' to that of 'cerebral cortex' used in the diagram. Considering these conceptual difficulties and several other examples emerging from the two-level multiple-choice probes (Appendices 1.2 (Probe set 2) and 1.6 (Probe set 6)) for both Figures 6.2 and 6.3, a total of 17% of students (see Table 6.5) showed a poor understanding of the terminology or concepts of the diagram (Difficulty KNOW). It stands to reason that these students may have difficulty interpreting the meaning of the arrow symbolism in the context of the diagram.

6.5 CONCLUSIONS AND IMPLICATIONS

The evaluation of Figures 6.2 and 6.3 using Criteria 1 - 9 (Chapter 5, Table 5.1) provided experts' opinion of the suitability of the arrow symbolism presented in the diagrams. As a result of the evaluation, several inappropriate forms of presentation of arrow symbolism were revealed. Investigations into student interpretations of the arrow symbolism in these diagrams as suggested by Criterion 10: Validity Check (Chapter 5, Table 5.1) revealed many perceptual (surface-level) and deeper-level difficulties that closely matched these inappropriate designs. Therefore these results show that expert opinion correlates well with novice performance and substantiate my claim (Chapter 5) that Criteria 1 – 9 are highly effective in exposing problems about which students are likely to experience difficulties. This also serves to confirm that the criteria are a valid tool for predicting the source of student difficulties and with determining problems with symbol and diagram design. The results also confirm the importance of including Criterion 10: Validity Check in the set of criteria to design questions to probe students' use of arrow symbolism. In addition, the wide range of difficulties and high percentage incidence (18 – 77%) of difficulties linked to inappropriately presented arrow symbolism demonstrate how important it is for both the syntactic and semantic dimensions of diagram features (Lowe, 1989), and of arrow symbolism specifically, to be well-designed if the message of the diagram is to be easily encoded and comprehended by the visual processing system. Similar contentions are held by a number of researchers (e.g. Brody, 1984; Hill, 1988; Kosslyn, 1989; Wheeler & Hill, 1990; Lowe, 1991; Kindfield, 1993/1994; Hardin, 1995; Chauvet *et al.*, 1999; Pinto *et al.*, 2000; Ametller & Pinto, 2002; Pinto & Ametller, 2002). The findings also support those of Pinto *et al.* (2000) and Ametller & Pinto (2002) that students have difficulty interpreting arrows presented in similar style but intending different purposes (Difficulty 3. SYN (S-L)) and in different style for similar purposes (Difficulty 12. POLY (S-L)). Further, Difficulty 10. SAL (S-L) is supported by the findings of Ametller & Pinto (2002), namely that arrows pointing outward tend to be ignored. My argument for greater awareness of, and accuracy in presenting arrow symbolism is thereby further strengthened.

The empirical data also showed that students experienced 14 other difficulties (described in Table 6.5) when processing arrow symbolism that was considered by experts to be appropriately presented according to the application of Criteria 1 - 9. The nature of these difficulties suggested that they were probably attributable to students' limited interpretive ability, including their level of understanding of graphics (graphical schemata), their ability to process graphics (cognitive schemata) and to their understanding of concepts used in the diagrams (conceptual schemata). In other words, students (considered as novices in the field of education) experienced difficulties not directly attributable to the experts' opinions of arrow design and therefore not anticipated by the expert evaluator. This finding is in line with the differences between expert and novice knowledge and skills for interpreting diagrams (not arrow symbolism specifically) noted by many researchers (e.g. Guri-Rosenblit, 1988a; Lowe, 1988b; 1991; 1993a; 1994b; 1996; 1997; 1999, 2003 and 2004; Pinker, 1990; Glaser, 1992; Sandmann *et al.*, 2002; Winn, 1993; Fisher *et al.*, 2000; Pinto *et al.*, 2000; Taconis *et al.*, 2001; Ametller & Pinto, 2002; Pinto & Ametller, 2002; Kirschner, 2002; Goldman, 2003; Kozma, 2003; Lewalter, 2003) and highlighted in Chapter 3, Table 3.2, page 24. It is therefore important to investigate the information processing abilities of the students for whom the diagrams are intended. Again, the importance of including Criterion 10: Validity Check in the set of criteria (Chapter 5, Table 5.1) was confirmed.

The evidence provided in this chapter, therefore, suggests that students have difficulties with both inappropriately and appropriately presented arrows and therefore supports the hypothesis presented on page 2, namely: *Secondary-level students have difficulty with the use of arrow symbolism in biology diagrams.* The difference in incidence (based on difficulties emerging from the multiple-choice probes) between difficulties associated with inappropriate presentation (Range: 18% - 77%; Mean: 41%) of arrow symbolism and difficulties due to interpretive ability (Range: 11% - 41%; Mean: 22%) appear to be marked. Calculations based on these figures showed standard deviations of 21,56 and 10,75 respectively. In light of these statistics, I contend that it is important to consider the design of arrow symbolism in diagrams and its possible influence on student interpretations. However, it is also, and probably just as, important to consider the frames of reference of students as suggested by Schönborn and Anderson's multi-factor model (Schönborn, 2005). All areas (factors R, C, M, C-M, R-M, and R-C) are potential sources of difficulties with diagrams including the use of arrow symbolism. I therefore concur with Lowe (1993c) that both the quality of the design of the diagram and the ability of the reader are important if a diagram is to fulfil its purpose as an information source.

CHAPTER 7
DEVELOPMENT OF A MODEL OF THE PROCESS OF INTERPRETATION OF ARROW SYMBOLISM

7.1 INTRODUCTION

Following rigorous and exhaustive analysis of various types of data accumulated through the investigations of this study of arrow symbolism, I have revealed a number of issues pertaining to both the design and interpretation of arrow symbolism in diagrams. I have shown how the diversity of modes of arrow presentation (spatial organisations and styles), purposes and meanings (Chapter 4, page 55) could be confusing. Using a range of criteria to evaluate arrow symbolism in diagrams, I revealed a relatively high incidence of inappropriately presented arrow symbolism (Chapter 5, Table 5.1) that could lead to a range of surface- and deeper-level reasoning difficulties during interpretation of diagrams (Chapter 6, Table 6.3, 132). In addition, this study also showed that students experience a range of other difficulties related to their cognitive, graphical and conceptual schemata when interpreting arrow symbolism used in diagrams (Chapter 6, Table 6.5, page 146). To identify possible sources of difficulties encountered by learners during the process of interpretation of arrows, I therefore needed to consider the possible influences of both the design of arrows and students' individual schemata on the interpretation of arrow symbolism in diagrams. To answer Research question 4 (Chapter 1, page 3), *How can the emerging empirical data and ideas from literature be combined to illustrate the process of interpretation of arrow symbolism?* I considered that the various findings on the presentation of arrows in diagrams (Chapters 4 and 5) and on student interpretations of arrow symbolism (Chapter 6) could be usefully combined into a suitable model.

Modelling was deemed a suitable vehicle for such an amalgamation, as a model is 'an idea or theoretical construct that has been developed to organise and account for the available evidence in the field' (Hill, 1988, page 35). In addition, and according to Del Re (2000), the method of modelling is also regarded as an essential part of the dynamics of developing scientific knowledge. Effective models focus on individual aspects (Wisely, 1994), as well as show patterns of interactions (Winn *et al.*, 1991) and relationships among the elements (Wisely, 1994). A model would therefore assist in bringing together the information about the presentation of arrows in diagrams and the processes used by students during interpretation of arrows.

Gobert & Discenna (1997) suggest that models may be used to reveal and predict sources of difficulties that would, in turn, guide remedial strategies. Although there are models described in the literature to explain diagrams (e.g. Stern & Robinson, 1994; Ittelson, 1996) and diagram processing (e.g. Hegarty *et al.*, 1988; Mayer, 2003), none of the models relates to arrow symbolism specifically. In my opinion, it was therefore necessary to design a model to explain the influence of both the design of arrows and of students' frames of reference on their reasoning abilities during the process of interpretation of arrow symbolism. Modelling the process of interpretation of arrow symbolism (including both arrow presentation and student knowledge) will enable us to predict the source of a particular difficulty i.e. whether it is a consequence of inappropriate arrow presentation or attributable to students' graphical, cognitive or conceptual schemata.

7.2. RESEARCH QUESTIONS

To address Research question 4: *How can the emerging empirical data and ideas from literature be combined to illustrate the process of interpretation of arrow symbolism?*

A well-designed model should guide the thinking of graphic designers, educators and researchers with regard to the following sub-questions:

1. What is the nature of cognitive processing engaged by learners when interpreting arrow symbolism and what are the essential components of the process?
2. In what way might inappropriate presentation of arrow symbolism (based on expert evaluations using the set of criteria) impact on the process of interpretation?
3. At what stages of the process of interpretation of arrow symbolism do students have difficulty and what are possible sources of such difficulty?

By answering these research sub-questions, we should better understand the process of interpretation of arrow symbolism (Research question 1) and be able to predict possible sources of difficulty (Research questions 2 and 3) and what strategies might remediate the difficulties. If so, the purposes of the model will have been satisfied.

7.3. METHOD

The framework of Justi & Gilbert (2002) was used as the primary method to build and express the intended model of the process of interpretation of arrow symbolism. This modelling procedure (presented as Stages 1 – 7 in Figure 7.1, page 166) uses a combination of a serial and a cyclical process to ensure that the development of the model is systematic and that due consideration is given to each essential step of the process.

Stages 1 – 5 form the serial process, explained as follows. Firstly, the purpose for which the model is being constructed, including the intended audience, should be considered. Secondly, the modeller should undertake an in-depth literature search to ensure adequate prior knowledge and experience in the field of the phenomenon being represented. Thirdly, an analogy suited to the target of the model should be selected. Following deliberation, the purpose, prior knowledge and selected analogy should be integrated to form an initial mental model. Within the serial process just described, several cyclical developmental processes of thought experiments and empirical testing allow modification of the mental model and consequently of the mode of representation (expressed model) until considered suitable for its purpose. The suitability of the analogy and limitations of the model should be further evaluated by several researchers against both the intended purpose of the model and supporting literature for final acceptance, review or rejection.

This cyclically developmental process is rigorous and ensures thorough evaluation of the design at several levels using a variety of sources such as literature, a range of empirical data and research evaluators. It also ensures input from the researcher on a number of levels, such as reflection on the purpose, selection of a relevant analogy (source), mental modelling and thought experiments. These methods of persistent review of mental and expressed models by various means contribute to the testing of the validity of the proposed model. The final product should therefore inspire confidence in its purpose.

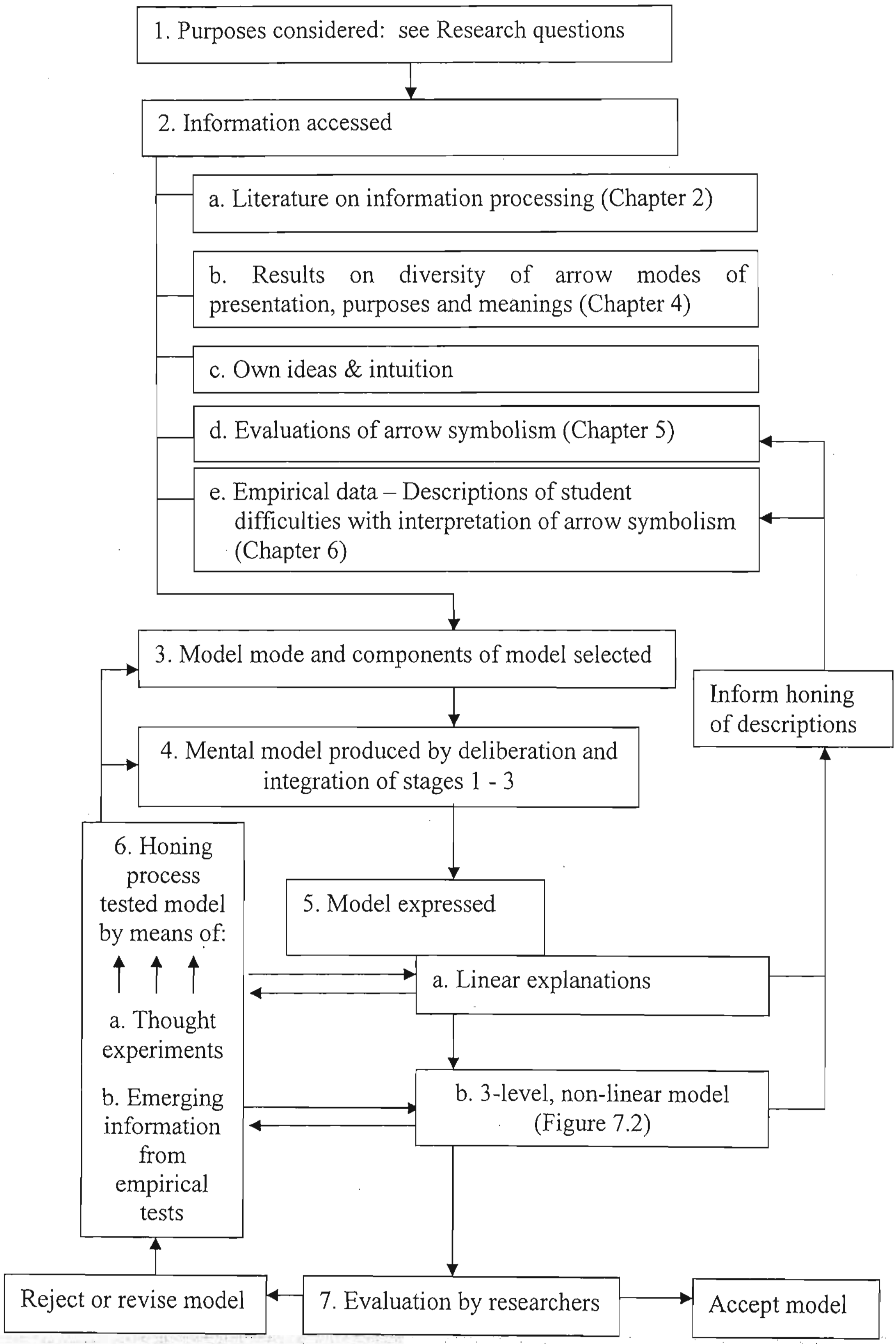


Figure 7.1 Summary of the procedure, adapted from Justi and Gilbert (2002), used to develop a model to explain the procedure of interpretation of arrow symbolism, including the impact of inappropriate presentation and possible sources of difficulty that may arise during the process of interpretation.

The model of the process of interpretation of arrow symbolism was first conceptualised as a mental model. To inform the process of mental modelling (Stages 3 and 4), information from various sources was considered and integrated (Stage 2 of Figure 7.1, page 166), as suggested by Gilbert *et al.* (1998a) including the suitability of analogies, diversity of modes of arrow presentations, purposes and meanings (Chapter 4), supporting literature on diagram processing (e.g. Larkin & Simon, 1987; Kosslyn, 1989; Buzan, 1991; Winn *et al.*, 1991; Winn, 1993; Mayer *et al.*, 1995; Mayer, 2003), application of design criteria during evaluations of arrow symbolism (Chapter 5) and student difficulties with the interpretation of arrow symbolism (Chapter 6), as well as own intuition and thought. All this information also facilitated the decision on what components the model should be composed of.

The mental model was then externalised as an expression model (Stage 5) in a linear (Stage 5a) and later in a 3-level (tiered) and non-linear format (Stage 5b). For each level, the implications of the analogies were explored against the purposes of the model using thought experiments (Stage 6). To guide my thinking, a series of pertinent questions was considered, such as:

- Does the model accommodate the M (nature of the diagram), R (reasoning) and C (reader's prior knowledge) diagram factors proposed by Schönborn & Anderson (Schönborn, 2005)?
- Is it suitable for all types of science diagrams (realistic, stylised and abstract)?
- Does the model show the process of interpretation effectively?
- Does it allow for the influence of the reader's prior knowledge and experience (schemata)? Does it allow for diverse pathways of thinking (Ittelson, 1996) used by both experts and novices?
- Does it cater for the graphic design criteria of Table 5.1, Chapter 5?
- Can it be used to direct attention toward potential sources of difficulties with the process of interpretation?
- Is it interactive and therefore useful as an investigative tool to be used by educators and researchers as an explanatory tool; as a predictive tool; as a teaching or learning tool and as a tool for facilitating diagram design?

As the model evolved, it was tested against both qualitative and quantitative empirical data (Stage 6b) that emerged during evaluation of arrow symbolism in diagrams (Chapter 5) and during analysis of student responses to the variety of written probes and interviews designed to investigate interpretation of arrow symbolism in diagrams (Chapter 6). Once considered appropriate, research colleagues evaluated the scope (Stage 7), including the suitability of the analogy and limitations of the model against both the intended purposes of the model and supporting literature (e.g. Stern & Robinson, 1995; Ittelson, 1996; Schönborn, 2005). The model could then be revised by further cycles of honing until accepted.

By following these exhaustive sequences of reflection, I am confident that the design of the model is firmly grounded in findings of previous researchers as well as in empirical data from this dissertation specifically designed to investigate arrow symbolism. The model should therefore fulfil the purposes for which it was created.

7.4. RESULTS AND DISCUSSION

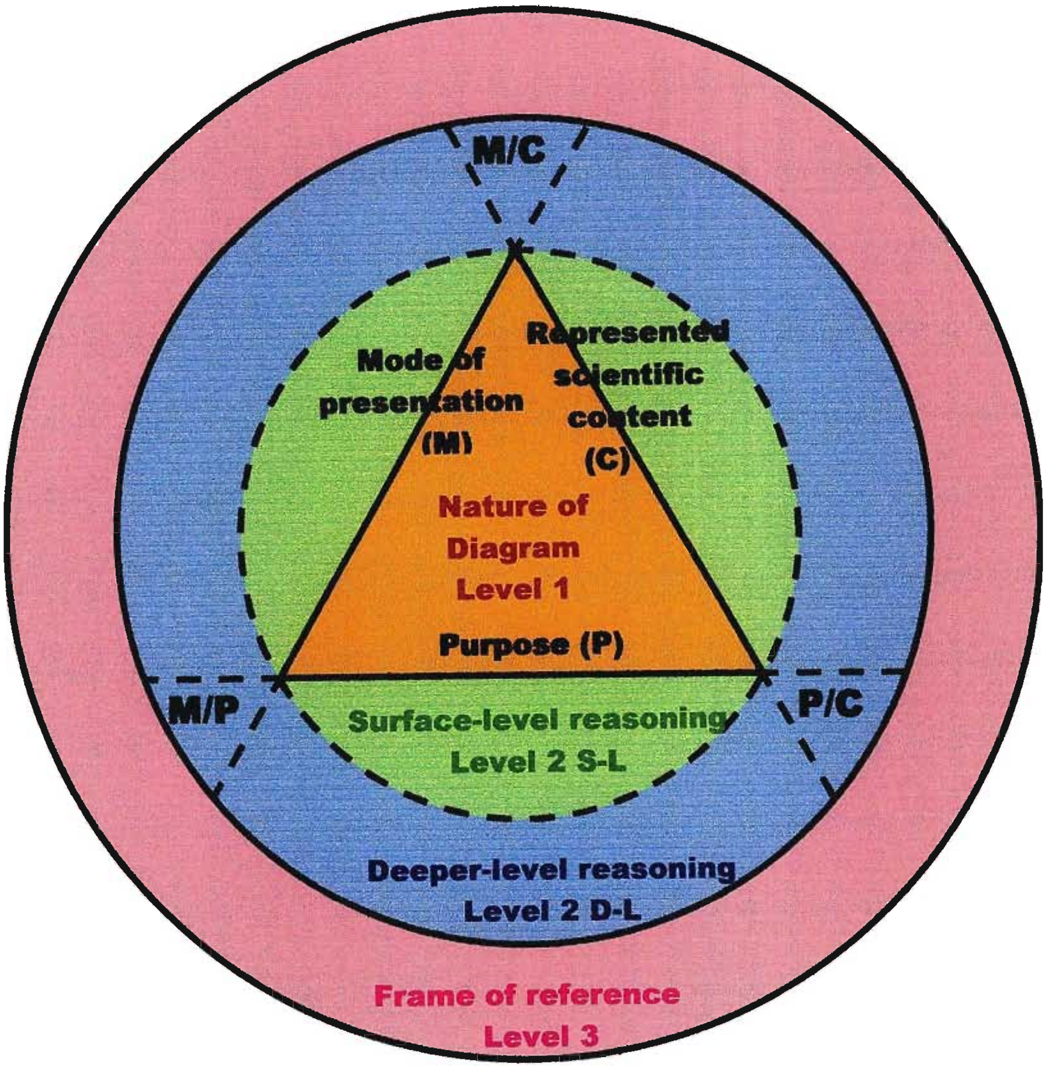
7.4.1 Development of the model

I selected the tiered and circular format proposed by Stern & Robinson (1995) and Ittelson (1996) to develop the 3-level, non-linear model presented in Figure 7.2, page 170. This mode allowed for the strong interdependency of various factors relevant to the interpretation of arrow symbolism and facilitated the multi-directional access to the model that the complex nature of the process of interpretation necessitated. In addition, this format represented the diagram, the source of the visual information, as the central focus of the model. As the design of this model fulfilled the requirements of the intended purposes (outlined as sub-research questions, Section 7.2, page 164) and the questions addressed during the thought experiments detailed above (in Section 7.3, page 164), it was accepted as a consensus model.

The various levels of the model are described below and summarised in Table 7.1 (page 169). This table also includes the operational mechanism of the model, showing how the student interacts at surface- and deeper-levels of reasoning with the M, C and P aspects of arrow symbolism in a diagram. However, the linear nature of the table does not clearly demonstrate the non-linear nature of the model (and of the process of interpretation) and cannot therefore be regarded as a substitute for the model.

Table 7.1 An explanation of the process of interpretation of arrow symbolism as shown by the model (Figure 7.2, page 170).

	LEVELS OF MODEL	Operational mechanism: THE PROCESS OF OBTAINING INFORMATION FROM DIAGRAM					
	1. NATURE OF THE DIAGRAM: **Arrows relative to** Scientific content (C) Mode of presentation (M) Purpose of arrows (P)	**Represented scientific content of the diagram (C of model)** **Explicit** propositional guidelines (caption, labels, annotations etc); **Implicit** cues of recognisable supporting /pictorial cues, conventional styles and spatial organisations		**Mode of presentation of arrows (M of model)** **Explicit and implicit** cues of spatial organisations and arrow styles in relation to supporting information		**Purpose of arrow symbolism (P of model)** **Explicit** propositional guidelines; **Implicit** cues of relationships; Implicit cues of spatial organisations & styles	
		C		**M**		**P**	
Cognitive schemata support reasoning at all levels	**2a. SURFACE-LEVEL REASONING** Use perceptual and verbal skills	**Access explicit cues of C**		**Access explicit cues of M**		**Access explicit cues of P**	
	2b. DEEPER-LEVEL REASONING INTEGRATE INFORMATION Use information & cues from S-L reasoning & schemata to understand each of C, M and P.	**Access implicit cues of C Determine significance in the context of the diagram**		**Access implicit cues of M Determine significance in the context of the diagram**		**Access implicit cues of P Determine significance in the context of the diagram**	
			C/M		**M/P**		**P/C**
	INTEGRATE INFORMATION Use information and cues from S-L reasoning and D-L reasoning with each of C, M and P to integrate information.		Match verbal and pictorial cues (C) and symbols (M); Recognise conventions of spatial organisations and arrow styles relative to content; Determine significance of above; Integrate C (content) & M (modes of presentation). **Link pictorial, verbal (C) and symbolic cues (M)**		Determine relationships; Evaluate symbolism; Determine significance of spatial organisations and arrow styles relative to purpose; Integrate M (mode of presentation) & P (purpose of arrows). **Link symbolism (M) with purpose of arrows (P)**		Decide purpose of arrows relative to content; Integrate C (scientific content) & P (purpose of arrows); Assign meaning. **Link purpose of arrows (P) to content (C)**
	3. Frame of reference guides search for cues & integration	**Domain specific /conceptual schemata support C, C/P and C/M**		**Graphical schemata support understanding of M, C/M and M/P**		**Cognitive schemata support reasoning with P, M/P and C/P**	



KEY:
Level 1: Nature of diagram represented by three facets:
C: Represented scientific content of the diagram
M: Mode of presentation of the arrow symbolism in the diagram
P: Purpose of arrow symbolism (specifying relationships between referents)

Level 2: Diagram processing (reasoning) by reader represented by two concentric circles and three interfaces:

- **2 S-L: Surface-level reasoning (Perceptual)**
- **2 D-L: Deeper-level reasoning (Integrative)**
- **Interface M/C: Integration of represented science content and Mode of presentation**
- **Interface M/P: Integration of mode of presentation and purpose**
- **Interface P/C: Integration of purpose and represented science content**

Level 3: Frame of reference of reader (including conceptual (K), cognitive (T) and graphical (G) schemata)

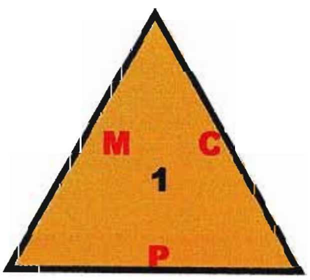
Figure 7.2 The 3-level, non-linear model of the process of interpretation of arrow symbolism. The model was grounded in empirical evidence from the investigations in this dissertation of the presentation and interpretation of arrow symbolism and developed according to the method of Justi & Gilbert (2002).

7.4.2 Description and explanation of the facets of the 3-level, non-linear model

The 3-level, non-linear model of the process of interpretation of arrow symbolism uses three levels to respectively explain the various stages of information processing (Level 2), and the influences of both arrow presentation (Level 1) and students' frames of reference (Level 3) on interpretation of arrows used in diagrams.

- ***Level 1 of the model representing the nature of the diagram***

I expressed Level 1, representing the nature of the diagram, as a centrally positioned triangle (Figure 7.3, below). The three sides of the triangle respectively represent: the context independent syntactic features of arrow symbolism or mode of presentation of arrow symbolism (M); the context dependent semantic criteria that provide cues about the purpose of the arrows in the diagram (P); and, the scientific content represented in the diagram (C) that give cues to the meaning of the arrows in the context of the diagram. These three facets (C, M and P) together contribute to the encoded message of the diagram (Brody, 1984; Hill, 1988; MacEachren, 1995; Mayer *et al.*, 1995; Ittelson, 1996). Level 1 of the model therefore represents the nature of the diagram, and the cues (both explicit and implicit) that may be expected from it. This data about the nature of the diagram is summarised in row 2 of Table 7.1.



Facets of the model:

C = Represented scientific content of the diagram

M = Mode of presentation of arrow symbolism

P = Purpose of arrow symbolism

Figure 7.3 The nature of the diagram (Level 1) is represented by three facets, C, M and P.

- ***Level 2 of the model representing the stages of information processing***

Level 2 of the model was included to represent the stages of processing or reasoning (described by many researchers e.g. Winn, 1993; Scaife & Rogers, 1996; Mayer, 2003) that readers use to access the explicit cues of the diagram. Surface-level reasoning includes:

a. Perceptual strategies of observation (including detection, selection, recognition and organisation) that are used with the syntactic features (style and spatial organisation) of the mode of presentation (M), and

b. Verbal skills that are used to read propositional guidelines for clues to the represented scientific content of the diagram (C) and /or purposes of the arrow symbolism (P).

As these processes use different and independent strategies (as proposed by Mayer, 2003) with different facets of the diagram, Level 2 S-L was presented as three separate segments each corresponding to a facet (C, M or P of Level 1) of the triangle (see Figure 7.4, below). Surface-level reasoning is summarised in Table 7.1, row 4.

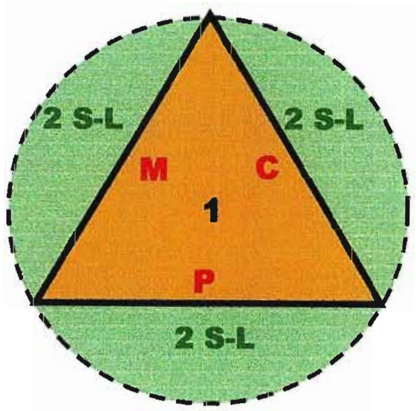


Figure 7.4 Surface-level (S-L) reasoning, represented by Level 2 S-L.
Reasoning at Level 2 S-L uses the individual facets of the nature of the diagram.

However, the reader is usually required to integrate the available explicit data with the implicit data about the mode of presentation (M), the purposes of arrow symbolism (P) and the represented scientific content (C) during stages of deeper-level reasoning (D-L). An additional level, Level 2 D-L was therefore incorporated into the model. Consequently, Level 2 of the model is divided into two stages (for each of C, M and P), representing surface-level (Level 2 S-L) and deeper-levels of reasoning (Level 2 D-L) as shown in Figure 7.5 (below) and summarised in Table 7.1 (columns 4 and 5).

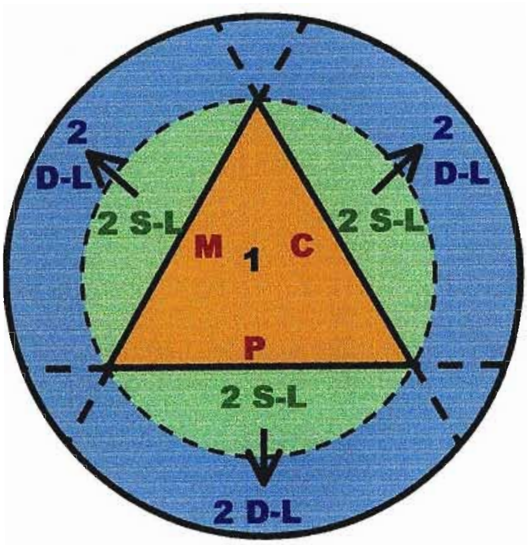


Figure 7.5 Level 2, representing surface-level (S-L) and deeper-level (D-L) reasoning. The arrows show the interdependency of the levels along a radial axis.

The arrows in Figure 7.5 provide for a continuum of stages from surface-level reasoning to deeper-levels of reasoning during interpretation of the diagram and therefore illustrate the dependency of Level 2 D-L on Level 2 S-L. This 'radial-effect' shows the progressive nature of interpretation of arrow symbolism. However, if the interrelationships between the represented scientific content (C), mode of presentation (M) and purpose (P) are to be understood, the information provided by each of the facets of C, M and P should be integrated. The interfaces (M/C, M/P, P/C) of the model (shown in Figure 7.6 and Table 7.1, rows 6 and 7) represent the various integrative stages of processing between adjacent facets, namely between represented scientific content of the diagram and mode of presentation of the arrow symbolism (M/C), mode of presentation and purpose of the arrow symbolism (M/P) and between purpose of the arrow symbolism and represented scientific content of the diagram (P/C). The interfaces therefore accommodate this interdependency of information by providing processing links in a lateral dimension between adjacent facets (shown by the arrows in Figure 7.6). The combination of radial and lateral processing explains the non-linear nature of cognitive processing used during interpretation of arrows in diagrams.

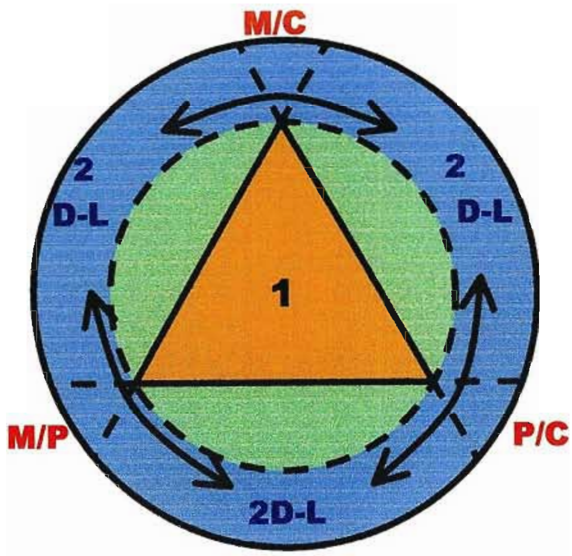


Figure 7.6 Lateral processing during deeper-level reasoning (Level 2 D-L).
Reasoning occurs through interfaces M/C, M/P and P/C corresponding to the areas of integration between the facets C, M and P of the nature of the diagram. The arrows show a lateral interdependency.

The 'V' shape of each interface (M/C, M/P and P/C) suggests that the degree of integration between the various facets can occur on a continuum, from (as expected) no integration at the inner dimension or point of the 'V' at the junction of Level 1 with Level 2 S-L, to an ever-increasing degree corresponding to the cognitive ability of the reader. Also, the depth of reasoning does not have to be at the same level at each of the interfaces, but can fluctuate along the length of each 'V'. Furthermore, each interface can be freely accessed in either direction during deeper-level reasoning. This bi-directionality (see arrows) allows progressive access to information contained in the facets (M, P and C) of the diagram. In my opinion, the progressive nature of integration (as shown by this expressed model) 'drives' the process of interpretation. In other words, the interfaces hold the clues to the dynamics of the decoding process. I suggest that in this respect, the model of the process of interpretation is unique.

- ***Level 3 of the model***

According to constructivist theory, on which this research is based, as well as the results of this and other investigations, information processing relies on the readers' various conceptual, graphical and cognitive schemata (e.g. Johnson-Laird, 1983; Gillespie, 1993; Lowe, 1999; Taconis *et al.*, 2001). I therefore introduced Level 3 (Figure 7.7, below) representing these various schemata within the readers' frames of reference, as an outer encompassing concentric circle adjacent to Level 2 D-L. The encompassing nature of the concentric circle and the adjacency of this position to Level 2 clearly show the influence of the reader's frame of reference on all of the processing stages (Level 2) during interpretation of the diagram. The greater proximity of Level 2 D-L to Level 3 suggests that this level of reasoning makes use of a greater range and depth of schemata than Level 2 S-L. The influence of the frame of reference on the interpretive process is illustrated in Table 7.1 (in both rows 8 and 9 and column 1).

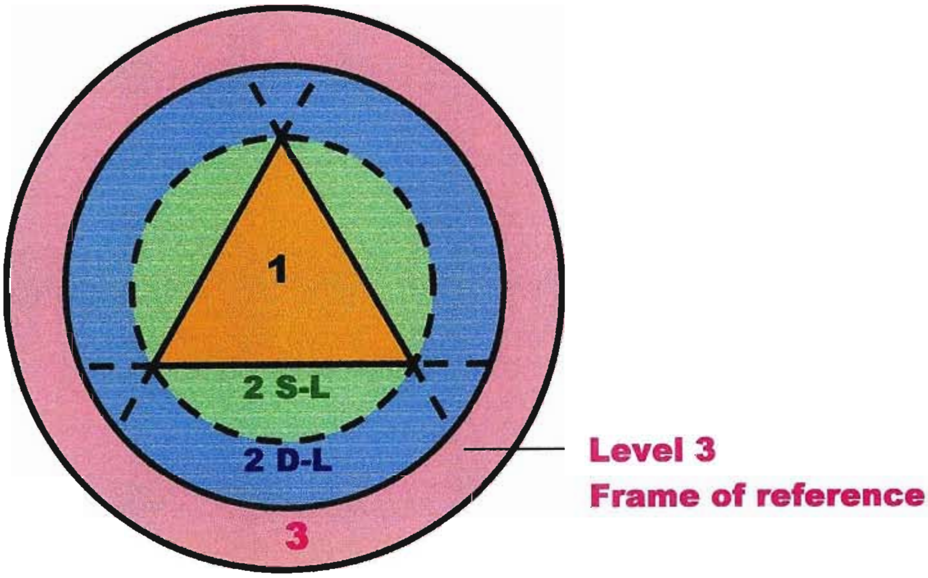


Figure 7.7 The frame of reference of the reader is illustrated by an outer concentric circle encompassing the levels of reasoning (2 S-L and 2 D-L).

- ***In summary:***

In my opinion, the circular pattern of three concentric rings surrounding a triangle, on which the model (Figure 7.2, page 170) is based, is appropriate to explain the strong interdependency of the various factors relevant to interpretation of arrow symbolism, including the nature of the diagram (the triangle, Level 1), the information-processing stages (Level 2, including surface-level and deeper-level reasoning) that readers use to access the facets of the diagram, and the influences of the conceptual, graphical and cognitive schemata contained within readers' frames of reference (Level 3). The three levels therefore bring together the functional aspects (interactions during reasoning) and structural aspects (graphical design features) of diagrams, discussed by Blackwell & Engelhardt (2002).

7.4.3 Justification for, and validation of, each level of the model

To further justify the inclusion of each of the levels, namely Level 1 (representing the nature of the diagram), Level 2 (representing information processing or reasoning of the reader) and Level 3 (representing the frame of reference of the reader) in the expressed model of the process of arrow symbolism, I shall:

- provide an operational definition,
- further justify for inclusion of each level in the model, and
- validate the inclusion of each level against empirical data resulting from the investigations reported in Chapters 4 (content analysis of arrow symbolism), Chapter 5 (development of criteria and evaluation of arrow symbolism) and Chapter 6 (student difficulties with the interpretation of arrow symbolism).

Table 7.2 summarises the justification process by providing information about the level of the model (Column 1), the analogies relative to the process of interpretation of arrow symbolism (Column 2) and the cues, processes and schemata required to interpret arrow symbolism (Column 3). Column 4 provides references to data supporting the inclusion of each facet in the model, including the relevant criteria according to Chapter 5, Table 5.1 (page 95) for presenting arrow symbolism as well as students' difficulties with interpretation of arrow symbolism (Column 5) that emerged during the investigations (Chapter 6, Tables 6.3 and 6.5, pages 132 and 146 respectively).

Level 1 of the model: Nature of the diagram

Operational definition of Level 1

Level 1 represents the nature of the diagram including the three facets, M (mode of presentation), P (purpose of arrow symbolism) and C (represented scientific content of the diagram). It therefore represents the source of visual information.

Table 7.2 Justification for the model of the process of interpretation of arrow symbolism (Fig. 7.2). Columns 1 and 2 describe the structure of the model. Column 3 shows the cues, processes and schemata required for the process of interpretation. Column 4 lists related criteria (Chapter 5, Table 5.1) for evaluating the nature of the diagram (Level 1) and empirical data that emerged from investigating students' interpretations of arrow symbolism in Figs 6.2 and 6.3 (Chapter 6) that justified the inclusion of Levels 2 and 3.

Level	Analogy	Cues /Processes /Schemata for interpretation of diagram using arrow symbolism	Empirical evidence
1. Triangle	**Nature of diagram**	**Cues for interpretation of diagram using arrow symbolism**	**Criteria** (TABLE 5.1)
C	Represented scientific content of diagram	Explicit propositional guidelines (caption, labels, annotations etc); Implicit cues of recognisable spatial organisations.	7b 4
M	Mode of presentation	Explicit cues of spatial organisations and arrow styles in relation to supporting information; Implicit cues of spatial organisations and arrow styles	1, 2, 3 4, 5
P	Purpose of diagram	Explicit propositional guidelines; Implicit cues of relationships; Implicit cues of spatial organisations & styles including commonplace styles	7b 6a, b 4, 5a
C, M, P	Harmony of above		7a
2. Two rings	**Diagram Processing by student**	**Processes for interpretation of diagram using arrow symbolism** Surface-level reasoning (Level 2 S-L): Deeper-level reasoning (Level 2 D-L)	**Difficulties** (TABLES 6.3, 6.5)
2 S-L	Surface-level reasoning using perceptual & verbal skills on diagram	Access explicit cues of C, M & P separately using skills of observation (search, detect, select /match, organise patterns)	Inappropriate presentations S-L: COMP, SYN, EMT, FREQ, SAL, POLY Appropriate presentations S-L : CUE, PU (4), C-E, STYLE, PLACE + PROP
2 D-L	Deeper-level reasoning using schemata and cues from S-L reasoning	Access implicit cues of M (modes of presentation); Apply significance; Integrate C, P, M with each other (C/M, M/P, P/C) using Level 3 schemata (as below)	D-L: CORR, COMP
C/M	C/M: D-L reasoning processes (link verbal & symbolic cues)	Match verbal cues (C) and symbols (M); Recognise conventions of spatial organisations and styles relative to content; Apply significance to above; Integrate C (content) & M (modes of presentation) using Level 3 schemata	D-L: SAL, EMT
M/P	M/P: D-L reasoning processes (link symbolism with purpose)	Determine relationships; Evaluate symbolism; Apply significance to spatial organisations and styles relative to purpose; Integrate M & P using Level 3 schemata	D-L: C-E, STYLE, SYN, POS, FREQ1
P/C	C/P: D-L reasoning processes (link purpose to content)	Decide purpose relative to represented scientific content; Integrate C (scientific content) & P (purpose); Assign meaning in context	D-L: MEAN, KNOW, FREQ2
3. Ring	**Frame of Reference of student**	**Schemata for interpretation of diagram using arrow symbolism** To guide the search for cues and the process of integration	**Criteria** (TABLE 5.1) Criterion 8
	Domain specific /conceptual schemata (K)	Previous conceptual knowledge supports C, C/M & C/P	**Difficulty:** D-L: KNOW
	Graphical schemata (G)	Previous graphical knowledge of design principles supports M, C/M & M/P	See G, Tables 6.3, 6.5 for details
	Cognitive schemata (T)	Processing schemata support Level 2 (S-L and D-L reasoning)	See T, Tables 6.3, 6.5 for details

Justification for including Level 1 in the model

The content analysis of textbook diagrams (Chapter 4) exposed the diversity of arrow styles (Table 4.2, page 61 and Table 4.4, page 66), spatial organisations of arrows (Table 4.3, page 64) and purposes of arrows (Table 4.5, page 69), as well as the importance of determining meaning within the context (purposes of arrows and represented scientific content) of the diagram (Table 4.6, page 75). This in itself justifies the inclusion of facets M (mode of presentation), C (represented scientific content) and P (purposes of arrows). However, the importance of these factors has been further demonstrated by the inclusion of criteria to evaluate for each in Chapter 5, Table 5.1 (page 95).

Criteria 1 – 3 were included to evaluate the context-independent, syntactic or explicit features of arrow styles and spatial organisations (M). Further criteria were designed to evaluate the implicit, context-dependent, semantic aspects of M, including arrow spatial organisations (Criterion 4), styles (Criterion 5), positions (Criterion 6a) and placements (Criterion 6b) that give clues to the context of the diagram (purposes of arrow symbolism and scientific content). In addition, Criterion 7b was included to evaluate the propositional guidelines to purposes and to the represented scientific content, including labels, captions and annotations. To understand the message of the diagram, the explicit and implicit cues of M, C and P should be integrated. Effective integration is only possible if the information represented by the three facets is sufficient and in harmony. Therefore, Criterion 7a was included to evaluate for harmony of arrow symbolism used in diagrams.

The above information clearly shows that each facet of the triangle (M, P and C), representing the nature of the diagram, is an integral part of the communication of the diagram. The triangular analogy for Level 1 is therefore grounded in the content analysis (Chapter 4, Tables 4.2 – 4.6) as well as in the set of criteria (Criteria 1 - 7, Chapter 5, Table 5.1) that is itself, formulated from an in-depth review of literature and empirical evidence.

Empirical validation of Level 1

Not only can the inclusion of Level 1 be justified according to evidence emerging from the content analysis of arrow symbolism and from the development of the set of criteria as mooted above, but also from the empirical data obtained from the application of the criteria to diagrams in the selected textbooks (Chapter 5), as well as to both diagrams (Figures 6.2 and 6.3, Chapter 6, page 121) used to probe students' interpretation of arrows. A range of syntactic and semantic aspects of arrow symbolism was judged inappropriate. As diagrams are the source of information, it is possible that inappropriate presentations could be a cause of student difficulties during interpretation of the arrow symbolism – which in fact, they proved to be (Table 6.3, Chapter 6, page 132)!

Level 2 of the model: Reasoning by the student

Operational definition of Level 2

Level 2 represents information processing by the student at both surface- and deeper-levels of reasoning, with the three facets (M, C and P of Level 1) of the diagram in order to interpret the message of the diagram.

Motivation for including Level 2 in the model

Inclusion of Level 2 in the model to represent the readers' interactions with the facets of the diagram was grounded in a wealth of literature on the nature of information processing (e.g. Kosslyn, 1989; Gillespie, 1993; Winn, 1993; Zhang & Norman, 1994; Scaife & Rogers, 1996; Taconis *et al.*, 2000; Brna *et al.*, 2001; Lewalter, 2003; Mayer, 2003). To accommodate the main stages of information processing, Level 2 was sub-divided into two levels, namely:

- Level 2 S-L representing the perceptual stages of surface-level reasoning. This level encompassed the three sides of Level 1 to illustrate that the explicitly expressed cues of the modes of presentation (M), represented scientific content (C) and purpose (P) can be accessed independently.
- Level 2 D-L representing the stages of integration during deeper-levels of reasoning. The second encompassing circle included three interfaces of M/C, M/P and C/P, to show integration of the explicit and implicit clues along the radial (Figure 7.5, page 173) and lateral (Figure 7.6, page 174) axes of the model.

Empirical validation of Level 2 in the model

Empirical data obtained from the analysis of student responses to the written and interview probes revealed that students experienced difficulties with the interpretation of both inappropriately and appropriately presented arrow symbolism at both surface- and deeper-levels of reasoning, as reported in Chapter 6, Tables 6.3 and 6.5.

Empirical validation of Level 2 S-L

According to the radial correspondence described above, the model suggests that any insufficient or inappropriate message in terms of arrow presentation in Level 1, about the represented scientific content (C), purpose of arrow symbolism (P) or the modes of presentation (M) might influence or even precipitate difficulties with perceptual processing during surface-level reasoning (Level 2 S-L). The empirical data confirmed that inappropriately presented modes of presentation (M), including presentation of synonymy, polysemy, unintended emergent features, misleading salience, inappropriately presented frequency effect and level of complexity, (i.e. Difficulties COMP (S-L), SYN (S-L), EMT (S-L), FREQ (S-L), SAL (S-L) and POLY (S-L), as reported in Chapter 6, Table 6.3, page 132) were a source of difficulty during surface- level reasoning.

However, some students did not adequately or correctly access the mode of presentation (M) when the arrow symbolism was, according to expert opinion, appropriately presented. For example, some students did not use the arrow symbolism to guide interpretation of the diagram (Difficulty CUE1 (S-L), Chapter 6, Table 6.5), sometimes explaining about the content of the diagram using prior knowledge only (Difficulty CUE2 (S-L)). Many students had difficulty forming the intended perceptual units (Difficulties PU (S-L), including OV; REL; SEQ; EXC) or identifying the placement of arrows and therefore the correct relationships (Difficulty PLACE (S-L)), sometimes reversing the cause-effect relationship (Difficulty C-E (S-L)). In addition, some students interpreted the style of arrows literally (Difficulty STYLE (S-L)).

In addition to the above difficulties, several students did not adequately access the propositional guidelines such as captions and labels (Difficulty PROP) used in diagrams, for cues to the represented scientific content (C) and purpose (P) of the diagram. (As this difficulty was classified at Level 2 of the 4-level framework, it was not included in Table 6.5, Chapter 6.) For example, in interviews students were asked: 'What is the topic of this diagram?' From responses, it was clear that several students in interviews with both Figures 6.2 and 6.3 (page 121) did not read the clearly stated captions in order to find this information, instead using frames in the diagram (S1) or previous knowledge and the pattern of the diagram (S2), to explain the topic, as illustrated by the following typical quotations:

S1 I: First of all, what is the topic of the diagram?
S: Umm..................temperature
I: Why do you say temperature?
S: Because its showing how everything is affected by heat loss and heat gain and ..ya...
I: So what made you first decide on temperature as the topic?
S: Well, I saw the skin first of all, and I didn't even notice that [environmental temperature frame], I just saw the skin and then I saw that,
I: Environmental temperature?
S: And then I looked at the heat loss, ja, environmental temperature and then I looked at the heat loss and heat gain centres.

S2: I: First of all, what is the topic of that diagram?
S: Um, I get the impression that it's co-ordination.
I: Why?
S: Er..because I see things that are er huh, see hypothalamus and I've learnt that it's got to do with co-ordination'
I: Okay. Anything else that tells you its co-ordination?
S: Um. Also because it looks like a negative feedback mechanism.
S: What makes you think that?
I: Arrows going around and, um, the parasym, er ..um.. also because there's writing feedback mechanism.. um.. and just how the parasympathetic, parasymp, ya, would that be decreased sympathetic parasympathetic and then there's sympathetic.
(Appendix 1.5, Thermoregulation interviews)

This difficulty corroborates conclusions reached by Ametller & Pinto (2002) during their research into the interpretation of diagrams, that students might not read the verbal components of diagrams such as captions.

Together, these difficulties with the mode of presentation (M), purpose of arrow symbolism (P) and represented scientific content (C) at surface-level reasoning (S-L), validate the inclusion of Level 2 S-L in the model and suggest its usefulness in identifying and predicting flaws in the design of diagrams and symbols and identifying student difficulties with surface-level processing of arrow symbolism.

Empirical validation of Level 2 D-L of the model

It can be expected that, if students do not access the modes of arrow presentation (M), or do not access them adequately during the stage of surface-level reasoning, further processing may be compromised. This will be illustrated with empirical data showing difficulties along both the radial (from S-L to D-L) and lateral (through Interfaces M/C, M/P and P/C) axes.

- *Empirical validation of radial axis*

Empirical data uncovered difficulties that limited interpretation to the perceptual or surface-level stage of reasoning (Level 2 S-L), not permitting the student to advance to Level 2 D-L (deeper-level reasoning) "along" the radial axis of the model. For example, some students may have difficulty integrating information in diagrams with a large number of arrows (Difficulty COMP) or have difficulty satisfactorily matching and correlating complementary arrows (Difficulty CORR).

- *Empirical validation of lateral axis*

According to the lateral processing dimension (explained in Figure 7.6, page 174), deeper-level reasoning should progress through Interfaces M/C, M/P and P/C. This suggests that difficulties with interpretation of any one facet (M, C, or P) will impact on interpretation of the interface. For example, difficulties with the interpretation of the mode of presentation (M) may influence understanding of the scientific content (C) and purpose of the symbolism (P).

Interface M/P

For the relationship between M and P to be understood, the reader should understand the intention (purpose) of the style and /or spatial organisation of arrows. However, some students did not integrate the various data relative to the cause-effect relationships (Difficulty C-E (D-L)), and therefore did not understand the purpose of the arrow symbolism in the relationship. On the other hand, some students interpreted arrow styles literally (Difficulty STYLE (S-L)) and therefore did not consider the purpose of the style of arrow in the context of the diagram (Difficulty STYLE (D-L)). By means of Difficulty FREQ1 (D-L), the study also showed that many students using the stylised diagram of the cardiac cycle, Figure 6.2, page 121 did not use the groups of arrows (M) labelled 2 and 7 as a cue to syntactic emphasis (P). Furthermore, students who did not identify the precise positions of the arrowhead and shaft origin relative to supporting information including other arrows were not able to resolve the purpose of the relationship between the referents (Difficulty POS (D-L)). In addition, students who do not select and separate arrows of similar style intended for different purposes (Difficulty SYN (S-L)), may have difficulty understanding the purpose of arrows in the context of the diagram during deeper-level reasoning (Difficulty SYN (D-L)).

These examples suggest that the arrow modes of presentation (M) need to be processed in the context of the diagram to achieve the purpose of the arrow symbolism. This evidence supports the inclusion of Interface M/P.

Interface P/C

The following examples illustrate difficulties with processing of the purpose of arrow symbolism (P) in relation to the scientific content represented in the diagram (C) and provide evidence for the inclusion of interface P/C in the model.

Difficulty FREQ2 (D-L), Chapter 6, Table 6.3 (page 132) illustrates how inappropriately presented arrows, such as the size of the arrow groups 2 and 7 in Figure 6.2 (Chapter 6) can cause difficulty during processing in a lateral dimension. Students who perceived and recognised the cue-value or purpose (P) of the size of the groups of arrows for syntactic emphasis, became confused when integrating this purpose with the represented scientific content, as it did not correspond with their prior knowledge. Even with appropriately presented arrows, some students had difficulty correlating the purpose of the arrow (P) with the represented scientific content of the diagram (C) to derive meaning for arrows in the context of the diagram (Difficulty MEAN (D-L), Chapter 6, Table 6.5, page 146). Conversely too, students who did not understand aspects of the scientific content (including terminology) represented in the diagram (Difficulty KNOW (D-L)), such as the meaning of the word 'inhibition' used in Figure 6.3, were unable to interpret the purpose of the arrow symbolism effectively.

Interface C/M

Students who did not access the pattern of the spatial organisation (M) missed valuable cues to the represented scientific content (C). For example, students who perceive an incorrect emergent pattern may interpret the scientific content of the diagram incorrectly (Difficulty EMT (D-L)). Similarly, students who perceive an incomplete spatial organisation may not fully interpret the scientific content represented by the diagram (Difficulty SAL (D-L)). These examples therefore validate the inclusion of Interface C/M.

Level 3 of the model: Frame of reference

Operational definition

Level 3 represents students' frames of reference, namely their conceptual, graphical and cognitive schemata.

Justification for including Level 3 in the model

Constructivism, which explains the importance of prior knowledge in the acquisition of new knowledge, is one of the main theoretical frameworks underpinning this investigation of students' interpretation of arrow symbolism (see Chapter 3, page 20). In fact, Criterion 8 was introduced into the set of criteria (Chapter 5, Table 5.1) specifically to evaluate the use of arrow symbolism in diagrams according to students' frames of reference. The position of Level 3 in the model, completely surrounding and encompassing Level 2 shows the strong influence of students' schemata (Level 3) on students' reasoning (Level 2) and therefore on the process of interpretation of arrow symbolism.

Empirical validation of Level 3 of the model

Students who integrated prior knowledge with facets of the diagram were able to use the explicit and implicit cues of the diagram efficiently and were therefore better able to interpret the diagram. In the following example, the student used prior knowledge to understand the purpose of the curved arrows forming the cyclic pattern in Figure 6.2 (Chapter 6).

> S: Cyclic process. [referring to the intentions of arrows 8 and 9].
> I: Okay. Why [do arrows 8 and 9 indicate this?]
> S: Because these, the fact that the arrows are curved ..sort of um….it leads me to think that it is a cycle and I know.um..from my own knowledge, that this is a continuing cycle.
> (Appendix 1.3, Cardiac cycle interview)

On the other hand, there was overwhelming evidence (presented in Chapter 6, Table 6.5) showing difficulties (Difficulty KNOW (D-L)) related to students' inadequate conceptual understanding (prior knowledge). In addition, a range of difficulties was attributed to poor graphical and cognitive schemata (see G and T respectively, in Chapter 6, Table 6.5, Column 6), most of which have been discussed in preceding paragraphs. By identifying inadequate graphical, cognitive and conceptual schemata of students as possible sources of difficulties, I have justified the inclusion of Level 3 (students' frames of reference) in the 3-level, non-linear model of the process of interpretation (Figure 7.2, page 170).

7.5 DISCUSSION AND CONCLUSIONS

The modelling process of Justi & Gilbert (2002) enabled us to develop an interactive visual model (Figure 7.2) to show the process of interpretation of arrow symbolism. The various stages of the process of interpretation, the influence of the nature of the diagram and of the various schemata held by the student on the process of interpretation, were explained and expressed by means of operational definitions. Each facet of the model was validated using the considerable empirical data gathered from the investigations into the presentation and interpretation of arrow symbolism in diagrams, as reported in Chapters 4, 5 and 6. To ensure that the purposes of the model have been satisfied, and to justify the suitability of the analogies and operational definitions used for the model, the model was evaluated against the research sub-questions posed at the beginning of this chapter.

7.5.1 Application of the model to research questions

Research question 1: What is the nature of the cognitive processing engaged by learners when interpreting arrow symbolism?

Level 2 of the model (Figure 7.2) illustrates the cognitive processing engaged by the learner when interpreting arrow symbolism in a diagram. According to the model, the interpretive processes at both surface- and deeper-levels of reasoning (Level 2) are dependent on the nature of the diagram (Level 1) and on the reader's various conceptual, graphical and cognitive schemata (Level 3). The radial analogy implies that the three facets (M, P and C) of the model are accessed differently and independently, first during surface-level reasoning and then during deeper levels of reasoning. During surface-level reasoning perceptual and verbal clues are used, whereas integrative strategies using a greater degree of prior knowledge are used during deeper-levels of reasoning. The lateral analogy indicates additional stages of processing that together allow integrative processing between the facets (M, C and P) of the diagram. This combination of radial and lateral processing clearly illustrates the non-linear nature of cognitive processing used during interpretation of diagrams and is, in my opinion, the key to successful interpretation and to the effectiveness of the model.

In support of the idea of non-linear cognitive processing, Lowe (1997) advocates that the process of interpretation has no set pattern or direction. Therefore, to accommodate the various visual routines (cognitive strategies) of readers (Level 2) and the readers' prior knowledge (Level 3), the model should allow for 'multiple choices and complex contingencies' (Ittelson, 1996, page 184). The circular nature of the model implies such multi-directional pathways - it can be entered at any point and adjacent elements, between and within levels, can be accessed in any order. In fact, the model suggests that several bi-directional transactions between adjacent segments (C/M, M/P and P/C) are necessary to assign satisfactory meaning to arrow symbolism. Furthermore, the model can be re-entered any number of times to search for more information, which, according to Winn (1993), is an important step during the process of interpretation.

Although a sequence of numbers (Levels 1, 2 and 3) has been used to label the levels of the model and the process of interpretation has been explained as a sequence of steps (as suggested by various researchers including Gillespie, 1993; Winn, 1993, Taconis *et al.*, 2000; Lewalter, 2003; Mayer, 2003), the stages in the process are not necessarily sequential and may, in accordance with the theory of constructivism, depend on the individual's mental model.

In short, the various analogies used in each level of the expressed model of the process of interpretation confirm its suitability as a tool to explain the process of interpretation of arrow symbolism used in diagrams. A better understanding of this process would inform the development of strategies to guide the thinking of graphic designers, educators and researchers. To this end, I address guidelines (in Chapter 8) based on the model of the process of interpretation of arrow symbolism.

Research question 2: In what way might inappropriate presentation of arrow symbolism (based on expert evaluations using the set of criteria) impact on the process of interpretation?

The model (Figure 7.2) shows the dependence of Level 2 (information processing) on Level 1 (the nature of the diagram - the source of visual information). During surface-level reasoning (Level 2 S-L) each of the facets, M, C and P of the nature of the diagram is individually accessed. This suggests that any insufficient or inappropriate cues in Level 1, about the represented scientific content (C), purpose (P) or the modes of presentation (M) may influence or even precipitate difficulties with perceptual processing during surface-level reasoning (Level 2 S-L). Using the radial analogy, the surface level difficulties might, in turn, negatively influence deeper levels of reasoning (Level 2 D-L). Furthermore, according to the lateral analogy, inappropriately presented modes of presentation (M) will affect interpretation of content and purpose at the Interfaces of M/C and M/P respectively. In fact, as purpose of arrow symbolism and scientific content (P/C) are together integral to the interpretation of meaning, any misleading or confusing aspect of mode of presentation (M) can lead to misunderstanding of the 'message' of the diagram i.e. M, C and P are indispensable for a sound interpretation of a diagram with arrow symbolism.

Investigation of student difficulties with arrow symbolism (reported in Chapter 6) linked various inappropriate presentation modes (M) in both Figure 6.2 (evaluated by Criteria 2b, 2c, 3, 5bi, 7a) and Figure 6.3 (evaluated by Criteria 2a, 3, 5bii) to specific perceptual (S-L) and integrative (D-L) difficulties listed in Table 6.3, Chapter 6. The model therefore reaffirms the importance of evaluating the presentation of arrow symbolism in diagrams using criteria such as those developed in Chapter 5 to ensure that the arrow symbolism is suitably presented for the message of the diagram is to be interpreted.

Research question 3: At what stages of the process of interpretation of arrow symbolism do students have difficulty and what are possible sources of such difficulty?

Mapping of the empirical data against the facets of the model during validation has shown that students have difficulty with arrows at all stages of the process of interpretation (2 S-L and 2 D-L, including the Interfaces M/C, M/P and P/C). Difficulties can be attributed to both inappropriately presented arrow symbolism (M of Level 1, as summarised in Table 6.3, Chapter 6, page 132) and to ineffectual graphical (G), cognitive (T) and conceptual (C) schemata (as summarised in Table 6.5, Chapter 6). However, for interpretation to fully effective, the whole process, as defined by the model, should be totally functional.

Students with inadequate graphical schemata might not understand nor appreciate the significance of the mode of presentation of arrow symbolism (M) and therefore show evidence of perceptual (S–L) difficulties. Such difficulties (e.g. Difficulties CUE, PU, PLACE, POS, C-E and STYLE) may result in students missing vital clues to the nature of the diagram (Level 1).

Students who have inadequate cognitive schemata may have difficulty integrating data associated with arrow symbolism. For example, students who did not recognise the cue-value of arrows (for example, Difficulty CORR (D-L)) were not able to move from the surface-level to deeper-levels of reasoning along the radial axis of the model (that is from Level 2 S-L to Level 2 D-L). Similarly, students who had difficulty integrating information specified by each of the interfaces (C/M, M/P and P/C) were not able to move in a lateral dimension through the interfaces of the diagram, resulting in difficulties such as Difficulty C-E (D-L) and STYLE (D-L) for Interface M/P of the model (Figure 7.2); Difficulties KNOW (D-L) and MEAN (D-L) for Interface P/C and Difficulty FREQ (D-L) for Interface C/M. Difficulties of a cognitive nature, with either the radial or lateral steps of processing as shown by the model, will compromise the progressive nature of the interpretive process.

In addition, and in line with constructivist theory (discussed in Chapter 3, page 20), I have shown that difficulties (such as Difficulty KNOW) may also result if students do not have the required conceptual schemata (K).

It is very clear from the data presented in Table 6.5, Chapter 6 that educators cannot assume that students either realise the importance of skills and strategies (schemata) or have the necessary expertise. This suggests that relevant instruction and /or guidelines should be provided in graphical and content knowledge as well as cognitive skills and strategies to ensure successful interpretation of arrow symbolism in diagrams. To this end, the close correlation of the empirical data from Chapters 5 and 6 with the various levels and facets of the model validates the strength of the model as a tool to predict sources of difficulty with interpretation of arrow symbolism and thereby inform the design of focused and therefore more effective remediation strategies for students with difficulties. Ideas to facilitate the remediation of difficulties experienced with arrow symbolism will be discussed in Chapter 8.

7.5.2 Summary

In accordance with the ideas of Ittelson (1996), and in support of Scaife & Roger's (1996) theory of external cognition, the model (Figure 7.2) shows that the success of interpretation of arrows in diagrams depends both on the accuracy of the communication (arrows in the diagram) and on the decoding ability of the interpreter i.e. on the whole process as defined by the model. It also affirms the combined structural and functional approach (explained in the methods section of Chapter 6) that informed probe design and contributed to the success of the investigation into student difficulties with interpretation. The model also supports the M, R and C factors described by Schönborn and Anderson (Schönborn, 2005) and Roth's (2002) suggestions that semiotically informed researchers should focus on students' familiarity with symbolism and conventions (or commonplace presentations), the evaluation of presentations and on the interpretation of symbolism.

Although the complexity of the process of interpretation demands a level of sophistication that detracts from the simplicity of design expected of a model, I believe that this is offset by the many possible advantages and diverse applications of the model explained above. Within the field of interpretation of arrow symbolism, the model has numerous learning and teaching applications and may assist designers, educators, researchers and students to better understand the process of interpretation, the role of the mode of presentation of arrows in that process and the sources of difficulties that students may experience during interpretation of inappropriately and appropriately designed arrow symbolism. In addition, it may prove useful for a wider application as it appears to fulfil the relevant factors needed for the interpretation of any symbolism (and not just arrow symbolism) used in science diagrams.

CHAPTER 8

GUIDELINES FOR THE PREVENTION AND REMEDIATION OF DIFFICULTIES WITH ARROW SYMBOLISM IN BIOLOGY DIAGRAMS

In this chapter I address the implications of the research reported in this dissertation for improving the design of arrow symbolism and the interpretive abilities of students, both of which (according to the model, Figure 7.2, Chapter 7) strongly influence interpretation of arrow symbolism in diagrams. Strategies should be devised for the prevention and remediation of the difficulties through improved teaching and learning approaches (e.g. those suggested by Ametller & Pinto (2002)) and better diagram design (e.g. those suggested by Mayer *et al.* (1995) and Lowe (1993b)). For this to be effective, guidelines should target the various role players, including diagram designers, educators (the communicator between diagrams and students), students and researchers. This is in line with the opinions of many researchers e.g. de Jong (2000), Pinto *et al.* (2000) and Pinto & Ametller (2002) who have called for closer interaction between these role players to ensure a comprehensive strategic plan. Remedial strategies aimed at all role players would foster a greater awareness and help to reduce the gap between authors and users of diagrams.

In the preceding chapters I have already presented tables and figures of information that may be used as tools to facilitate student interpretation of arrow symbolism as well as the prevention and remediation of difficulties, including:

1. Guidelines to the diversity of arrow symbolism, including classifications of types of diagram that use arrows, arrow styles including commonplace presentations, spatial organisations using arrows and purposes of arrows as reported in Chapter 4. These ideas could be further developed in future studies and packaged into sets for distribution to relevant role players.
2. A set of criteria to evaluate the design of arrow symbolism in diagrams, either the comprehensive version (Chapter 5, Table 5.1, page 95) or the more convenient set of criteria (Chapter 5, Table 5.2, page 115).
3. A model of the process of interpretation that can be used to explain processing of arrow symbolism and predict sources of difficulties with interpretation of arrow symbolism (Figure 7.2, Chapter 7, page 170).

Drawing ideas from the above tools, especially from the model of the process of arrow symbolism (Figure 7.2, Chapter 7), and from literature, the following further range of guidelines and remedial strategies for improving the presentation and interpretation of arrows used in biology diagrams are proposed:

1. Guidelines to improve the design of inappropriately presented arrow symbolism in diagrams (see Table 8.1, page 193).
2. Ideas on guidelines for developing students' schemata relevant to interpretation of arrow symbolism in biology diagrams (Table 8.2, page 195) including students':
    a. Conceptual schemata
    b. Graphical schemata
    c. Cognitive schemata
3. Suggested strategies based on the 3-level, non-linear model (Figure 7.2, page 170) for interpreting arrow symbolism in diagrams including:
    a. A 12-point strategy for interpretation of arrow symbolism (Figure 8.1, page 201).
    b. A strategy to guide experts on understanding the process of interpretation and implementation of the 12-point strategy (Table 8.3, page 203).
    c. A strategy to guide students during interpretation of arrow symbolism (Figure 8.2, page 202).
4. Information booklets on interpreting arrow symbolism specifically designed for the use of students.
5. Information packages of the above information for each category of designers, educators, students and researchers (Table 8.4, page 205).

8.1 Guidelines for improving the design of arrow symbolism in diagrams

The model, and the empirical data from which it was developed, clearly showed that any insufficient, incorrect, misleading or inappropriate cues in the nature of the diagram (M, C or P of Level 1) may negatively influence or even precipitate difficulties at both surface- and deeper-levels of reasoning. To ensure the success of the interpretive process, the mode of presentation of arrow symbolism should be evaluated using criteria such as those developed in Chapter 5 (Table 5.1, page 95 or 5.2, page 115) and modified accordingly. To facilitate modification of the inappropriately presented arrow symbolism I assembled guidelines using the results of this dissertation as well as ideas from the literature (e.g. Hewson, 1981; Geva, 1983; Gillespie, 1993; Henderson, 1999; Pinto *et al.*, 2000; Stylianidou *et al.*, 2002; Mayer, 2003). Although most suggestions made in the literature are for the design of diagrams in general, some may be adapted for the design of arrow symbolism specifically. These guidelines are presented in Table 8.1. Column 2 suggests ways of modifying the design of arrow symbolism for each of the criteria presented in Chapter 5, Table 5.2 (Column 1). For example, a number of suggestions are made for ensuring easily identifiable spatial organisations – an essential design feature to avoid unanticipated emergent effects (as explained in Chapter 4 and illustrated in Chapter 6, Table 6.3). Further modifications are suggested to promote the formation of perceptual units – an area of interpretation that attracted a high incidence of difficulty (Difficulties 13 – 16, Table 6.5, Chapter 6). Other modifications are given to reduce the level of complexity of the diagram (in response to Criterion 7, Table 5.2 and Difficulties 1 and 2, Table 6.2, page 130). Diagrams that have been carefully evaluated using the convenient set of criteria (Chapter 5, Table 5.2, page 115) and modified according to these guidelines should come much closer to conveying the intended message.

8.2 Guidelines for developing students' ability to interpret arrow symbolism

8.2.1 Guidelines for developing students' schemata

According to the theory of constructivism, the acquisition of new knowledge is influenced by the individual's prior knowledge. In line with this theory, the 3-level, non-linear model of the process of interpretation of arrow symbolism (Figure 7.2, Chapter 7) shows the strong influence of students' frames of reference or schemata (Level 3) on the stages of information processing (Level 2). We would therefore expect that students' ability to interpret arrows used in diagrams is in some measure at least attributable to their various schemata.

Kindfield (1993/1994) points out that science diagrams are knowledge and reasoning tools, not just illustrative devices and readers need specialised skills to carry out the relatively sophisticated forms of mental processing that diagrams demand (Lowe, 1991). According to many researchers (e.g. Glaser, 1992; Lowe, 1993c; Lowe, 1994a; b; 1999; Johnstone, 2000; Goldman, 2003; Kozma, 2003; see also Chapter 3, Table 3.2, page 24) experts in a particular domain usually possess the relevant schemata (conceptual and procedural knowledge) to interpret diagrams, sometimes doing so without much thought. However, our investigations by revealing a range of processing difficulties (Chapter 6, Table 6.5, page 146) corroborated the suggestions of Lowe (1997) and Henderson (1999) that students might not possess the relevant conceptual, graphical and cognitive schemata. For example, as pointed out by many researchers (e.g. Barlex & Carre, 1985; Lowe, 1986a; 1989; 1991 and 1999; Serpell & Boykin, 1994; Stylianidou *et al.*, 2002; Yair *et al.*, 2003) students need to learn to recognise the significance of visual patterns – the process is not innate.

Table 8.1 Suggestions for modifying inappropriately presented arrow symbolism after evaluation using the criteria presented in Chapter 5, Table 5.2. The suggestions are grounded in literature and the empirical data (#) of this investigation. # = ideas emanating from the present study.

Criterion	Suggested improvements to arrow
1: To improve the visibility of arrow	Increase the size of small arrows.# Magnify the relevant part of the diagram (including the arrow).# Adjust the size of arrows relative to other features of the diagram (Hardin, 1995). Change the style (including colour) of arrows.#
2: To ensure an easily identifiable spatial organisation	Ensure suitable perceptual precedence by attending to the positioning and salience of elements (Colin *et al*., 2002) especially of several images integrated into one (Stylianidou *et al*., 2002). Remove unnecessary detail.# Adjust the number of arrows used in the layout to ensure simplicity but retain sufficient cues to promote the intended interpretation (Szlichcinski, 1979; Kosslyn, 1989; Lowe, 1989) as over-simplified spatial organisations may prove ambiguous (Storey, 1991). Use recognisable spatial organisations where appropriate (Hardin, 1993; Schnotz & Bannert, 2003). Redraw the diagram using design principles such as those of continuity, proximity and similarity (Kress & van Leeuwen, 1996). Present information in a logical sequence (Hewson, 1981) cued by sequential arrows (Lowe, 1997). Redraw diagram or re-position arrows or elements in the diagram to avoid unintentional emergent effects. To avoid unintentional effects of continuity and proximity, separate arrows by increasing spatial frequency; use different arrow styles including colours; add opposing lines; add labels; or enclose perceptual units in boundaries to promote category membership. Adjust the arrow pattern according to the readers' culture (Henderson, 1999).
3: To ensure spatial organisation appropriate to content and purpose	Use a recognisable spatial organisation (or combinations of recognisable spatial organisations) appropriate to the information being communicated (Hardin, 1993; Schnotz & Bannert, 2003).
4: To promote the formation of appropriate perceptual units	Re-group arrows into clearly identifiable and preferably recognisable patterns and groups (Reid, 1990a). Use a specific arrow style per concept or entity (Ametller & Pinto, 2002). Use compensatory cueing such as separating elements or shading (Lowe, 1996). Apply graphic design principles, such as those of proximity, similarity and frequency (Winn, 1993). Adjust the number of arrows used in perceptual units to ensure simplicity but with sufficient cues to promote the intended interpretation (Szlichcinski, 1979; Kosslyn, 1989; Lowe, 1989).
7: To minimise complexity	Limit arrow groups to a maximum of seven, or four for simultaneous mental processing (Kosslyn, 1989). Remove irrelevant information (arrows) from the diagram (Mayer, 2003). Keep diagrams simple (Butcher, 2006) Use recognisable layouts and commonplace styles to reduce the load on working memory (Mayer, 2003). Highlight corresponding features with cues e.g. colours.# Guard against directing focus to surface features of arrows; semantic cues may be preferable.# Use multiple versions of the same diagram to reduce overloading (Lowe, 1997). For example, use several consecutive diagrams to show animation (such as movement) (Henderson, 1999). Introduce symmetry (Chipman, 1977). Add annotations to provide supporting information (Koedinger & Anderson, 1990).
8 – 10: To ensure that arrow style is suited to purpose	Redraw unsuitably styled arrows that do not convey the intended purpose.# Present arrows intended for different functions in clearly different styles (Geva, 1983; Henderson, 1999; Ametller & Pinto, 2002; Stylianidou *et al*., 2002). Present arrows used for similar purposes in similar styles (Pinto *et al*., 2002). Ensure conformity of style including commonplace presentations within diagrams and between diagrams (Waller, 1981; Kosslyn, 1989; Kress & van Leeuwen, 1996). Develop a set of conventions (or commonplace presentations) to minimise misunderstandings (Lowe, 1987a).
11: To promote intended relationships	Redraw arrows to ensure suitable arrow placement and accuracy of arrow positions when used as links in relationships (Hardin, 1993; Lowe, 1996). Place cause on the left in cause-effect relationships (Henderson, 1999) or according to cultural preference.
12: To achieve harmony	Redraw arrows to explicitly promote the main focus of the diagram (Bennett & Flach, 1992; Lowe, 1996; Henderson, 1999) e.g. change colour intensity, size or shape of the arrows or by numbering the arrows.# Ensure that only the intended elements are highlighted (Stylianidou *et al*., 2002). Re-position arrows to promote or lessen the effects of juxtaposition (adjacency).# Avoid or take care with mixing symbolic (such as arrows) & real entities (Stylianidou *et al*., 2002). Avoid or change ambiguous symbols (Hardin, 1995; Colin *et al*., 2002). Add, or correct where necessary, labels, annotations or caption (Guri-Rozenblit, 1988b).
Criterion 13: To ensure sufficient explicit cues to interpretation	Reword propositional guidelines (captions, labels, annotations, keys, text) to positively clarify the message of the diagram (Colin *et al*, 2002), including the role of the arrow symbolism in the context of the diagram (Gillespie, 1993; Mayer *et al*., 1995; Henderson, 1999; Stylianidou *et al*., 2002). Create clear links between text and diagrams [including arrows] to allow dual coding (Paivio, 1986) and integration (Mayer, 2003). Use corresponding styles e.g. colours to foster links between sources of similar information (Kozma, 2003). Provide verbal explanations for diagrams with many elements (Guri-Rozenblit, 1988b). Include explanations for, or meanings of, represented objects; reasons for particular forms of representation; and the intended relationships amongst different representations (Kindfield, 1993/1994). Supply linking words along the shafts of arrows as commonly promoted in concept mapping (Novak, 1996). Supply explicit supporting information (Butcher, 2006) to compensate for lack of background knowledge (Lowe, 1996).

Consequently, students as novices in the field may have difficulty interpreting diagrams, particularly if the information or presentation type is unfamiliar (Lowe, 1989). Therefore, to assist them in processing diagrams, students should be:

1. Guided (e.g. Levie & Lentz, 1982) or given explicit support (e.g. Lowe, 1996 and 1997; Butcher, 2006); and
2. Taught appropriate skills (e.g. Lord, 1985; Hardin, 1993; Blackwell & Engelhardt, 2002).

In fact, reports indicate that students with no training in visual literacy have a high level of misinterpretation (Hill, 1988), whereas students with arts training have a distinct advantage (Lohse *et al.*, 1991). Teachers, on the other hand, often presume that students have the necessary skills and are motivated to listen, try and do (Pinto *et al.*, 2000). It is therefore imperative that students studying science be instructed in appropriate schemata, including:

a. Graphical schemata to understand what the arrow symbolism in diagrams is designed to show and how it is designed to show its intention;

b. Cognitive schemata, including perceptual skills to look for the appropriate cues and deeper-reasoning skills to integrate the cues; as well as

c. Relevant conceptual schemata or domain-specific knowledge (e.g. Wheeler & Hill, 1990; Hofstein & Walberg, 1995; Lowe, 1996).

Only then will students be able to effectively process the cues provided by the design of the diagram (Beck, 1984). Informed by literature and the results of the investigations, I suggest some broad guidelines (Table 8.2) for equipping students with appropriately developed conceptual, graphical and cognitive schemata.

Conceptual schemata

Probing of student interpretations of arrow symbolism showed that conceptual understanding is an important factor for effective interpretation (Chapter 6, Table 6.5, Difficulty KNOW). There is much information in the literature, promoting adequate prior domain knowledge for diagram interpretation to be successful (e.g. Reid, 1990a; Wheeler & Hill, 1990; Bennett & Flach, 1992; Lowe, 1993c; 1994a and b; Winn, 1993; Fredette, 1994; Scaife & Rogers, 1996; Henderson, 1999; Stylianidou *et al.*, 2002; Schnotz & Bannert, 2003; Chittleborough and Treagust, 2006). Lowe (1997) claims that, without the support of domain-specific knowledge, students may not be able to distinguish the overall concepts from the detail. In addition, students might interpret diagrams at a superficial (or literal) level (Hill, 1988; Lowe, 1994a), without identifying the conceptually relevant information (Lowe, 1996).

Table 8.2 Guidelines from literature and ideas emanating from the results of this study, for developing students' conceptual, graphical and cognitive schemata. * RESULTS = Ideas generated from the results of my investigations into the presentation and interpretation of arrow symbolism.

GUIDELINE FOR DEVELOPING STUDENTS' SCHEMATA	REFERENCES
CONCEPTUAL SCHEMATA	
Educators should ensure that students have adequate knowledge of concepts underpinning the context of the diagram, including for terminology used in the diagram.	Reid, 1990a; Wheeler & Hill, 1990; Bennett & Flach, 1992; Lowe, 1993c; 1994a and 1994b; Winn, 1993; Fredette, 1994; Scaife & Rogers, 1996; Henderson, 1999; Stylianidou *et al.*, 2002; Schönborn, 2005; Chittleborough & Treagust, 2006
To ensure that the conceptual focus of the diagram is explicit to students, appropriate textual support (propositional guidelines) should be provided.	Henderson, 1999; Butcher, 2006
Educators should explain the concepts represented by diagrams so that students can better understand the functional intentions of arrows used in the diagram.	Lowe, 1989 and 2003; Stylianidou *et al.*, 2002
Concepts presented using arrow symbolism should be represented in various ways to reinforce the relationship and not just the features of the diagram.	Hill, 1988.
GRAPHICAL SCHEMATA	
Students should be taught the language of diagrams, including of arrow symbolism.	Lord, 1990; Pinto & Ametller, 2002.
The more pertinent graphic design principles (discussed in Chapters 2 & 5), such as those of continuity, proximity, similarity and frequency, governing the presentation of arrow symbolism should be explained to students.	Kindfield, 1993/1994
Students should be made aware of the diversity of modes of presentation (spatial organisations and styles), particularly of the commonplace presentations and their possible purposes and meanings, as detailed in Chapter 2. Awareness can be fostered by explicitly teaching the graphical (arrow) conventions used in the diagram.	Lowe, 1987a; 1991 and 1996 Constable *et al.*, 1988; Hardin, 1993; Henderson, 1999
Students should understand that representation of symbolism [including arrows] in diagrams might be at syntactic (style) and semantic (meaning) levels.	Lowe, 1988a
Students should recognise that ideas can be expressed in a variety of ways. Exposure to multiple diagrammatic forms will improve translation skills.	Treagust *et al.*, 2002; Seufert, 2003
Students should be made aware of the importance of arrows as links showing relationships between two elements and the resulting importance of placement and positioning of arrows in relation to their referents (diagram features, words and other arrows).	Hardin, 1993 and 1995; Lowe, 1996
Teaching text structure to explain the role of arrows as conjunctions and the corresponding time sequence could improve the making of flow charts.	Geva, 1983
Understand the symbolic form of the diagram (and arrows).	Guri-Rozenblit, 1988a
Define meaning of symbolism used in various contexts.	Guri-Rozenblit, 1988a
Students should be encouraged to use, and therefore become familiar with, the criteria for evaluating arrow symbolism in diagrams, presented in Table 5.2.	* RESULTS
Students' should be made aware of the significance of modes of arrow presentation and encouraged to use arrows appropriately.	Lowe, 1991; Stylianidou *et al.*, 2002
Arrow symbolism should be modified where necessary using guidelines such as those presented in Table 8.1.	* RESULTS
To become familiar with the use of arrows in diagrams, students should practise using commonplace [arrow] presentations.	Lowe, 1991; Roth, 2002
Students should generate their own diagrams including stylised and abstract types that use arrow symbolism.	Lowe, 1987a; Ward & Wandersee, 2002
Students should translate the diagram into a verbal explanation. This is particularly relevant to flow diagrams.	* RESULTS
COGNITIVE SCHEMATA	
A range of reasoning strategies (defined in the Glossary) should be encouraged and practised, including focussing and scanning strategies; learning strategies using a sequence of activities; elaboration strategies for building connections between new information and prior knowledge or experiences to allow deeper-level comprehension; control strategies to plan or regulate subsequent steps in the process and therefore control the level of comprehension; and problem solving strategies involving planned sequences of activities leading to a goal.	Roth & Frisby, 1986; Taconis *et al.*, 2000; Lewalter, 2003
To encourage the development of reasoning ability, the meanings and false meanings of images should be talked through.	Stylianidou *et al.*, 2002

Students should be made aware of diagram limitations including those for arrow symbolism.	Hill, 1988; Lowe, 1997; Roth, 2002
To facilitate the formation of perceptual units (Table 6.5, Difficulties 13 – 16: PU), a suitable level of chunking should be ensured (see a – f below).	Egan & Schwartz, 1979; Lowe, 1996 and 1997
a. Students should be encouraged to build on their pattern search ability.	Hewson, 1981
b. Students should be guided to differentiate the central idea of the diagram from the rest of the information.	*RESULTS
c. A process of partitioning should follow the differentiation stage, particularly if the diagram is complex. The aim should be to build sufficiently large chunks to avoid overloading short-term memory (Table 6.3, Difficulty 1, 2: COMP) but facilitate higher order information structures.	Lowe, 2003
d. Students should be taught to recognise the multi-layered nature of diagrams and be able to access both global and local views including the broader relational aspects often cued by arrow symbolism.	Lowe, 1997 and 2004
e. Students should avoid placing undue significance on spatial organisations and other salient features (Table 6.3, Difficulty 10: SAL (S-L)) rather than on thematically relevant information.	Pinto *et al.*, 2000; Lowe, 2004
f. To hone the strategies required for chunking, exposure to, and practise with a wide range of diagrams and arrow style may be necessary.	Lowe, 1997
The syntactic structure should be imbued with meaning (see a – c below)	Schnotz, 1993
a. Students should be encouraged to consider the implications of symbolism used in diagrams including the style of the arrow.	Hardin, 1993; Lowe, 1994b; Cheng *et al.*, 2001; Kozma, 2003
b. Students should understand the parameters of processing synonymy and polysemy of arrow symbolism.	Pinto *et al.*, 2000
c. Support should be provided to the students during interpretation of each type of arrow.	*RESULTS
As the central purpose of diagrams is to depict relationships and interactions, often presented by means of arrow symbolism, students should learn to detect relational aspects in diagrams, not just accumulate facts. The key challenge is to recognise the nature of the relationship between the different elements, and then map the relationships on to the real-world situation (see a – d below).	Winn & Holliday, 1981; Lowe, 1996; 1997; 2004; Roth, 2002
a. Students should be taught to differentiate between important relationships and seemingly salient features.	Lowe, 1996
b. Students should provide linking words to explain the intention of arrows in relationships.	Novak, 1996; *Own idea
c. Students should combine the arrows and referents into phrases, taking cognisance of the origin of the arrow shaft and position of the arrowhead in relation to surrounding diagram features. This will also help students to understand the concept of cause and effect (Table 6.5), cued by arrow symbolism.	Geva, 1983; Fisher, 1990; Hardin, 1995; Kress & van Leeuwen, 1996
d. Visual-spatial skills (3-dimensional skills) needed to recognise patterns and relationships should be taught and practised.	Pallrand & Seeber, 1984; Lord, 1985 and 1990; Rochford *et al.*, 1989; Tuckey *et al.*, 1991; Winn *et al.*, 1991; Sanders, 2002
To reduce extraneous cognitive load, techniques of integrating diagrammatic and textual information should be taught or encouraged. Bodemer *et al.* (2004) suggest the concept of structure-mapping.	Paivio, 1986; Moore *et al.*, 1993; Mayer, 2003; Bodemer *et al.*, 2004
The meanings applied to the arrows should be validated by comparison to the information supplied in the accompanying text.	Kress & van Leeuwen, 1996
Students should be taught and encouraged to use a training sequence, such as the 12-point strategy described in Section 8.2.2, page 199. For students' convenience this sequence is simplified in Figure 8.1, page 201.	e.g. Gillespie, 1993; Taconis *et al.* 2000; Lewalter, 2003; * RESULTS
An understanding of the process of interpretation (as explained by the model, Figure 7.2, page 170) would guide interpretation, as well as help to predict and identify difficulties with arrow symbolism.	* RESULTS
The dependency of the facets (C, M and P) of diagrams on each other, as shown by the Interfaces (C/M, M/P and P/C) of the model (Figure 7.2) and the value if these interrelationships as cues to interpretation, should be explained.	* RESULTS
Interpretive strategies, both encoding and decoding, should be practised.	Barlex & Carre, 1985; Lowe, 1987a and 1987b; 1988a; 1988b and 1991; Wheeler & Hill, 1990; Gillespie, 1993; Cheng *et al.*, 2001
Students should be encouraged to re-inspect the diagram, thereby using it as an external memory aid.	Hegarty, 2004
Encouraging mental animation of static diagrams should enhance internal visualisation skills.	Hegarty, 2004

To facilitate the process of interpretation, I included guidelines presented in Table 8.2 (page 195) for developing students' conceptual schemata. These guidelines include that educators should ensure that students have sufficient conceptual knowledge for the task at hand (e.g. Henderson, 1999; Stylianidou *et al.*, 2002; Schönborn, 2005; Chittleborough & Treagust, 2006), that the focus of the diagram is explicit to students (e.g. Henderson, 1999; Butcher, 2006), or that students with insufficient prior domain knowledge should be prompted with supporting or propositional information (Butcher, 2006). By doing this, difficulties such as Difficulty 26 (Table 6.5, Chapter 6) would be minimised.

Graphical schemata

Several researchers claim that diagrams are more complex than they appear (e.g. Barlex & Carre, 1985; Lowe, 1987a and b; Hill, 1988). Using Roth's explanation (Roth, 2002) students are required to correlate the symbolism (sign forms) with the situations in the world that they represent and also to be able to translate between the two. To do this, students need graphical schemata (see G in Chapter 6, Table 6.5) to understand the role of arrow symbolism in diagrams, to realise the significance of the modes of presentation of arrows used in diagrams and to effectively interpret the relationships cued by arrows. Various forms of learner support are advised in the literature to promote familiarity with the intentions of the diagram-type or spatial organisation (e.g. Kosslyn, 1989; Lowe, 1991; Kindfield, 1993/4; Lowe, 1996; Henderson, 1999), including that students be taught the 'visual language' of diagramming (Lord, 1990; Pinto & Ametller, 2002). I have adapted these suggestions and included my own ideas to provide guidelines in Table 8.2 (page 195) for promoting graphical schemata for arrow symbolism specifically. These guidelines include a range of ideas such as:
Students should be made aware of the most pertinent graphic principles (Kindfield, 1993/1994). Students should be taught the relevance of symbolism, specifically the language of arrow symbolism (Lord, 1990; Pinto & Ametller, 2002) and the importance of arrows in showing relationships (Hardin, 1993 and 1995; Lowe, 1996). Furthermore, they should be exposed to a diversity of arrow styles and spatial organisations (Treagust *et al.*, 2002; Seufert, 2003).

I speculate that by implementing these ideas, students will become familiar with the modes of presentation and intentions of arrow symbolism. For example, by explicitly teaching students the arrow conventions used in the diagram, they will better understand the modes of presentation (M) of arrow styles and spatial organisations. In turn, and according to the lateral dimension of processing explained in the 3-level, non-tiered model (Figure 7.2, Chapter 7), students will thereby gain valuable insight into other facets of the diagram (C and P) during diagram processing.

Cognitive schemata

Many researchers (e.g. Zhang & Norman, 1994; Scaife & Rogers, 1996; Brna *et al.*, 2001) describe cognitive schemata as the procedural knowledge required to integrate the external (diagrammatic message) and internal representations (mental models of students). The results of investigations of students' interpretations of arrow symbolism (Table 6.5, Chapter 6) revealed a range of cognitive difficulties with the process of interpretation of arrow symbolism. This diversity of difficulties suggests that students should be trained in, and practise using cognitive skills (competencies) and strategies (methods of applying procedural knowledge - see definitions) to ensure successful interpretation of arrow symbolism used in diagrams. I therefore adapted suggestions for interpreting diagrams (not for symbolism or arrows specifically) described in the literature in order to develop a range of broad guidelines for improving students' abilities to interpret arrow symbolism in diagrams. Examples selected from the many guidelines presented in Table 8.2 (page 195) include that a range of reasoning strategies (defined in the glossary of terms) should be encouraged and practised, including focussing and scanning strategies; learning strategies using a sequence of activities; elaboration strategies for building connections between new information and prior knowledge or experiences to allow deeper-level comprehension; control strategies to plan or regulate subsequent steps in the process and therefore control the level of comprehension; and problem solving strategies involving planned sequences of activities leading to a goal (Roth & Frisby, 1986; Taconis *et al.*, 2000; Lewalter, 2003). In addition, I shall also suggest a hierarchical processing strategy (Figure 8.1, page 201) to guide students when interpreting arrow symbolism in diagrams.

By using guidelines such as those in Table 8.2 (page 195) for developing students' conceptual, graphical and cognitive schemata, students should have the necessary domain-specific and domain-general knowledge for interpreting arrow symbolism more effectively. Further research is required to fully test these guidelines in multiple contexts, diagrams and symbolism.

8.2.2 A suggested strategy for interpreting arrow symbolism in diagrams based on a model of the process of interpretation (Chapter 7, Figure 7.2, page 170)

Several researchers (e.g. Danserau *et al.*, 1979; Thorndyke & Stasz, 1980; Moore *et al.*, 1993; Lowe, 1997 and 2003) have suggested the importance of students being aware of, and using strategies to maintain a purposeful approach to interpreting learning materials, including diagrams, in order to achieve deeper levels of comprehension. Taconis *et al.* (2000) suggested a combination or series of cognitive activities to guide the process of interpretation to find the solution during problem-solving tasks. Lewalter (2003, page 179) described learning strategies as 'a schematic structure combining a sequence of specific learning activities that will be executed by the learner to gain new knowledge.' He suggested 'four main components [for the process of interpretation]: selection, acquisition, construction and integration'. Gillespie (1993) posed four questions to guide the interpretation of diagrams, namely:

1. What is the main idea? (for which I substitute: What is the content represented in the diagram?)
2. What are the supporting details?
3. What is the purpose of the diagram? and
4. What do the words /symbols mean?

I used these various ideas, in conjunction with the 3-level, non-linear model of the process of interpretation (Figure 7.2, Chapter 7) to develop a sequential 12-point strategy (Figure 8.1) as an algorithm or training exercise to guide students and educators in the process of interpretation of arrow symbolism. The 12-point strategy would lead students through a sequence of steps to ensure that all aspects of the diagram are adequately considered. Briefly, the sequence (explained more fully in Figure 8.1) includes that students:

- consider the context of the diagram by reading the propositional guidelines
- access graphical design features of arrows and patterns formed by groups of arrows
- detect, select and organise the relevant information into perceptual units
- establish the intended relationships cued by the arrow symbolism
- determine the significance of implicit cues, spatial organisations, perceptual units and styles of arrows
- integrate information to attribute meaning to arrows and, ultimately, to interpret the diagram
- apply control strategies (Pick & van Broek, 1992)

I consider it important that students first practise a sequential pattern, as the multi-directional nature of the process of interpretation (as illustrated by the concentric ring structure of the model (Figure 7.2)) is considered too complex for training. The 12-point strategy on the other hand can be considered flexible. However, students should be made aware of the wide variety of alternative pathways available to practiced readers.

Once students have mastered the basic sequence of the 12-point strategy, they may progress to using a simplified and interactive guideline (Figure 8.2, page 202), based on the 12-point strategy (Figure 8.1, page 201), to guide interpretation of arrow symbolism in diagrams. Assisted by the educator (initially at least), the student can seek out the required information according to each step of the 12-point strategy and record his /her progress in the appropriate frames. In this way, the 12-point strategy training sequence will be reinforced.

More detailed guidelines and supporting information, also based on the model (Figure 7.2), were specifically developed for the use of educators. These guidelines, presented in Table 8.3, should help educators to understand how to better prepare students for the process of interpretation of arrow symbolism and implementation of the 12-point strategy (Figure 8.1). This set of educator guidelines (Table 8.3, page 203), describes the source of information to be used at each step of the process of interpretation (Column 1), the level of processing according to the model (Column 2), the cues to look for in the diagram (Column 3), the processing skills required by the student (Column 4) and teaching suggestions for the educator (Column 5). By understanding and implementing these guidelines, the educator would be in a good position to ensure that students are adequately prepared for the process of interpretation of arrow symbolism in biology diagrams. However, the guidelines in Table 8.3 are considered too detailed for students to understand and use.

8.2.3 Booklet to guide the interpretation of arrow symbolism.

A self-study booklet was designed for students to work through to make them aware of the various aspects involved in the interpretation of arrow symbolism. The booklet is submitted in a folder at the back of the dissertation.

The steps of the suggested 12-point sequence include:

1. Read any propositional guidelines present including caption, labels, annotations, keys and supporting text to establish the content represented and purpose of the arrow symbolism in the diagram.

2. Access graphical design features including arrow symbolism for supporting information to the content represented and purpose of the arrow symbolism in the diagram.

3. Discern the global pattern or major patterns (spatial organisations) of arrows or groups of arrows in the diagram.

4. Detect, select and organise individual and groups of arrows with their referents into perceptual units.

5. Note the explicit cues to represented content and purpose of arrow symbolism in the diagram such as recognisable spatial organisations and commonplace styles.

6. Establish the relationships, including cause-effect relationships, cued by the arrows.

7. Determine the significance of the implicit cues of spatial organisation/s in respect of the content represented in the diagram and /or purpose of the arrow symbolism in the diagram.

8. Determine the significance of the perceptual units in respect of content and /or purpose.

9. Analyse and determine the significance of the styles of arrows, including commonplace styles in respect of the purpose of the arrow symbolism.

10. Integrate the purpose of the arrow cues with the represented content of the diagram in order to attribute meaning to arrow symbolism.

11. Integrate the meanings of the arrows, own prior knowledge and supporting information (point 2 of these guidelines) to ensure a reconstruction of the abstraction and the emergence of new knowledge.

12. Apply control strategies (Pick & van Broek, 1992) as follows:
    a. Check for the validity of domain knowledge against the newly emerged content of the diagram.
    b. Check previous understanding of symbolism against that presented in the diagram and check for validity.
    c. Apply deeper-level reasoning skills to check integration.
    d. If any of the checks prove unsatisfactory, repeat the process (steps 1 – 12) in order to try and detect inaccuracies in the process of interpretation.

Figure 8.1 A suggested 12-point strategy to guide interpretation of arrow symbolism in diagrams.

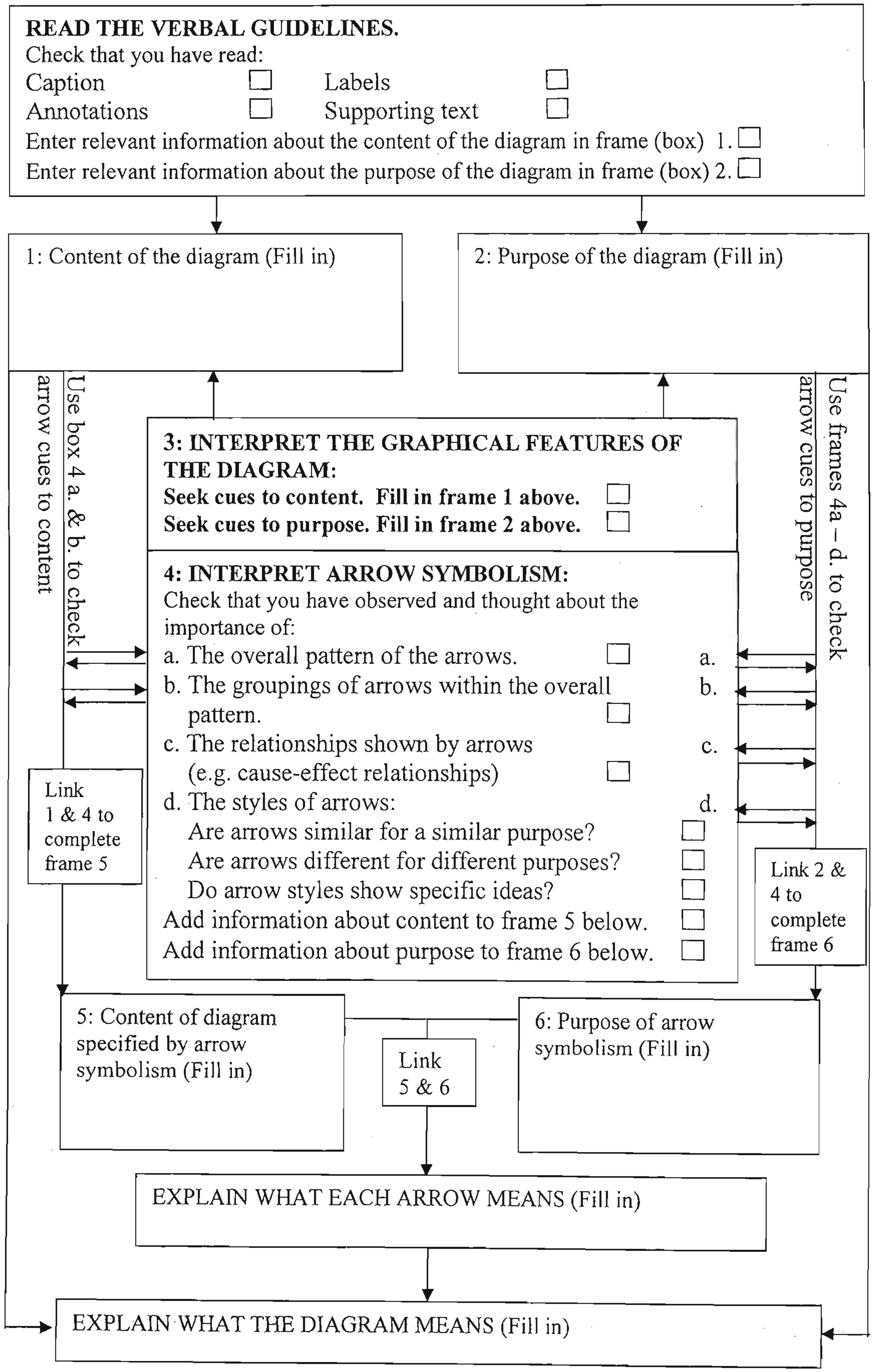


Figure 8.2 Suggested guidelines based on the model of the process of interpretation of arrow symbolism (Figure 7.2) for educators to guide students during the interpretation of arrow symbolism in biology diagrams.

Table 8.3 Detailed guidelines for researchers, designers and educators based on the model (Figure 7.2, Chapter 7) for understanding the process of interpretation of arrow symbolism and the implementation of the 12-point strategy.

Model correspondences		Process of interpretation of arrow symbolism			Teaching ideas for the educator:
Source of information	**Processing level**	**Process to follow**	**Cue**	**Skills required**	**Student should be taught:**
Level 1C	2 S-L Surface-level reasoning	Read the propositional guidelines (caption, labels, annotations, keys, text) Scan diagram for domain-specific features	Explicit verbal cues to content Domain-specific features of diagram	Reading and comprehension Recognition of supporting diagram features about represented content	The cue-value of propositional guidelines Dual-coding Content knowledge
Level 1P	2 S-L	Read the propositional guidelines	Explicit verbal cues to purpose	Reading and comprehension	The cue-value of propositional guidelines; Dual-coding
Level 1M	2 S-L	Access modes of presentation of arrows	Graphical design presentation techniques	Graphical schemata Skills of observation	Graphical design principles Skills of observation
Level 1 (C, P and M)	2 S-L	Access explicit cues to nature of diagram Observe: discern form of spatial organisation; detect, select and organise arrows with referents into perceptual units; observe commonplace styles	Patterns of arrows Placement and positioning of arrows with referents to form relationships. Commonplace styles of arrows and recognisable spatial organisations	Graphical schemata Skills of observation Prior knowledge of commonplace arrow styles and recognisable spatial organisations	Observation techniques for effective detection, selection and organisation of arrows at surface-level (or literal) interpretation. The intention of commonplace styles and spatial organisations relative to the context Graphical design principles
Level 2 S-L: C/M	2 D-L Deeper-level reasoning	Access implicit cues of arrow symbolism (1M) to content represented in the diagram (1C) Determine significance of cues	Overall spatial organisation Perceptual units relative to content represented in diagram	Graphical and conceptual schemata (to anticipate, match data, plan and recognise significance of symbolism in context); cognitive schemata (to integrate arrow symbolism with other information)	To recognise patterns and groupings Determine significance in relation to content Content knowledge, graphical design principles, cognitive schemata
Level 2 S-L: M/P	2 D-L	Access implicit cues of arrow symbolism (1M) to purpose (1P) Determine significance in respect of cues	Overall spatial organisation Perceptual units Relationships Arrow styles	Graphical and conceptual schemata (to recognise significance of symbolism in context); cognitive schemata (to integrate arrow symbolism and purpose)	To recognise patterns, groupings, relationships and styles and determine significance in relation to purpose Cognitive schemata
Level 2 S-L: P/C	2 D-L	Integration of represented content (C) and purpose (P)	Content from 1C and C/M Purpose from 1P and M/P	Cognitive schemata (deeper-level reasoning) and conceptual schemata	To decide on and assign possible meanings to arrows allowing new knowledge to emerge Conceptual and cognitive schemata
Levels 1 and 2	2 D-L	Integrate meaning of arrow symbolism (2 D-L) with supporting information (1C)	Meaning from Level 2 (integration of C/P) and supporting information (1C)	Cognitive schemata Conceptual schemata	That all information in a diagram is relevant to the content and purpose of the diagram
Level 3	2 D-L Controls	Check cues and outcomes against domain and graphical design knowledge	New knowledge in context of represented content	Objective evaluation	Conceptual, graphical and cognitive schemata Reflection /evaluation

8.3 IMPLICATIONS AND CONCLUSIONS

Using various sources, including a wide range of literature, the results of the investigations reported in this dissertation, and the 3-level, non-linear model of interpretation of arrow symbolism (Figure 7.2, Chapter 7), I have suggested a range of guidelines for improving the presentation and interpretation of arrow symbolism used in biology diagrams. However, they need to be implemented if difficulties are to be addressed. Furthermore, the full extent of their effectiveness needs to be established by further research. I therefore elaborate briefly on the possible involvement of each of the role players: designers, educators, students and researchers in the remediation process for the presentation and interpretation of arrow symbolism in diagrams. For example, designers, educators and researchers would benefit from a guide to the diversity of arrow symbolism, the use of a set of criteria for evaluation of arrow symbolism, knowledge of the model (Figure 7.2) as a predictive and instructional tool, as well as guidelines for improving arrow design. Educators would also benefit from guidelines for developing students' schemata (e.g. Table 8.2) and strategies (e.g. Table 8.3). Students however, would best benefit from guidelines to the diversity of arrows and to strategies for interpreting arrow symbolism, such as those outlined in Figures 8.1 and 8.2. Table 8.4, page 205 summarises the guidelines and strategies envisaged for each of these role players.

As arrows have a range of potential uses in instructional diagrams, it is of the utmost importance that textbook editors and designers be more aware of, and pay careful attention to, the presentation of arrow symbolism. However, until this dissertation, there was no comprehensive information on this specific aspect of symbolism nor on the difficulties students experience when interpreting arrow symbolism in diagrams, prompting Colin *et al.* (2002) to suggest that textbook editors and diagram designers would also benefit from research and guidelines in this field. It is of the utmost importance that these role players pay careful attention to the presentation of diagrams and in particular to arrow symbolism for the intended communication to be accurately portrayed, and in such a way that it is easily understood. Thus, referring to Table 8.4, I suggest that guidelines 1, 2, 3 and 4 would be most useful to textbook editors and diagram designers. In addition, and as Lowe (1996) and Butcher (2006) also suggest, designers should provide sufficient domain knowledge as text, if the intended readers are novices in the field.

Table 8.4 Suggestions for remedial guidelines and strategies to be assembled into a portfolio for use by each of the various role players.

Remedial guidelines and strategies		Role players			
		Designer	Educator	Student	Researcher
1. A guide to the diversity of arrow symbolism (to be developed)		X	X	X	X
2. Use of the criteria (Chapter 5, Tables 5.1, 5.2)		X	X		X
3. Model (Figure 7.2) as a tool to inform about arrow design, to predict potential sources of difficulty & to guide instruction on arrow symbolism		X	X		X
4. Guidelines for improving the design of arrow symbolism (Table 8.1)		X	X		X
5. Guidelines for developing students' schemata (Table 8.2)			X		
6. Strategies to guide interpretation	a). 12-point strategy (Figure 8.1)		X	X	X
	b). Expert (Table 8.3)		X		X
	c). Novice (Figure 8.2)		X	X	

Many researchers, including Lowe (1991) and Hardin (1993), have noted that there is little guidance for educators on teaching diagram interpretation. Yet, educators fill the communicative role between innovative designers and the users of the diagrams. In fact, Pinto *et al.* (2000) suggest that educators should be one of the targets of remediation initiatives. Their role is two fold: to select diagrams that will promote student learning during the teaching of biology and to ensure that students can effectively interpret them. To reduce the formation of misconceptions, educators should acknowledge that diagrams might not always fulfil their purpose (Lohse *et al.*, 1991) and therefore ensure that the diagrams used as teaching tools are of good quality (Winn *et al.*, 1991) or appropriately modified before being presented to students. I therefore suggest that educators may benefit from using all the guidelines listed in Table 8.4.

Hofstein & Walberg (1995) advise that students' abilities and needs should first be assessed if the effectiveness of a teaching or learning process is to be maximised. Instructional techniques could then be matched to learners' characteristics such as their age and complexity of thinking (Reid & Miller, 1980; Reid, 1984 and 1990a; Goldsmith, 1987; Lazarowitz & Penso, 1992). If this is done, the educator will be in a better position to instruct the students appropriately. The students could, therefore, make use of items 1 and 6a and 6c (Table 8.4) to improve their interpretation of arrow symbolism. On the other hand, Roth (2002) suggested that semiotically informed researchers should focus on students' familiarity with symbolism & conventions. Therefore researchers could benefit most from items 1, 2, 3, 5, 6a and 6b (Table 8.4)

Although certain remedial materials have been allocated to different role players, the distribution is flexible. In fact, all materials could be relevant to all role players in certain circumstances. Based on this information, comprehensive guidelines could be developed to target all role players that use arrow symbolism in biology (and other) diagrams. In addition, most of the methods could also find useful application to other types of symbolism used on both diagram and other visual displays such as computer images and animation. This research could be extended to address these issues.

CHAPTER 9
GENERAL DISCUSSION AND IMPLICATIONS

In Chapter 1 I put forward a range of research questions to direct the investigations into the presentation and interpretation of arrow symbolism in biology diagrams at secondary-level. To conclude this study, I revisit these questions and discuss to what extent they were successfully addressed and what major outcomes were achieved.

9.1 Were the research questions successfully addressed and what were the major outcomes of the study?

In this section I pose each research question, show how it was addressed and discuss the major outcomes of the study.

1. How much of a problem is arrow symbolism in biology diagrams?

There appear to be major problems with the use of arrow symbolism in biology diagrams. The literature review (Chapter 2) revealed that diagrams are used extensively as explanatory tools, that there is a wide range of guidelines for the design of diagrams and that a wealth of information exists on diagrams and about the interpretation of diagrams in general. However, there appears to be little research into arrow symbolism, particularly in the field of biology. This convinced me of the important need to further investigate the use of arrow symbolism in biology diagrams. This decision was strengthened by a content analysis of seven textbooks, as reported in Chapter 4, that revealed a wide diversity of modes of presentation, purposes and meanings of arrows in the textbooks studied. Assuming that such a plethora of presentations may be confusing to students, further research was considered worthwhile.

2. *How effectively is arrow symbolism used in diagrams to promote the communication of intended ideas?*

To answer this question satisfactorily, I addressed several sub-questions:

a. ***From an expert's points of view, is arrow symbolism used in biology textbook diagrams, appropriately designed?***

My findings showed that this is not always the case. The evaluation in Chapter 5 of 614 diagrams using arrow symbolism showed that arrow symbolism may be inappropriately presented and therefore prove confusing or misleading in approximately 30% of diagrams.

b. In this regard, can a suitable tool, such as a set of criteria, be developed for evaluating arrow symbolism?

A set of criteria was developed based on, and adapted from, the opinions of experts on diagrams in general in the fields of graphic design and education, for objectively evaluating arrow symbolism specifically (Chapter 5, Figure 5.1, page 95). From this set of criteria, a further more convenient set of criteria was developed for more practical use by designers, educators and researchers, who are not experts in the field of graphic design (Chapter 5, Table 5.2, page 115). The criteria were validated by input from a range of users.

c. Are criteria for the evaluation of arrow symbolism generalisable to all diagrams using arrow symbolism?

I consider that the criteria are generalisable to all diagrams as they were effective in analysing the syntactic, semantic and pragmatic dimensions of arrow presentation in a large number of diagrams (614) spanning a wide variety of diagram types in textbooks drawn from three different South African publishing houses. Despite the localised origin of the textbooks, I was confident of the reliability of the criteria. Consequently, the criteria were considered suitable to evaluate arrow symbolism in the diagrams (Figures 6.2 and 6.3, Chapter 6) selected to assess student interpretations. They also showed great potential as a valuable tool for screening diagrams with arrow and other symbolism.

3. *To what extent does the design of arrow symbolism in diagrams influence students' interpretation and difficulties?*

In this regard, I posed further sub-questions.

a. Do students experience difficulties with the processing of arrow symbolism in diagrams that is considered by experts to be inappropriately presented?

Empirical evidence in Chapter 6 (Table 6.3, page 132) showed that students (regarded as novices) have difficulties with all aspects of inappropriately presented arrow symbolism identified by experts using the set of criteria (Table 5.1, page 95) to evaluate Figures 6.2 and 6.3 (Chapter 6, page 117). The range of student difficulties attributable to inappropriately designed arrow symbolism (Chapter 6, Table 6.3, page 132) strongly suggests that inappropriately presented arrow symbolism increases the chances of difficulties. These findings further validated the set of criteria as a reliable evaluation tool for arrow presentation and interpretation.

If so: What is the nature of such difficulties? Both surface-level reasoning and deeper-level reasoning difficulties emerged during interpretation of inappropriately presented arrows. The difficulties were defined, coded and presented in Chapter 6, Table 6.3. Poor graphical and cognitive schemata may exacerbate such difficulties with inappropriately presented arrow symbolism.

b. Do students experience difficulties with the processing of arrow symbolism considered by experts to be appropriately presented?

In addition to difficulties with inappropriately presented arrow symbolism, some students experienced a range of surface-level reasoning and deeper-level reasoning difficulties during interpretation of arrows judged as appropriate by the criteria (reported in Chapter 6, Table 6.5, page 146). However, incidence of difficulties tended to be lower (Range:
11% - 41%; Mean: 22%) than those for difficulties with inappropriately presented arrow symbolism (Range: 18% - 77%; Mean: 41%).

If so: What is the nature of such difficulties? The difficulties reported in Chapter 6, Table 6.5 showed that students' difficulties were attributable to ineffective graphical, cognitive and conceptual schemata. The nature of each difficulty within these categories was described and coded.

4. How can the emerging empirical data and ideas from literature be combined to illustrate the process of interpretation of arrow symbolism?

A 3-level, non-linear model of the process of interpretation of arrow symbolism brought together, and in so doing, emphasised the importance of both arrow presentation in diagrams (Level 1) and arrow interpretation by students (Level 2) within students' frame of reference (Level 3). The circular and tiered structure of the model allowed for the progressive processing of information in both radial and lateral directions. Each facet of the model was grounded in empirical data that emerged from the investigations and backed by ideas in the literature. The model can therefore be regarded as both an explanatory tool to understand the process of interpretation of arrow symbolism and as a predictive tool to identify sources of student difficulties with arrow symbolism.

By satisfactorily answering Research Questions 1- 4, I am confident that I have thoroughly investigated the use of arrow symbolism in biology diagrams. One question remained: How can this information be used constructively? I therefore addressed Research Question 5.

5. What measures can be suggested for improving the use of arrow symbolism in biology diagrams?

The findings of these investigations, reported in Chapters 4, 5, 6 and 7 and ideas from diverse sources of literature (including Chapter 2), show convincingly that arrow symbolism may confuse and mislead students, leading to a range of difficulties with the interpretation of arrow symbolism in biology diagrams. These conclusions in turn provide very strong justification for developing guidelines and remedial tools to assist designers, educators, students and researchers to better understand the use (both presentation and interpretation) of arrow symbolism in biology diagrams. In Chapter 8 I therefore presented a range of ideas for altering diagram design, guidelines for improving students' schemata and strategies to direct diagram processing.

9.2 WHERE TO NOW?

Through this investigation, I have provided overwhelming evidence of inappropriately presented arrow symbolism and of the difficulties that students experience while interpreting arrow symbolism. I have therefore made a strong case for giving arrow symbolism the attention it deserves as an integral part of science diagrams. Where to now?

Ben-Zvi & Hofstein (1996) suggest several steps for bringing work on learning difficulties to the stage where it is useful in practice. This research has in essence followed the first three steps of their model for remediation. I first identified design features of arrow symbolism that could be confusing or misleading to students (Question 1; Chapter 4, and Question 2; Chapter 5) and diagnosed the nature of difficulties experienced during interpretation of both inappropriately and appropriately presented features of diagrams (Question 3; Chapter 6). I then developed a model to explain the process of interpretation of arrow symbolism (Chapter 7). I also proposed that the model could be used to predict and identify possible sources of difficulties - considered an important step toward remediation.

To achieve steps 4 and 5 of Ben-Zvi & Hofstein's (1996) model I need to develop and implement remedial tools and evaluate the effectiveness of the remediation programmes. I have proposed preliminary guidelines and teaching tools for improving the interpretation of arrow symbolism. The design of these guidelines and tools should be further developed and the relevant materials combined into portfolios specifically tailored to meet the requirements of each category of role player. I am in the process of doing just that! (see accompanying booklet). I then need to implement and test the suggestions by addressing student difficulties with the devised teaching strategies and materials. The effectiveness of these programmes should be evaluated to provide feedback at each level of the process. Without these implementation and evaluative steps, the investigations reported on in this dissertation would remain mainly of academic interest. Therefore this more practical aspect of the research process should form part of ongoing investigations into the presentation and interpretation of arrow symbolism in biology diagrams at secondary-level as well as in other levels of education and areas of science.

By clearly demonstrating that secondary-level students have difficulty with the presentation and interpretation of arrow symbolism in biology diagrams, I have opened the doors to opportunities for making an impact in a much-neglected field. The implications of this research are thus far-reaching and constitute a strong argument for further studies on the subject of the presentation and interpretation of arrow and other symbolism in biology and other science diagrams at both secondary and tertiary levels, so that we can better address the problems of visual literacy among all learners. Future research will address this.

REFERENCES

Abimbola, I. O. & Baba, S. (1996). Misconceptions and alternative conceptions in science textbooks: The role of teachers as filters. *The American Biology Teacher*, 58 (1), 14 - 19.

Alesandrini, K. L. (1984). Pictures and adult learning. *Instructional Science*, 13, 63 - 77.

Ametller, J. & Pinto, R. (2002). Students' reading of innovative images of energy at secondary school level. *International Journal of Science Education,* 24 (3), 285 - 312.

Amir, R. & Tamir, P. (1994). In-depth analysis of misconceptions as a basis for developing research-based remedial instruction: The case of photosynthesis. *The American Biology Teacher*, 56 (2), 94 - 100.

Anderson, G. & Arsenault, N. (1998). *Fundamentals of educational research* (2nd ed.), Falmer Press, London.

Anderson, T. R., Grayson, D. J., Crossley, L. G. & Schonborn, K. J. (2000). Do students really understand metabolism the way we think they do? *Invitation paper delivered at the 18th International Union for Biochemistry and Molecular Biology (IUBMB) Congress,* Birmingham, United Kingdom, 16 - 20 July.

Ausubel, D.P. (1968). *Educational psychology: A cognitive view*, Holt, Rinehart and Winston, New York.

Baddeley, A. (1992). Working memory. *Science,* 255, 556 – 559.

Barlex, D. & Carre, C. (1985). *Visual Communication in Science*, Cambridge Science Education Series, Cambridge University Press, London.

Barman, C. R., Griffiths, A. K. & Okebukola, P. A. O. (1995). High school students' concepts regarding food chains and food webs: A multinational study. *International Journal of Science Education*, 17 (6), 775 - 782.

Barman, C. R. & Mayer, D. A. (1994). An analysis of high school students' concepts & textbook presentations of food chains and food webs. *The American Biology Teacher*, 56 (3), 160 – 163.

Beck, C. R. (1984). Visual cueing strategies: Pictorial, textual and combination effects. *Educational Communication and Technology Journal*, 32, 207 - 216.

Bell, J. (1999). *Doing your research project: a guide for first-time researchers in education and social science* (3rd ed.), Open University Press, Buckingham.

Bell, P. (2001). Content analysis of visual images. In T. van Leeuwen & C. Jewitt (Eds.), *Handbook of Visual Analysis,* Sage Publications Ltd., London, pp.10 - 34.

Bennett, K. B. & Flach, J. M. (1992). Graphical displays: Implications for divided attention, focused attention, and problem solving. *Human Factors*, 34 (5), 513 - 533.

Ben-Zvi, R. & Hofstein, A. (1996). Strategies for remediating learning difficulties in chemistry. In D. F. Treagust, R. Duit, & B. Fraser (Eds.), *Improving teaching & learning in science and mathematics*, Teachers College Press, Columbia University, pp. 109 – 119.

Bisanz, J., Bisanz, G. L. & Korpan, C. A. (1994). Inductive reasoning. In R.J. Sternberg, (Ed.), *Thinking and problem solving: Handbook of perception and cognition* (2nd ed.), E. C. Carterette, & M. P. Friedman (Series eds.), Academic Press, USA, pp. 179 - 213.

Blackwell, A. F., & Engelhardt, Y. (2002). A meta-taxonomy for diagram research. In P. Olivier, M. Anderson & B. Meyer (Eds.), *Diagrammatic representation and reasoning*, Springer-Verlag, New York.
www.cl.cam.ac.uk/users/afb21/publications/yuri-chapter.html

Bodemer, D., Ploetzner, R., Feuerlein, I. & Hans, S. (2004). The active integration of information during learning with dynamic and interactive visualisations. *Learning and Instruction*, 14, 325 - 341.

Bowen, C. W. (1994). Think-aloud methods in chemistry education. *Journal of Chemical Education*, 71 (3), 184 - 190.

Brna, P. Cox, R. & Good, J. (2001). Learning to think and communicate with diagrams: 14 questions to consider. *Artificial Intelligence Review,* 15 (1 – 2), 115 – 134.

Brody, P. J. (1984). In search of instructional utility: A function-based approach to pictorial research. *Instructional Science*, 13, 47 - 61.

Bruner, J. (1960). *The process of education*, Harvard University Press, Cambridge, MA.

Bruner, J. (1986). *Actual minds, possible worlds*, Harvard University Press, Cambridge, MA.

Butcher, K.R. (2006). Learning from text with diagrams: promoting mental model development and inference generation. *Journal of Educational Psychology,* 98 (1) 182 – 197.

Buzan, T. (1991). *Use both sides of your brain* (3rd ed.), Plume Penguin Group, Great Britain.

Chandler, P. (2004). Commentary: The crucial role of cognitive processes in the design of dynamic visualizations. *Learning and Instruction*, 14, 353 - 357.

Chandler, P. & Sweller, J. (1991). Cognitive load theory and the format of instruction. *Cognition and Instruction*, 8 (4), 293 - 332.

Chauvet, F., Colin, P. & Viennot, L. (1999). Images in optics and corresponding learners' difficulties: awareness and decision-making in teachers. In M. Komorek, H. Behrendt, H. Dahncke, R. Duit, W. Graber & A. Kross (Eds.), *Proceedings of the Second International Conference of the European Science Education Research Association*, 31 August - 4 September, Kiel, Germany, Vol. 2, pp. 626 - 629.

Cheng, P. C. H, Lowe, R. K. & Scaife, M. (2001). Cognitive science approaches to understanding diagrammatic representations. *Artificial Intelligence Review,* 15, 79 - 94.

Chi, M. T. H., Feltovitch, P. J. & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science*, 5, 121 - 152.

Chittleborough, G. & Treagust, D. (2006). Students' understanding diagrams of laboratory equipment: valuable, variable, visualisation and misconceptions. *Proceedings of the NARST Annual Meeting*, San Francisco, CA, United States.

Clark, J. M. & Paivio, A. (1991). Dual coding theory and education. *Educational Psychology Review*, 3 (3), 149 - 210.

Claxton, G. (1993). Minitheories: a preliminary model for learning science. In P. J. Black & A. M. Lucas (Eds.), *Children's informal ideas in science*, Routledge, London, pp. 45 - 61.

Cohen, L., Manion, L. & Morrison, K. (2000). *Research Methods in Education* (5th ed.), Routledge, New York.

Colin, P., Chauvet, F. & Viennot, L. (2002). Reading images in optics: students' difficulties and teacher's views. *International Journal of Science Education*, 24 (3), 313 - 332.

Collier, M. (2001). Approaches to analysis in visual anthropology. In T. van Leeuwen & C. Jewitt (Eds.), *Handbook of visual analysis*, Sage, London.

Collins English Dictionary Complete and Unabridged (6th ed.) (2003). HarperCollins, Great Britain.

Constable, H., Campbell, B. & Brown, R. (1988). Sectional drawings from science textbooks: an experimental investigation into pupils' understanding. *British Journal of Educational Psychology,* 58, 89 - 102.

Cullen, J. (1990). Using concept maps in chemistry: An alternative view. *Journal of Research in Science Teaching*, 27 (1), 1067 - 1068.

Danserau, D. F., Collins, K. W., McDonald, B. A., Holley, C. D., Garland, J., Diekhoff, G. & Evans, S. H. (1979). Development and evaluation of a learning strategy training program. *Journal of Educational Psychology*, 71 (1) 64 - 73.

de Berg, K. C. & Treagust, D. F. (1993). The presentation of gas properties in chemistry textbooks and as reported by science teachers. *Journal of Research in Science Teaching*, 30 (8), 871 - 882.

Dean, R. S. & Kulhavy, R. W. (1981). Influence of spatial organisation in prose learning. *Journal of Educational Psychology*, 76, 57 - 61.

Degenaar, J. P., Scholtz, D. A., Thomas, A. M. L. & Kuhn, M. S. F. (1999). *Active Biology Standard 9* (2nd ed.), Kagiso Publishers, Pretoria, South Africa.

Degenaar, J. P., Scholtz, D. A., Thomas, A. M. L. & Kuhn, M. S. F. (2000). *Active Biology Standard 10* (7th ed.), Kagiso Publishers, Pretoria, South Africa.

De Jong, O. (2000). Crossing the borders: Chemical education research and teaching practice. *University Chemistry Education*, 4 (1), 29 - 32.

Driver, R. (1989). Students' conceptions and the learning of science. *International Journal of Science Education*, 11 (5), 481 - 490.

Driver, R. & Bell, B. (1986). Students' thinking and the learning of science: a constructivist view. *School Science Review*, March, 443 - 456.

Driver, R, Squires, A., Rushworth, P. & Wood-Robinson, V. (1994). *Making sense of secondary science: research into children's ideas.* Routledge, London.

Duchastel, P. C. (1978). Illustrating instructional text. *Educational Technology*, 18, 36 - 39.

Duit, R. & Treagust, D. F. (1995). Students' conceptions and constructivist teaching approaches. In B. J. Fraser & H. J. Walberg (Eds.), *Improving science education*, NSSE, USA, Chapter 3, pp. 46 - 69.

Duit, R. & Treagust, D. F. (2003). Conceptual change: a powerful framework for improving science teaching and learning. *International Journal of Science Education*, 25 (6), 671 - 688.

Duit, R., Treagust, D. F. & Mansfield, H. (1996). Investigating student understanding as a prerequisite to improving teaching and learning in science and mathematics. In D. F. Treagust, R. L. Duit & B. J. Fraser (Eds.), *Improving teaching and learning in Science and Mathematics*, Teachers College Press, USA, pp. 17 - 31.

Dutkiewicz, T. (1982). The symbolism of a chemical reaction and the teaching of biochemistry. *Biochemical Education*, 10 (1), 25.

Dwyer, F. M. (1970). Exploratory studies in the effectiveness of visual illustrations. *AV Communication review*, 18, 235 - 249.

Egan, D. E. & Schwartz, B. J. (1979). Chunking in Recall of Symbolic Drawings. *Memory & Cognition*, 7, 149 - 158.

Etlinge, E. M. & Roberts, C. W. (1993). Linguistic content analysis: A method to measure science as enquiry in textbooks. *Journal of research in Science teaching,* 30 (1), 65 - 83.

Evans, M. A., Watson, C. & Willows, D. M. (1987). A naturalistic inquiry into illustrations in instructional textbooks. In H. A. Houghton & D. M. Willows (Eds.), *Psychology of Illustration Vol. 2, Instructional Issues*, Springer-Verlag Inc., New York, pp. 86 - 115.

Ferk, V. & Vrtacnik, M. (2003). Students' understanding of molecular structure representations. *International Journal of Science education*, 25 (10), 1227 - 1245.

Finke, R. (1990). *Creative imagery discoveries and inventions in visualization.* Texas A. & M. University, Lawrence Erlbaum Associates Inc. Publishers, New Jersey.

Fisher, K. M. (1985). A misconception in biology: Amino acids and translation. *Journal of research in Science teaching*, 22 (1), 53 - 62.

Fisher, K. M. (1990). Semantic networking: The new kid on the block. *Journal of Research in Science Teaching,* 27 (10), 1001 - 1018.

Fisher, K. M., Wandersee, J. H. & Wideman, G. (2000). Enhancing cognitive skills for meaningful understanding of domain specific knowledge. In *Proceedings of the American Association for the Advancement of Science, Annual Meeting - Shaping the future learning of mathematics & science*, Washington, DC.

Fleming, M. L. (1967). Classification and analysis of instructional illustrations. *AV Communication Review,* 15, 246 - 256.

Fleming, M. L. (1977). The picture in your mind. *AV Communication Review,* 25, 43 - 62.

Fleming, M. L. (1979). On pictures in educational research. *Instructional Science,* 8, 235 - 251.

Fleming, M. L. (1987). Designing pictorial/verbal instruction: Some speculative extensions from research to practice. In H.A. Houghton & D.M. Willows (Eds.), *The Psychology of Illustration Volume 2: Instructional Issues*, Springer-Verlag Inc., New York, pp. 136 - 158.

Fletcher, T. J. (1971). Thinking with arrows. *Mathematics Teaching,* 57, 2 - 5.

Fredette, B. W. (1994). Use of visuals in schools (curriculum and instruction). In D. M. Moore & F. M. Dwyer (Eds.), *Visual Literacy: A spectrum of visual learning*, Educational technology publications, Englewood Cliffs, New Jersey, pp. 235 - 256.

Frisby, J. P. (1986). In I. Roth & J. P. Frisby, *Perception and representation: A cognitive approach, parts 1 & 2.* Open University Press, Milton Keynes, Philadelphia, USA, pp.19 - 134; 185 - 190.

Gall, M. D., Borg, W. R. & Gall, J. P. (1996). *Educational research: an introduction (6th* ed.), Longman, New York.

Garland, K. (1979). Some general characteristics present in diagrams denoting activity, events and relationship. *Information Design Journal*, 1, 15 - 22.

Garnett, P. J., Garnett, P. J. & Hackling, M. W. (1995). Students' alternative conceptions in chemistry: a review of research and implications for teaching and learning. *Studies in Science Education,* 25, 69 - 95.

Geva, E. (1983). Facilitating reading comprehension through flowcharting. *Reading Research Quarterly,* 18 (4), 384 - 405.

Gilbert, J. K., Osborne, R. J. & Fensham, P. J. (1982). Children's science and its consequences for teaching. *Science Education*, 66 (4), 623 - 633.

Gillespie, C. S. (1993). Reading graphic displays: What teachers should know. *Journal of Reading,* 36 (5), 350 - 354.

Glaser, R. (1992). Learning, cognition & education: Then & now. In H. L. Pick, P. van den Broek & D. C. Knill, *Cognition: Conceptual and methodological issues*, American Psychological Association, Washington, DC, pp. 239 - 265.

Glenberg, A. M. & Langston, W. E. (1992). Comprehension of illustrated text: Pictures help to build mental models. *Journal of Memory and Language,* 31, 129 - 151.

Gobert, J. & Discenna, J. (1997). The relationship between students' epistemologies and model-based reasoning. *Paper presented at the Annual Meeting of the American Educational Research Association*, Chicago: Illinois ED 409164.

Goldman, S. R. (2003). Learning in complex domains: when and why do multiple representations help? *Learning and Instruction*, 13, 239 - 244.

Goldsmith, E. (1987). The analysis of illustration in theory and practice. In H. A. Houghton & D. M. Willows (Eds.), *Psychology of Illustration, Volume 2, Instructional Issues*, Springer-Verlag, New York, pp. 51 - 85.

Gould, C. D. (1977). The readability of school biology textbooks. *Journal of Biological Education*, 11 (2), 248 - 252.

Grayson, D. J. (1996). A holistic approach to preparing disadvantaged students to succeed in tertiary science studies, part 1. Design of the Science Foundation Programme (SFP). *International Journal of Science Education*, 18 (8), 993 - 1013.

Grayson, D. J., Anderson, T. R. & Crossley, L. G. (2001). A four-level framework for identifying and classifying students conceptual and reasoning difficulties. *International Journal of Science Education*, 23, 611 - 622.

Gropper, G. L. (1963). Why is a picture worth a thousand words? *A.V. Communication*

Review, 11 (4), 75 - 95.

Gropper, G. L. (1970). The design of stimulus materials in response-oriented programs. *AV Communication Review,* 18 (3), 129 - 159.

Guri-Rozenblit, S. (1988a). The interrelationships between diagrammatic representations and verbal explanations in learning from social science texts. *Instructional Science,* 17, 219 - 234.

Guri-Rozenblit, S. (1988b). Impact of diagrams on recalling sequential elements in expository texts. *Reading Psychology,* 9 (2), 121 - 139.

Hardin, P. (1993). A theoretical framework for diagrams and information graphics in research and education, visual literacy in the digital age. *Selected readings from the 25th annual conference of the International Visual Literacy Association, October 13 - 17,* pp. 20 - 25.

Hardin, P. (1995). Arrows: a special case of graphic communication. In *Eyes on the future: converging images, ideas, and instruction, Selected readings from the Annual Conference of the International Visual Literacy Association, October 18 – 22,* pp. 343 - 350.

Haslam, F. & Treagust, D. F. (1987). Diagnosing secondary students' misconceptions of photosynthesis and respiration in plants using a two tier multiple-choice instrument. *Journal of Biological Education,* 21 (3), 203 - 211.

Hegarty, M. (1992). Mental animation: inferring motion from static displays of mechanical systems. *Journal of Experimental Psychology: Learning, Memory and Cognition,* 18 (5), 1084 - 1102.

Hegarty, M. (2004). Commentary on: Dynamic visualizations and learning: getting to the difficult questions. *Learning and Instruction,* 14, 343 - 351.

Hegarty, M., Just, M. A. & Morrison, I. R. (1988). Mental models of mechanical systems: Individual differences in qualitative and quantitative reasoning. *Cognitive Psychology,* 20, 191 - 236.

Heiser, J. & Tversky, B. (2006). Arrows in comprehending and producing mechanical diagrams. *Cognitive Science,* 30, 581- 592.

Henderson, G. (1999). Learning with diagrams. *Australian Science Teachers' Association,* 15 (2), 17 - 25.

Hewson, P. W. (1981). A conceptual change approach to learning Science. *European Journal of Science Education,* 3 (4), 383 - 396.

Hill, D. M. (1988). Difficulties with diagrams. *Journal of Science and Mathematics in S. E. Asia,* 11 (2), 32 - 40.

Hofstein, A. & Walberg, H. J. (1995). Instructional strategies. In B. J. Fraser & H. H. J. Walberg (Eds.), *Improving Science Education*, NSSE, USA, pp. 70 - 89.

Holliday, W. G. (1976). Teaching verbal chains using flow diagrams and text. *A V Communication Review*, 24, 63 - 78.

Holliday, W. G. (1990). Textbook illustrations: fact or filler? *The Science Teacher*, *57* (9), 27 - 29.

Holliday, W. G., Brunner, L. L. & Donais, E. L. (1977). Differential cognitive and affective responses to flow diagrams. *Science Journal of Research in Science Teaching,* 14 (2), 129 - 138.

Horn, R. E. (1998). *Visual language: Global communication for the 21st century*. MacroVu Inc., Bainbridge Island, WA.

Hortin, J. A. (1994). Theoretical foundations of visual learning. In D. M. Moore & F. M. Dwyer (Eds.), *Visual Literacy: A spectrum of visual learning*, Educational technology publications, Englewood Cliffs, New Jersey, pp. 5 - 30.

Hull, T. L., Anderson, T. R. & Grayson, D. J. (2002). Student difficulties with a diagram of the complement pathways in the immune system. In C. Malcolm & C. Lubisi (Eds.), *Proceedings of the Tenth Annual Conference of the Southern African Association for Research in Mathematics, Science and Technology Education*, pp. III-129 -134.

Hull, T. L. (2003). Students' use of diagrams for the visualisation of biochemical processes. *Unpublished MSc. Thesis*, University of Natal, South Africa.

Hunter, B., Crismore, A. & Pearson, P. D. (1987). Visual displays in basal readers and social studies textbooks. In H. A. Houghton & D. M. Willows (Eds.), *Psychology of Illustration, Volume 2 Instructional Issue*, New York, Springer-Verlag, pp.117 - 135.

Ingham, A. M. (1991). The use of analogue models by students of chemistry at higher education level. *International Journal of Science Education*, 13 (2), 193 - 202.

Ittelson, W. (1996). Visual perception of markings. *Psychonomic Bulletin & Review*, 3 (2), 171 - 187.

Jacobs, J. K., Kawanaka, T. & Stigler, J. W. (1999). Integrating qualitative and quantitative approaches to the analysis of video data on classroom teaching. *International Journal of educational research*, 31, 717 - 724.

Jiminez-Valladares, J. de Dios & Perales-Palacios, F. J. (2001). Graphic representation of force in secondary education: analysis and alternative educational proposals. *Physics Education*, 36, 227 - 235.

Johnson, P. & Gott, R. (1996). Constructivism and evidence from children's ideas. *Science*

Education, 80 (5), 561 - 577.

Johnson-Laird, P. N. (1983). *Mental models: Towards a cognitive science of language, inference, and consciousness.* Cambridge University Press, Cambridge.

Johnston, K. S. (1985). Biology textbook special. *Science books and films*, 20 (5), 245 - 286.

Johnstone, A. H. (1993). The development of chemistry teaching. *Journal of Chemical Education*, 70 (9), 701 - 705.

Johnstone, A. H. (2000). The nature of chemistry. *Education in Chemistry*, 36 (2), 45 - 47.

Jonassen, D. & Hawk, P. (1984). Using graphic organizers in instruction information. *Design Journal*, 4, 58 - 68.

Justi, R. & Gilbert, J. (2002). Modelling, teachers' views on the nature of modelling, implications for the education of modellers. *International Journal of Science Education*, 24 (4), 369 - 387.

Kamman, R. (1975). The comprehensibility of printed instructions and the flowchart alternative. *Human Factors*, 17 (2), 183 - 191.

Kindfield, A. C. H. (1993/1994). Biology Diagrams: Tools to Think With. *The Journal of the Learning Sciences*, 3 (1), 1 - 36.

Kirby, J. R. & Cantwell, R. H. (1985). Use of advance organizers to facilitate higher level text comprehension. *Human Learning*, 4, 159 - 168.

Kirschner, P. A. (2002). Cognitive load theory: implications of cognitive load theory on the design of learning. *Learning and Instruction*, 12, 1 - 10.

Koedinger, K. R. & Anderson, J. R. (1990). Abstract planning and perceptual chunks: elements of expertise in geometry. *Cognitive Science*, 14, 511 - 550.

Kosslyn, S. M. (1985). Graphics and human information processing: a review of five books. *Journal of American Statistical Association,* 80 (391), 499 – 512.

Kosslyn, S. M. (1987). Seeing and imagining in the cerebral hemispheres: a computational approach. *Psychological Review*, 94 (2), 148 - 175.

Kosslyn, S. M. (1989). Understanding charts and graphs. *Applied Cognitive Psychology*, 3, 185 - 226.

Kosslyn, S. M. (1994). Image and brain. The MIT Press Cambridge, Masachusetts & London, England.

Kozma, R. B. (1991). Learning with media. *Review of educational research,* 61 (2), 179 - 211.

Kozma, R. (2003). The material features of multiple representations and their cognitive and social affordances for science education. *Learning and Instruction*, 13, 205 - 226.

Krampen, M. (1965). Signs and symbols in graphic communication. *Design quarterly*, 62, 3 - 31.

Kress, G. & van Leeuwen, T. (1996). Reading images. *The grammar of visual design*, Routledge, London.

Krishnan, S. R. & Howe, A. C. (1994). The Mole concept. *Journal of Chemical Education*, 71 (8), 653 - 655.

Kuiper, J. (1994). Student ideas of science concepts: alternative frameworks? *International Journal of Science Education*, 16 (3), 279 - 292.

Larkin, J. H. & Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words? *Cognitive Science*, 11, 65 - 99.

Lazarowitz, R. & Penso, S. (1992). High school students' difficulties in learning biology concepts. *Journal of Biological Education*, 26 (3), 215 - 223.

Leonard, W. H. & Penick, J. E. (1993). What's important in selecting a textbook? *The American Biology Teacher*, 55 (1), 14 - 19.

Levie, W. H. & Lentz, R. (1982). Effects of text illustrations: A review of research. *Educational Communication and Technology Journal*, 30 (4), 195 - 232.

Levin, J. R. & Mayer, R. E. (1993). Understanding illustrations in text. In A. Woodward, M. R. Binkley & B. K. Britton (Eds.), *Learning from textbooks: theory and practice*, Hillsdale, New Jersey, pp. 95 - 114.

Lewalter, D. (2003). Cognitive strategies for learning from static and dynamic visuals. *Learning and Instruction*, 13, 177 - 189.

Lincoln, Y. S. & Guba, E. G. (1985). *Naturalistic inquiry*, Sage Publications Inc., Newbury Park.

Lohse, G., Walker, N., Biolsi, K. & Rueter, H. (1991). Classifying graphical information. *Behaviour & Information Technology*, 10 (5), 419 - 436.

Lord, T. R. (1985). Enhancing the visuo-spatial aptitude of students. *Journal of research in science teaching*, 22 (5), 395 - 405.

Lord, T. R. (1990). Enhancing learning in the life sciences through spatial perception. *Innovative Higher Education*, 15 (1), 5 - 16.

Lowe, R. (1986). The scientific diagram: Is it worth a thousand words? *The Australian Science Teachers' Journal*, 32 (3), 7 - 13.

Lowe, R. K. (1987a). Drawing out ideas. A neglected role for scientific diagrams. *Research in Science Education*, 17, 56 - 66.

Lowe, R. K. (1987b). Mental representation and diagram interpretation. *Australian Education Researcher*, 15 (1), 37 - 50.

Lowe, R. (1988a). Drawing comparisons: School science and professional science. *The Australian Science Teachers' Journal*, 33 (4), 32 - 39.

Lowe, R. K. (1988b). "Reading" scientific diagrams: Characterising components of skilled performance. *Research in Science Education*, 18, 112 - 122.

Lowe, R. K. (1988c). Diagram construction and the improvement of science. *Journal of Science and Mathematics Education in S. E. Asia*, 11 (2), 22 - 30.

Lowe, R. K. (1989). Search strategies and inference in the exploration of scientific diagrams. *Educational Psychology*, 9 (1), 27 - 44.

Lowe, R. (1991). Expository illustrations: A new challenge for reading instruction. *Australian Journal of Reading*, 14, 215 - 226.

Lowe, R. K. (1993a). Constructing a Mental Representation from an abstract technical diagram. *Learning and Instruction*, 3, 157 - 179.

Lowe, R. (1993b). *Successful instructional diagrams,* Kogan Page Ltd., London, United Kingdom.

Lowe, R. K. (1993c). Diagrammatic information: techniques for exploring its mental representation and processing. *Information Design Journal*, 7 (1), 3 - 17.

Lowe, R. K. (1994a). Selectivity in diagrams: Reading beyond the lines. *Educational Psychology,* 14 (4), 467 - 491.

Lowe, R. K. (1994b). Diagram prediction and higher order structures in mental representation. *Research in Science Education*, 24, 208 - 216.

Lowe, R. K. (1996). Background knowledge and the construction of a situational representation from a diagram. *European Journal of Psychology of Education,* 11 (4), 377 - 397.

Lowe, R. (1997). How much are pictures worth? Putting you in the picture. *Proceedings of Workshop,* 15 – 16 July, Uniserve, Australia.

Lowe, R. K. (1999). Extracting information from an animation during complex visual learning. *European Journal of Psychology of Education*, 14, 225 - 244.

Lowe, R. (2000). Visual literacy and learning in science. *ERIC Digest*, *ED463945*, www.ericfacility.net/ericdigests/ed463945.html

Lowe, R. K. (2003). Animation and learning: selective processing of information in dynamic graphics. *Learning and Instruction*, 13, 157 - 176.

Lowe, R. (2004). Interrogation of a dynamic visualization during learning. *Learning* *and Instruction*, 14, 257 - 274.

MacEachren, A. M. (1995). *How maps work. Representation, Visualization, and Design,* The Guildford Press, New York.

Mathewson, J. H. (2005). The visual core of science: definition and applications to education. *International Journal of Science Education*, 27 (5), 529 - 548.

Mayer, R. E. (1989). Systematic thinking fostered by illustrations in scientific text. *Journal of Educational Psychology*, 81, 240 - 246.

Mayer, R. E. (1993). Commentary on comprehension of graphics in texts: An overview. *Learning and Instruction*, 3, 239 - 245.

Mayer, R. E. (1997). Multimedia learning: are we asking the right questions? *Educational Psychologist*, 32 (1), 1 - 19.

Mayer, R. E. (2003). The promise of multimedia learning: using the same instruction design methods across different media. *Learning and Instruction*, 13, 125 - 139.

Mayer, R. E. & Anderson, R. B. (1992). The instructive animation: Helping students build connections between words and pictures in multimedia learning. *Journal of Educational Psychology*, 84 (4), 444 - 452.

Mayer, R. E., Bove, W., Bryman, A., Mars, R. & Tapangco, L. (1996). When is less more: Meaningful learning from visual and verbal summaries of science textbook lessons. *Journal of Educational Psychology*, 88 (1), 64 - 73.

Mayer, R. E. & Gallini, J. K. (1990). When is an illustration worth ten thousand words? *Educational Psychology*, 82, 715 - 726.

Mayer, R. E., Steinhoff, K., Bower, G. & Mars, R. (1995). A generative theory of textbook design: Using annotated illustrations to foster meaningful learning of science text. *Educational Technology Research and Development*, 43 (1), 31 - 43.

McMillan, J. H. & Schumacher, S. (1993). *Research in Education: A conceptual introduction* (3rd ed.), Harper Collins, New York.

McNamara, T. P. (1994). Knowledge representation. In R. J. Sternberg (Ed.), *Thinking and Problem solving, Handbook of Perception and Cognition* (2nd ed.), E. C. Carterette & M. P. Friedman (Series eds.), Academic Press, USA, pp. 81 - 117.

Messaris, P. (1994). *Visual "literacy". Image, mind, and reality.* Westview Press Inc., U.S.A.

Moore, D. M. (1994). Action and object language. In D. M. Moore, & F. M. Dwyer (Eds.), *Visual Literacy: A spectrum of visual learning*, Educational technology publications, Englewood Cliffs, New Jersey, pp. 145 - 162.

Moore, P. J., Chan, L. K. S. & Wing, K. A. (1993). High school students' use of diagrams during reading. *Research in Reading,* 16 (1), 57 - 71.

Nakleh, M. B. & Krajicik, J. S. (1996). Reply to Daniel S. Domin's Comment on Concept Mapping and Representational Systems. *Journal of Research in Science Teaching*, 33 (8), 937 - 938.

Navon, D. (1977). Forest before trees: The precedence of global features in visual perception. *Cognitive Psychology*, 9, 353 - 383.

Nickerson, R. S. (1994). The teaching of thinking and problem solving. In R. J. Sternberg, (Ed.), *Thinking and Problem solving, Handbook of Perception and Cognition* (2nd ed.), E. C. Carterette & M. P. Friedman (Series eds.), Academic Press, USA, pp. 409 - 449.

Novak, J. D. (1990). Concept mapping: A useful tool for science education. *Journal of Research in Science Teaching*, 27 (10), 937 - 949.

Novak, J. D. (1996). Concept mapping: A tool for improving science teaching and learning. In D. F. Treagust, R. Duit & B. J. Fraser (Eds.), *Improving Teaching and Learning in Science and Mathematics*, Teachers' College Press, New York, pp. 32 - 43.

Odom, A. L. & Barrow, L. H. (1995). Development and application of a two-tier diagnostic test measuring college biology students' understanding of diffusion and osmosis after a course of instruction. *Journal of Research in Science Teaching*, 32 (1), 45 - 61.

Ogborn, J. (1993). A view of 'understanding'. In P.J. Black & A. M. Lucas, (Eds.), *Children's informal ideas in science*, Routledge, London & New York, pp. 102 - 119.

Paivio, A. (1986). *Mental representations: A dual coding approach.* Oxford University Press, Great Britain.

Pallrand, G. J. & Seeber, F. (1984). Spatial ability and achievement in introductory physics. *Journal of research in Science Teaching*, 21 (5), 507 - 516.

Paquette, G., Leonard, M., Lundgren-Cayrol, K., Mihaila, S. & Gareau, D. (2006). Learning design based on graphical knowledge-modelling. *Educational Technology and Society,* 9 (1), 97 – 112.

Pendley, B. D., Bretz, R. L. & Novak, J. D. (1994). Concept maps as a tool to assess learning in chemistry. *Journal of Chemical Education*, 71 (1), 9 - 15.

Perini, L. (2005). Explanation in two dimensions: diagrams and biological explanation. *Biology and Philosophy*, 20, 257 - 269.

Petre, M. & Green, T. R. G. (1993). Learning to read graphics: some evidence that 'seeing' an information display is an acquired skill. *Journal of Visual Languages and Computing*, 4, 55 - 70.

Peuckert, J. & Fischler, H. (1999). *Concept maps as a tool for investigating and analysing the development of students' conceptions*. ESERA, Kiel, Germany.

Pfundt, H. & Duit, R. (1994). *Bibliography: Students' alternative frameworks and science education* (4th ed.), Kiel, Germany.

Phelps, A. J. (1994). Qualitative methodologies in chemical education research. *Journal of Chemical Education*, 71 (3), 191 - 194.

Phillips, T. I. & Quinn, J. (1993). The effects of alternative flowcharting techniques on performance of procedural tasks. *Performance Improvement Quarterly*, 6 (1), 54 - 66.

Pinto, R. & Ametller, J. (2002). Students' difficulties in reading images. Comparing results from four national research groups. *International Journal of Science Education*, 24 (3), 333 - 341.

Pinto, R., Ametller, J., Chauvet, F., Colin, P., Giberti, G., Monroy, G., Ogborn, J., Ormerod, F., Sassi, E., Stylianidou, F., Testa, I. & Viennot, L. (2000). Investigation on the difficulties in teaching and learning graphic representations and on their use in science classrooms. *Transversal report WP2 (Work Package 2), Science Teacher Training in an Information Society (STTIS) project.* Retrieved April 15th, 2003 from http://www.blues.uab.es~idmc42/document/index.html

Pinto, A. J. & Howard, J. Z. (1997). Concept mapping: a strategy for promoting meaningful learning in medical education. *Medical Teacher*, 19 (2), 114-121.

Plotnick, E. (1997). Concept mapping: A graphical system for understanding the relationship between concepts. ED 407938.

Posner, G. J. & Gertzog, W. A. (1982). The clinical interview and the measurement of conceptual change. *Science Education*, 66 (2), 195 - 209.

Rasco, R. V., Tennyson, R. D. & Boutwell, R. C. (1975). Imagery instructions and drawings in learning prose. *Journal of Educational Psychology*, 67, 188 - 192.

Reed, S. K. (1988). *Cognition: Theory and applications* (2nd ed.), Brooks/Cole Publishing Company, California, U.S.A.

Reid, D. J. (1984). The picture superiority effect and biological education. *Journal of Biological Education*, 18 (1), 29 - 36.

Reid, D. (1990a). The role of pictures in learning biology: Part 1, perception and observation. *Journal of Biological Education*, 24 (3), 161- 172.

Reid, D. (1990b). The role of pictures in learning biology: Part 2, picture-text processing. *Journal of Biological Education*, 24 (4), 251 - 258.

Reid, D. J. & Beveridge, M. (1986). Effects of text illustration on children's learning of a school science topic. *British Journal of Educational Psychology*, 56, 294 - 303.

Reid, D. J. & Beveridge, M. (1990). Reading illustrated science texts: A micro-computer based investigation of children's strategies. *British Journal of Educational Psychology*, 60, 76 - 87.

Reid, D. J., Beveridge, M. & Wakefield, P. (1986). The affect of ability, colour and form on children's perceptions of biological pictures. *Educational Psychology*, 6 (1), 9 - 18.

Reid, D. J., Briggs, N. & Beveridge, M. (1983). The effect of picture upon the readability of a school science topic. *British Journal of Educational Psychology*, 53, 327 - 335.

Reid, D. J. & Miller, G. J. A. (1980). Pupils' perceptions of biological pictures and its implications for readability studies of biological textbooks. *Biological Education*, 14 (1), 59 - 69.

Reimann, P. (2003). Multimedia learning: beyond modality. *Learning and Instruction*, 13, 245 - 252.

Remington, R. & Williams, D. (1986). On selection and evaluation of visual display symbology: Factors influencing search and identification ties. *Human Factors*, 28 (4), 407 - 420.

Rigney, J. W. & Lutz, K. A. (1976). Effect of graphic analogies of concepts in chemistry on learning and attitude. *Journal of Educational Psychology*, 68, 305 - 311.

Roberts, M., Reiss, M. & Monger, R. (1993). *Biology Principles and Processes*. Thomas Nelson and Sons, Ltd, United Kingdom.

Rochford, K., Fairall, A. P., Irvings, A. & Hurly, P. (1989). Academic failure and spatial visualization handicap of undergraduate engineering students. *International Journal of Applied Engineering Education*, 5 (6), 741 - 749.

Rock, I. & Palmer, S. (1990). The legacy of Gestalt Psychology. *Scientific American*, 263 (6), 84 - 90.

Rogan, J. (2005). *Course readings: Short course on quantitative research methods in Science Education*, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Roth, I. (1986). In I. Roth & J. P. Frisby, *Perception and representation: A cognitive approach (parts 1 and 2)*, Open University Press, Milton Keynes, Philadelphia, USA, pp. 19 – 134, 185 - 190.

Roth, I. & Frisby, J. P. (1986). *Perception and representation: A cognitive approach (parts 1 and 2)*, Open University Press, Milton Keynes, Philadelphia, USA.

Roth, W-M. (2002). Reading graphics: contributions to an integrative concept of literacy. *Journal of Curriculum Studies*, 34 (1), 1 - 24.

Royer, J. M. & Cable, G. W. (1976). Illustrations, analogies and facilitative transfer in prose learning. *Journal of Educational Psychology*, 68, 205 - 209.

Salomon, G. (1984). Television is easy and print is tough: the differential investment of mental effort in learning as a function of perceptions and attributions. *Journal of Educational Psychology*, 76, 647 - 658.

Sanders, M. (1993). A framework for improving the quality of quantitative research in science education. *Paper presented at the annual conference of the National Association for Research in Science Teaching*, 15 -19 April, Atlanta, Georgia, USA.

Sanders, M. (1995). The nature and remediation of spatial problems associated with interpreting diagrams of biological sections. *Volume 1 of thesis submitted to the Faculty of Education*, University of Cape Town, March 1995.

Sanders, M. (2002). Secondary school biology learners' difficulties in interpreting diagrams of biological sections. In C. Malcolm and C. Lubisi (Eds.), *Proceedings of the Tenth Annual Conference of the Southern African Association for Research in Mathematics, Science and Technology Education*, pp. II-85 - 94.

Sanders, M. & Khanyane, M. (2002). The interpretation of biology textbook illustrations by grade 10 learners. In C. Malcolm & C. Lubisi (Eds.), *Proceedings of the 10th Annual Conference of the Southern African Association for Research in Mathematics, Science and Technology Education*, 22 – 26 January, in Durban, South Africa, pp. III – 364 – 370.

Sanders, M. & Mokuku, T. (1993). How valid is face validity? *Paper presented at the Second Annual Meeting of the Southern African Association for Research and Development in Mathematics and Science Education,* Durban, 27 - 30 January.

Sandmann, A., Mackensen, I. & Lind, G. (2002). How "experts" learn biology. *Paper presented at the ERIDOB Conference,* 22nd – 26th October, Toulouse, France.

Sanger, M. J. & Greenbowe, T. J. (1999). An analysis of college chemistry textbooks as sources of misconceptions and errors in electrochemistry. *Journal of Chemistry Education*, 76 (6), 853 - 860.

Scaife, M. & Rogers, Y. (1996). External cognition: how do graphical representations work? *International Journal of Human-Computer Studies*, 45, 185 - 213.

Schnotz, W. (1993). Introduction: External and internal representations in multimedia learning. *Learning and Instruction*, 3, 151 - 155.

Schnotz, W. & Bannert, M. (2003). Construction and interference in learning from multiple representation. *Learning and Instruction*, 13, 141 - 156.

Schnotz, W. & Lowe, R. (2003). External and internal representations in multimedia learning. *Learning and Instruction*, 13, 117 - 123.

Schollum, B. (1983). Arrows in Science diagrams: Help or hindrance for pupils. *Research in Science Education*, 13, 45 - 59.

Schönborn, K. J. (2005). Using student difficulties to identify and model factors influencing the ability to interpret external representations of IgG-Antigen binding. *Unpublished Ph.D. Thesis,* University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Schönborn, K. J. & Anderson, T. R. (2003). Biochemistry students' difficulties with chemical coupling. *Proceedings of the 11th Annual Meeting of the Southern African Association for Research in Mathematics, Science and Technology Education,* University of Swaziland, Swaziland, 11 - 15 January, pp. 777 - 783.

Schönborn, K. J. & Anderson, T. R. (2004). Conceptual and visualization difficulties with the interpretation of diagrams and images in biochemistry. *Federation of American Societies of Experimental Biology (FASEB) Journal*, 18 (8), C207.

Schönborn, K. J., Anderson, T. R. & Grayson, D. J. (2002a). Student difficulties with the interpretation of textbook diagrams of immunoglobulin G (IgG). *Biochemistry and Molecular Biology Education*, 30 (2), 93 - 97.

Schönborn, K. J., Anderson, T. R. & Grayson, D. J. (2002b). Developing and testing a model of the factors affecting student interaction with scientific diagrams. In C. Malcolm and C. Lubisi (Eds.), *Proceedings of the 10th Annual Meeting of the Southern African Association for Research in Mathematics, Science and Technology Education*, University of Natal, Durban, 22 - 26 January, 2002, Section III, pp. 377 - 383.

Seels, B. A. (1994). The definition problem. In D. M. Moore & F. M. Dwyer (Eds.), *Visual Literacy: A spectrum of visual learning*, Educational technology publications, Englewood cliffs, New Jersey, pp. 97 - 112.

Serpell, R. & Boykin, A. W. (1994). Cultural dimensions of cognition: A multiplex, dynamic system of constraints and possibilities. In R. J. Sternberg (Ed.), *Thinking and Problem solving, Handbook of Perception and Cognition* (2nd ed.), E. C. Carterette & M. P. Friedman (Series eds.), Academic Press, USA, pp. 369 - 408.

Seufert, T. (2003). Supporting coherence formation in learning from multiple representations. *Learning and Instruction*, 13 (2), 227 - 237.

Sewell, E. H. Jr (1994). Visual Symbols. In D. M. Moore & F. M. Dwyer (Eds.), *Visual Literacy: A spectrum of visual learning*, Educational technology publications, Englewood Cliffs, New Jersey, pp. 135 - 144.

Sless, D. (1984). Visual literacy: A failed opportunity. *Educational Communication and*

Technology Journal, 32, 224 - 228.

Smith, S. L. (1979). Letter size and legibility. *Human Factors*, 21b, 661 - 670.

Songer, C. J. & Mintzes, J. J. (1994). Understanding cellular respiration: An analysis of conceptual change in college biology. *Journal of Research in Science Teaching*, 31 (6), 621 - 637.

South African Concise Oxford Dictionary (2002). *Dictionary Unit for South African English* (Eds.), Oxford University Press, Cape Town, South Africa.

Staver, J. R. & Lumpe, A.T. (1993). A content analysis of the presentation of the mole concept in chemistry textbooks. *Journal of Research in Science Teaching*, 30 (4), 321 - 337.

Stenning, K. & Lemon, O. (2001). Aligning logical and psychological perspectives on diagrammatic reasoning. *Artificial Intelligence Review*, 15 (1 - 2), 29 - 62.

Stern, R. C. & Robinson, R. S. (1994). Perception and its role in communication and learning. Theoretical foundations of visual learning. In D. M. Moore & F. M. Dwyer, (Eds.), *Visual Literacy: A spectrum of visual learning*, Educational technology publications, Englewood cliffs, New Jersey, pp. 31 - 52.

Sterner, R. T. (1998). The Scientific Method: An instructor's flow chart. *The American Biology Teacher*, 60 (5), 374 - 378.

Storey, R. D. (1990). Textbook errors and misconceptions in biology: Cell structure. *The American Biology Teacher*, 52 (4), 213 - 217.

Storey, R. (1991). Textbook errors and misconceptions in biology: Cell metabolism. *The American Biology Teacher*, 53, 339 - 343.

Stylianidou, F., Ormerod, F. & Ogborn, J. (2002). Analysis of science textbook pictures about energy and pupils' reading of them. *International Journal of Science Education*, 24 (3), 257 - 283.

Sweller, J. & Chandler, P. (1994). Why some material is difficult to learn. *Cognition and Instruction*, 12 (3), 185 - 233.

Szlichcinski, K. P. (1979). Diagrams and illustrations as aids to problem solving. *Instructional Science,* 8, 253 - 274.

Taconis, R., Ferguson-Hessler, M. G. M. & Broekkamp, H. (2001). Teaching science problem solving: An overview of experimental work. *Journal of Research on Science Teaching*, 38 (4), 442 - 468.

Tamir, P. (1989). Some issues related to the use of justifications to multiple-choice answers. *Journal of Biological Education*, 23 (4), 285 - 292.

Thompson, M. E. (1994). Design considerations of visuals. In D. M. Moore & F. M. Dwyer (Eds.), *Visual Literacy: A spectrum of visual learning*, Educational technology publications, Englewood cliffs, New Jersey, pp.165 - 182.

Thorndyke, P. W. & Stasz, C. (1980). Individual differences in procedures for knowledge acquisition from maps. *Cognitive Psychology*, 12, 137 - 175.

Treagust, D. F. (1988). Development and use of diagnostic tests to evaluate students' misconceptions in science. *International Journal of Science Education*, 10 (2), 159 -169.

Treagust, D. F. (1995). Diagnostic assessment of students' science knowledge. In S. M. Glynn & R. Duit (Eds.), *Learning Science in the schools: research reforming practice*, Lawrence Erlbaum Mahwah, New Jersey, pp. 327 - 346.

Treagust, D. F., Chittleborough, G. & Mamiala, T. L. (2002). Students' understanding of the role of scientific models in learning science. *International Journal of Science Education*, 24 (4), 357 - 368.

Treagust, D. F., Duit, R. L. & Fraser, B. J. (1996). Overview: Research on students' preinstructional conceptions – the driving force for improving teaching and learning in Science and Mathematics. In D. F. Treagust, R. L. Duit & B. J. Fraser (Eds.), *Improving Teaching and Learning in Science and Mathematics*, U.S.A.: Teachers' College Press, New York, pp. 1 - 14.

Tuckey, H, Salvaratnam, M. & Bradley, J. (1991). Identification and rectification of student difficulties concerning three-dimensional structures, rotation, and reflection. *Journal of chemical education*, 68 (6), 460 - 464.

Tversky, B. & Morrison, J. B. (2002). Animation: can it facilitate? *International Journal of Human-Computer Studies*, 57, 247 – 262.

Tversky, B., Zacks, J., Lee, P. U. & Heiser, J. (2000). Lines, blobs, crosses and arrows: Diagrammatic communication with schematic figures. In M. Anderson, P. Cheng & V. Haarslev (Eds.), Theory and application of diagrams, *Proceedings of First International Conference, Diagrams 2000, held in Edinburgh, Scotland, United Kingdom*, Springer-Verlag, Berlin, Germany, pp. 221 – 230.

Van Dusen, L. M., Spach, J. D., Brown, B. & Hansen, M. (1999). Trio: A new measure of visual processing ability. *Educational Psychological*, 59 (6), 1030 - 1046.

Van Leeuwen, T. & Jewitt, C. (2001). Introduction. In T. van Leeuwen & C. Jewitt (Eds.), *Handbook of visual analysis*, Sage Publications, London.

von Glasersfeld, E. (1992). A constructivist's view of teaching and learning. In R. Duit, F.

Goldberg & H. Niedderer (Eds.), *Reset in physics learning: theoretical issues and empirical studies*, Kiel Germany, Institute for Science Education, University of Kiel, pp. 29 - 39, cited in Treagust *et al.* (1996).

von Glasersfeld, E. (1993). Questions and answers about radical constructivism. In K. Tobin (Ed.), *The practice of constructivism in science education*, American association for the advancement of science, Washington D. C., pp. 23 - 38, cited by Treagust *et al.* (1996).

von Glasersfeld, E. (1995). A constructivist approach to teaching. In L. Steffe & J. Gale (Eds.), *Constructivism in education*, Hillsdale, Erlbaum, New Jersey, pp. 3 - 15, cited in Treagust *et al.* (1996).

Wallace, J. D. & Mintzes, J. J. (1990). The concept map as a research tool: Exploring conceptual change in biology. *Journal of Research in Science Teaching*, 27 (10), 1033 - 1052.

Waller, R. (1981). Understanding network diagrams. *Paper presented at the Annual meeting of the American Educational Research Association*: ED 226695.

Ward, R. E. & Wandersee, J. H. (2002). Struggling to understand abstract science topics: a Roundhouse diagram-based study. *International Journal of Science Education,* 24 (6), 575 - 591.

Wheeler, A. E. & Hill, D. (1990). Diagram-ease: Why students misinterpret diagrams. *The Science Teacher*, 57 (5), 59 - 63.

White, R. & Gunstone, R. (1993). *Probing understanding* (2nd ed.), Falmer Press, Great Britain, pp. 15 - 43.

Willows, D. M., Borwick, D. & Hayvren, M. (1981). The content of school readers. In G. E. MacKinnon & T. G. Waller (Eds.), *Reading research: Advances in theory and practice Vol. 2,* Academic Press, New York, pp. 97 – 175, cited in Evans (1987).

Winberg, C. (1997). In H. Calitz (Ed.), *How to Research and Evaluate*, The Teaching and Learning Series, Juta & Company Ltd, Cape Town, South Africa, pp. 14 - 29.

Winn, W. (1991). Learning from maps and diagrams. *Educational Psychology Review*, (3), 211 - 247.

Winn, W. (1993). An account of how readers search for information in diagrams. *Contemporary Educational Psychology*, 18, 162 - 185.

Winn, W. D. & Holliday, W. G. (1981). Learning from diagrams: theoretical and instructional considerations. *Paper presented at the Annual Convention of the Association for educational Communications and Technology*, Philadelphia, United States of America.

Winn, W. D., Li, T. Z. & Schill, D. E. (1991). Diagrams as aids to problem solving: Their role in facilitating search and computation. *Educational Technology Research and Development*, 39, 17 - 30.

Winn, W. & Solomon, C. (1993). The effect of the spatial arrangement of the diagrams on the interpretation of English and nonsense sentences. *Educational Technology Research and Development*, 41 (1), 29 - 41.

Winn, W. & Sutherland, S. W. (1989). Factors influencing the recall of elements in maps and diagrams and the strategies used to encode them. *Journal of Educational Psychology*, 81 (1), 33 - 39.

Wright, D. (1989). *Human Biology*. Oxford: Heinemann Educational, Great Britain, p. 55.

Yager, R. E. (1991). The constructivist learning model. Towards real reform in science education. *The Science Teacher*, 58 (6), 52 - 57.

Yair, Y., Schur, Y. & Mintz, R. (2003). A "thinking journey" to the planets using scientific visualisation technologies: implications to astronomy education. *Journal of Science Education and Technology,* 12 (1), 43 - 49.

Zhang, J. & Norman, D. A. (1994). Representations in distributed cognitive tasks. *Cognitive Science*, 18, 87 - 122.

APPENDIX 1

Explanatory information including the design questions; propositional statements; and other relevant notes are provided in frames and brackets. This information was not supplied to students.

APPENDIX 1.1

Probe set 1a of cardiac cycle (Figure 6.2)

This is a semi-guided probe, focussing on specific areas of the diagram without guiding student responses.

Question 1

USING DIAGRAM A: Explain what is happening in this diagram. Note features shown in the diagram to account for your reasoning.

Propositional statements: Column 1 provides the concept about the cardiac cycle. Column 2 provides the reasoning strategy used to interpret the concept from the graphical features of the diagram.

CONCEPTS	GRAPHICAL FEATURES USED TO INTERPRET THE DIAGRAM
Atrium contracts	inward arrows or smaller atrium
Veins close	v shape or arrow not through wall
Pressure on blood or chamber	Arrows
Blood flow to ventricle	arrow through opening or valve
Both sides simultaneous	repetition of arrow
Ventricle relaxed	no arrows, larger size
Blood entering (alternate conception)	

The answers are separated into two groups to better distinguish between the features selected by the student and how the feature is used during reasoning.

Question 2

USING DIAGRAM B. Explain the path of blood shown in this diagram.

This question required a sequential interpretation with its accompanying explanation.

Propositional statements:

Blood enters atrium in response to suction or because the atria are relaxed. However, as the cuspid valves are closed, blood does not flow from the atria into the ventricles (an alternative conception).
Both ventricles contract simultaneously shown by 'dented' shape of ventricle and by inward pointing arrows. This creates pressure on blood.
In response to the contraction of the ventricles, blood flows in all directions, including in an upward direction. It will therefore press on and close the cuspid valves.
At the same time, blood flows into arteries and through the semilunar valves.

Question 3

Why are arrows drawn between Diagrams A and B?

Propositional statement: To indicate a repetitive or cyclic process or to show that processes follow each other.

Probe set 1b on the cardiac cycle (Figure 6.2)

This semi-guided probe was developed to guide students' focus toward arrow symbolism specifically as students tended to avoid using arrows in their answers to Probe 1a. The comparative format of this probe allowed probing of students' global/local observation.

Question:
Make a table to compare the processes occurring in Diagrams A and B. Remember, only ONE feature should be compared at a time. Rule off between each point of comparison.

Propositional statements:

DIAGRAM A	DIAGRAM B
Atrium contracts	Atrium relaxes
Ventricle relaxes	Ventricle contracts
Veins closed (or no blood enters)	Veins open (or blood enters)
Pressure on atria	No pressure on atria OR
	Suction from relaxed atria OR
	Pressure on ventricles
Blood flows from atria to ventricles	No blood flows from atria to ventricles
Valves (cuspids) open	Cuspids closed
Semilunar valves closed	Semilunar valves open
No backpressure/flow	Backpressure or flow or alternative flow
No blood to arteries	Blood from ventricles to arteries

Probe set 1c on the cardiac cycle (Figure 6.2)

Probe 3 was designed to specifically focus on the meaning attributed to arrows. A short answer was required to reduce the influence of additional supporting knowledge and weak language skills. The arrows were numbered as shown in Figure 5.2.

Question: What does each arrow (numbered 1 – 9) mean? (Replace each arrow with a word or short phrase).

Propositional statements:

Arrow 1 – flow of blood or entry blocked or closed valve or vein or pressure on closed valve/vein
Arrow 2 – pressure (of atrial wall) or change in size (of atrium)
Arrow 3 – flow or movement of blood from atrium to ventricle
Arrow 4 – flow of blood (into atrium)
Arrow 5 – backpressure or backflow of blood
Arrow 6 – flow of blood into artery
Arrow 7 – pressure (of ventricle wall) or change in size (of ventricle)
Arrow 8 – alternates with or is followed by
Arrow 9 – as above

APPENDIX 1.2

Probe set 2: Multiple-choice probes on the Cardiac cycle (Figure 6.2)

Selected questions of the multiple-choice probes in the cardiac cycle (Figure 6.2), including those mentioned in the results and discussion of Chapter 6. For questions 1 – 6, possible difficulties for other selected choices are suggested in brackets. However, the nature of the difficulty would require confirmation from the justification.

Question 1 probes perceptual criteria, including the selection of one arrow from a group of similarly styled arrows and the position of the arrow (and arrow features) relative to supporting data.

QUESTION 1 Circle the correct answer(s)

In diagram A, the arrow numbered 1

A. Shows blood surrounding the atrium (One arrow not selected, also possibly a conceptual difficulty)
B. Represents contraction of the muscles around the atrium (One arrow not selected)
C. Shows that pressure is exerted onto the atrium so that it contracts (One arrow not selected, also a conceptual difficulty)
D. Shows the direction of flow of blood in the veins leading to the atrium (Propositional statement)
E. Shows blood entering the atrium (Poor observational of diagram position/features relative to referents)
F. None of the above

Reason for each answer selected

Question 2 probes the purpose of the group of arrows labelled 2. This response can then be compared to the above response probing the purpose of the arrow labelled 1.

QUESTION 2 Circle the correct answer(s)

In Diagram A, the group of arrows numbered 2 represents

A. Pressure being exerted from the outside (Conceptual difficulty)
B. Pressure placed on this area as/because blood flows from the atrium into the ventricle (Conceptual difficulty)
C. Pressure on the atrium causing it to contract (Conceptual difficulty)
D. Blood outside the heart about to enter (Perceptual difficulty with the placement of the arrows)
E. A change in size of the atrium (Propositional statement)
F. None of the above.

Reason for each answer selected

Question 3 probes students' observations of the position of the arrow and arrow features relative to referents and the understanding of the functional attribute of an arrow as a connector, not as a label line.

QUESTION 3 Circle the correct answer(s)

In Diagram B, arrow 4 indicates

A. The opening (entrance) to the atrium (Poor conceptual understanding of the functional attributes of arrow symbolism)
B. An open valve into the atrium (Poor conceptual understanding of the functional attributes of arrow symbolism)
C. Inward pressure (Poor observation of arrow features and position relative to referents).
D. The direction of flow of blood (Propositional statement)
E. The relaxation of the atrium (Poor conceptual understanding and poor observation of arrow position)
F. None of the above

Reason for each answer selected

Question 4 probes students' observations of the position of the arrow and of its features relevant to its referents and also understanding of the functional attributes of arrow symbolism.

QUESTION 4 Circle the correct answer(s)
In Diagram B, arrow 5

A. Points to the atrium (Incorrect observation of arrow features relative to referents and the functional attributes of arrow symbolism, not just as a label line)
B. Points to the ventricle (Incorrect observation of arrow position relative to referents and the functional attributes of arrow symbolism)
C. Points to the closed cuspid valves (Incorrect observation of arrow position relative to referents and the functional attributes of arrow symbolism)
D. Indicates blood in the ventricle when the valves are closed (Poor understanding of functional attributes of arrow symbolism)
E. Shows the direction of flow of blood (Propositional statement)
F. None of the above

Reason for each answer selected

Question 5 probes students' understanding of the arrow as the connector between two referents.

QUESTION 5 Circle the correct answer(s)
In Diagram B, arrow 6 shows blood moving from

A. Ventricle to artery (Propositional statement)
B. Ventricle to body (Poor observation of arrowhead position)
C. Atrium to artery (Poor observation of origin position)
D. Ventricle to semilunar valve (Poor observation of arrow head position)
E. Ventricle of diagram B to atrium of diagram A (Poor observation of arrow position, spatial organisation difficulty)
F. None of the above

Reason for each answer selected

Question 6 probes the purpose of the group of arrows numbered 7. The response may be compared to question 2 (for arrow group 2). Choice C will give a first clue to a possible unintended emergent effect.

QUESTION 6 Circle the correct answer(s)
In Diagram B, what is the group of arrows numbered 7 showing?

A. The ventricle (muscle wall) moving inward (Propositional statement)
B. Pressure on the ventricle wall (Conceptual difficulty)
C. Blood flowing into the ventricle (Perceptual difficulty with the positions of the arrowheads)
D. Choices A and B
E. Choices A, B and C
F. None of the above

Reason for each answer selected

Question 7 probes for an understanding of synonymy and further probes the emergent properties. Also used to check against the purpose of arrows 1, 2, 7, 8, 9 probed in other questions).

QUESTION 7 Circle the correct answer(s)
Arrows that show the direction of flow of blood are numbered

A. 1 to 9
B. 8 and 9 only
C. 1, 2, 3, 4
D. 1, 3, 4, 5, 6 (Propositional statement)
E. 1 to 7
F. None of the above combinations

Reason for each answer selected

Question 8 provides a direct comparison the question 7 and helps to resolve the purpose of the various arrows (especially of arrows 1, 2, 7)

QUESTION 8 Circle the correct answer(s)
Arrows that show pressure on a structure or its contents are numbered

A. 1, 2, 5, 6, 7
B. 1, 2, 3, 4, 5, 6,
C. 2, 7 (Propositional statement)
D. 1, 2, 7
E. 1, 2, 5, 7
F. None of the above combinations

Reason for each answer selected

Question 9 resolves the purpose of arrows 1, 2 and 7 particularly and provides a direct comparison with questions 1, 2, 7 and 8.

QUESTION 9 Circle the correct answer(s)
Arrows that show a change in size are numbered

A. 1, 2
B. 1 to 9
C. 2, 7, 8, 9
D. 2, 7 (Propositional statement)
E. 1, 2, 3, 7
F. None of the above

Reason for each answer selected

Questions 10 & 11 probe the frequency effect – number of arrows in a group for a particular purpose

QUESTION 10 Circle the correct answer(s)
If the groups of arrows numbered 2 and 7 were intended to show pressure, they would show that

A. The pressure is greater at the ventricles (arrows numbered 7) than at the atria (arrows numbered 2)
B. The pressure shown by the arrows numbered 7 is equal to the pressure shown by the arrows numbered 2
C. The pressure is greater at the atria (arrows numbered 2) than at the ventricles (arrows numbered 7) (Propositional statement)
D. Pressure causes blood to enter the heart muscle at arrows numbered 2 and 7
E. The pressure on the left and right sides of the heart differs.
F. None of the above.

Reason for each answer selected

QUESTION 11 Circle the correct answer(s)
If the groups of arrows numbered 2 and 7 were intended to show a change in size,

A. The arrows numbered 7, would indicate a greater change in size than the arrows numbered 2
B. The arrows numbered 2 would indicate a greater change in size than the arrows numbered 7 (Propositional statement)
C. The change in size indicated by arrows 2 and arrows 7 would be similar
D. Arrows 2 and 7 cannot be interpreted as showing a change in size
E. The change in size on the left and right sides of the heart differs
F. None of the above

Reason for each answer selected

Questions 12, 13 and 14 were included to probe for understanding of cause (question 12 and 13) and effects (question 14 in cause-effect relationships. Various supporting data needs to be integrated with the relevant arrows. Students' understanding of arrow 1 is also probed.

Below is a list of features to use in order to answer questions 12, 13 and 14.

a. Size of ventricles
b. Shape of ventricles
c. Arrows labelled number 2
d. Arrow labelled number 3
e. Open cuspid valves
f. Arrow labelled number 1

QUESTION 12 Circle the correct answer(s)
In diagram A, the atria are in systole (i.e. are contracted). What feature or combination of features tell/s you this?

A. a only
B. a and b
C. a to e (Propositional statement)
D. c only
E. None of the above combinations

Reason for each answer selected

QUESTION 13 Circle the correct answer(s)
In diagram A, which feature or combination of features would show that there is pressure on the blood in the atria?

A. a only
B. a and b
C. all of a to f
D. a to e (Propositional statement)
E. c only

Reason for each answer selected

QUESTION 14
In diagram A, blood moves from the atria to the ventricles. What feature or combination of features tells you this?

A. a only
B. a and b
C. a to f
D. a, b, d and e (Propositional statement)
E. d only
F. None of the above combinations

Reason for each answer selected

Questions 15 probed the purpose of arrow 15. Did students take note of the placement of the arrow and positions of arrow features (origin and arrowhead)?

QUESTION 15
In diagram B, arrow 5 shows

A. That blood is being pumped out of the ventricle of the heart
B. That the ventricle is in systole therefore under high pressure and blood leaves through the semilunar valves
C. Upward moving blood that closes the cuspid valves (Propositional statement)
D. That blood circulates in the ventricles before the ventricles contract
E. That blood is moving up and out of the ventricle
F. None of the above

Reason for each answer selected

Questions 16, 17 and 18 further probed for understanding of cause (question 18 - 20) and effects (question 16 and 17 in cause-effect relationships. Various supporting data needs to be integrated with the relevant arrows.

QUESTION 16 Circle the correct answer(s)
In diagram A, what is the result or EFFECT of blood moving from atrium to ventricle (as shown by arrow 3)?

A. The arrow gets longer
B. The ventricle gets larger (Propositional statement)
C. The atrium contracts inward
D. Blood flows into arteries
E. The ventricle contracts
F. None of the above

Reason for each answer selected

QUESTION 17 Circle the correct answer(s)
In diagram B, what is the result or EFFECT of blood moving into arteries (as shown by arrow 6)?

A. The process shown by arrow 5
B. The process shown by arrow 6
C. The process shown by arrows 5 and 6
D. Open semilunar valves (Propositional statement)
E. Contraction of the ventricles
F. None of the above

Reason for each answer selected
QUESTION 18 Circle the correct answer(s)
What features CAUSE the blood to flow through the arteries (as shown by arrow 6 in the diagram)?

A. Open semilunar valves
B. The process indicated by arrow 5
C. The process indicated by arrow 7 (Alternative propositional statement)
D. A combination of the processes indicated by arrows 1, 2 and 3 (Propositional statement)
E. A combination of the processes indicated by arrows 1 and 2
F. None of the above

Reason for each answer selected

QUESTION 19 Circle the correct answer(s)
What features CAUSE the blood to flow into the atrium (as shown by arrow 4 in diagram B)?

A. Closed cuspid valves
B. Open veins
C. Larger atria (Propositional statement)
D. A combination f choices A, B and C (Alternative propositional statement)
E. A combination of choices A and B
F. None of the above

Reason for each answer selected

QUESTION 20 Circle the correct answer(s)
What CAUSES the indented shape of the ventricles as shown in diagram B?

A. The processes shown by the group of arrows labelled 7 (Propositional statement)
B. The processes shown by arrow 5
C. The process shown by arrow 6
D. The process shown by arrow 4
E. A combination of processes shown by arrows 4, 6 and 7
F. None of the above

Reason for each answer selected

Questions 21 probed students' conceptual understanding of the functioning of the chordae tendinae as this difficulty had emerged in previous probes. It did not probe the interpretation of arrow symbolism

QUESTION 21 Circle the correct answer(s)
The cuspid valves open when

A. The chordae tendinae relax
B. The chordae tendinae hold the cuspid valves open
C. The chordae tendinae contract
D. The muscles of the cuspid valves contract
E. Blood under pressure pushes the valves apart (Propositional statement)
F. None of the above

Reason for each answer selected

Questions 22, 23 and 27 probed understanding of the alternating contractions of the atria and ventricles shown by arrows 8 and 9 and by Diagrams A and B.

QUESTION 22 Circle the correct answer(s)
The arrow numbered 8 shows

A. That after contracting, the heart is returning to a relaxed position
B. A period of rest before the atrial muscles contract again
C. The change from atrial diastole (not contracted) to ventricular systole (contraction)
D. That atrial systole (contraction) follows ventricular systole (contraction) (Propositional statement)
E. The alternative pathways of blood to the lungs and to the body (pulmonary and systemic circulations)
F. None of the above

Reason for each answer selected

QUESTION 23 Circle the correct answer(s)
Arrow 9 represents

A. The circulation of the blood around the body, and back to the heart
B A continual cycle of contraction of different parts of the heart (Propositional statement)
C. Blood moving out of the body through aorta and pulmonary vein
D. The circulation of blood through the heart
E. The internal/time phase between the contraction and relaxation of the heart.
F. None of the above

Reason for each answer selected

Question 24: The students' perception (or lack thereof) of the placement of arrow 1 will be revealed by probing whether blood is entering the atrium.

QUESTION 24 Circle the correct answer(s)
In diagram A,

A. Blood is entering into the atria and systole (contraction) occurs
B. Deoxygenated blood is coming into the heart
C. The muscles in the heart are relaxed allowing blood to enter the heart
D. The muscles of the atria are contracted preventing blood from entering the heart (Propositional statement)
E. Pressure from outside the heart is preventing blood from entering the heart
F. None of these above

Reason for each answer selected

QUESTION 27 Circle the correct answer(s)
Diagram B shows that

A. There is a continuous pathway of blood into the left atrium, through the heart and then out of the ventricle
B. Blood flows into the atria and out of the ventricles at the same time (Propositional statement)
C. The pressure from contraction of the ventricle pushes the blood through the heart
D. The cavities in the heart are always full of blood
E. The valves are open allowing a continuous flow through the heart
F. None of the above

Reason for each answer selected

Question 30 probes students' perceptions of the repetitive process shown in the cardiac cycle.

QUESTION 30 Circle the correct answer(s)
The pattern of contraction of the muscles of the heart as shown in the two diagrams (A and B) is

A. The heart has two sides (left and right) that work alternately
B. The atria alternate contraction with the ventricles (Propositional statement)
C. The left side of the heart contracts first followed by the right side
D. The atria of the left side contract, followed by the ventricles of the right side of the heart
E. Each chamber of the heart works independently (on its own)
F. None of the above

Reason for each answer selected

APPENDIX 1.3
Probe set 3: Interview format for the cardiac cycle (Figure 6.2)

This format provides guidelines for the interviews.
The numbers in brackets next to the proposed questions cross-reference to the equivalent multiple-choice question from which the difficulties emerged.

Free response questions:
What is the topic of the diagram? Why did you say that?
Explain what is happening in diagram A? What shows you that? (24)
Explain what is happening in diagram B? What shows you that? (25 + 26)
Does the diagram as a whole tell you anything else?

Focussed questions where appropriate:

(1) What does the arrow numbered 1 indicate?
Probe for:
   a. Difference in meaning between arrows 1 and 2.
   b. Size of arrow relative to others.
   c. Position of arrow relative to others.
   d. Position of arrowhead relative to other structures.
   e. Pressure (see questions for arrow 2).

(2) What does number 2 refer to? What does this indicate?
Probe for:
   a. What do the arrows represent?
   b. What causes the pressure? / OR why did you decide that?
   c. The position of the arrows relative to that pressure
   d. Why is the feature mentioned, represented by a group of arrows?

(3) What does the arrow numbered 4 indicate?
Probe for:
   a. Can one arrow represent both a structure/position and direction?
   b. The difference between arrows 1 and 4 relative to their position.
   c. The difference between arrows 1 and 4 relative to pressure
   d. Why do arrows 1 and 4 show different phenomena – what has changed?
   e. Can similar arrow formats represent different phenomena?

(4) What does the arrow numbered 5 indicate?
Probe for:
   a. Does it show position/structure/blood/direction?
   b. Is there any difference in the format/style/structure of arrows 1, 4, 5?
   c. Comment on the shape of the arrow?
   d. What causes the blood flow in that direction? (15)

(5) What does the arrow numbered 6 represent?
Probe for:
   a. Position of arrow origin and head. – Why do you say that? Where is the blood going? Where has it come from?
   b. What causes the 'arrow'/blood flow (18)
   c. What is the effect of the blood flow? (17)
   d. What is the destination of the blood? How much does this diagram tell you about the destination? (22 and 23)
   e. How much prior knowledge is used in place of diagrammatic information?

(6) What does number 7 represent? What do the arrows indicate?
Probe for:
a. What is the source of the pressure represented by the arrows?
b. What happens to the heart when this pressure occurs (use their terminology) Find out if the arrows are related to a change in size?
c. How does the process shown by the arrows effect the flow of blood?
d. What is the difference (if any) between the two groups of arrows numbered 7? (Probe for arrow number or position if applicable)
e. What is the difference between the groups of arrows numbered 2 and 7? (Probe for position/pressure/arrow number where applicable)
f. Also see questions for (10) and (11).

(7) Which arrows show the flow of blood?
Probe for: What indicates this to you? (Relate to arrow structure/position/format).

(8) Which arrows/other arrows show pressure?
Probe for the following :- 1,2,5,7
Relate to position/ other structures/ format.

(9) Which arrows show a change in size
Relate to position/ other structures/ format.

(10)Where is the greatest pressure indicated on this diagram?
a. Why do you say that?
b. Probe for arrow features.

(11) Where is the greatest change in size on this diagram?
What tells you that? (Probe for arrow features).

(12) Which feature/combination of features tells you there is systole (contraction) in Diagram A?
Probe for:
a. Which features were included and why?
b. Which features were excluded and why?

(13) In Diagram A, which features/combination of features tells you there is pressure on the blood in the atria?
a. Which features were included and why.
b. Which features were excluded and why.
See also (14)

(Probe for features that cause blood to flow)
(14) What causes blood to move from the atria to the ventricles?
(19) What causes blood to flow into the atria as shown by arrow 4?
(26) What causes blood to flow into the arteries as shown by arrow 6?
(20) Describe the shape of the ventricles in diagram B. What causes the indented shape?
Relate to structure/position.

(16) What is the effect of blood moving from atria to ventricles? (Probe for features (effects) that respond to blood flow).

(21) How do the cuspid valves open? And close? (Probe for the concept of valve functioning)
Probe for:
a. What diagram features tell you that?
b. How are the semi lunar valves opened? Closed?
c. What diagram features tell you that?

(22) What does the arrow labelled 8/9 indicate?
Probe for:
a. Relate to arrow features.
b. Relate to diagram features.
c. How much does the diagram tell you?

(25) Why is the blood not leaving the heart in diagram A?

(28) Explain the cardiac cycle.
Probe for:
a. What does it show?
b. What features tell you that?

(29) Why are two diagrams used to explain this process?
Probe for:
a. systole/diastole – What do you mean by ....?
b. Which areas have blood during ....?
c. Where is the blood going?

(30) Explain the pattern of contraction as shown in this diagram.

What is your opinion of this diagram?
Would you change it in any way if you were going to present it to your class?
If so, how would you change it?
Why would you change it in that way?

APPENDIX 1.4
Probe set 4 on the Thermoregulation flowchart (Figure 6.3)

A semi-guided approach was used in order to reduce the effects of complexity.
Question 1 probes students' observations. Question 2 probes students' understanding of the meaning of arrows in the context of the diagram.

Study the accompanying flow chart about thermoregulation in the mammalian body. Answer the following questions that are based on that chart.

1. Answer these questions FROM THE INFORMATION PROVIDED IN THE FLOW CHART.
   a. What does a low environmental temperature do to skin temperature?
   b. What is/are the functions of cold receptors in the skin?
   c. In how many ways can the heat gain centre be affected (or stimulated)? Name them.
   d. What do the cold receptors do with the information about the changes in skin temperature?
   e. Name the changes directly caused by the heat gain centre.

2. What do each of the arrows marked 1 – 5 mean? (Give an alternative word/term for each of the arrows numbered 1 – 5).
   1.
   2.
   3.
   4.
   5.

Propositional statements:

1 a. Decreases it.

b. Monitor/sense skin temperature (incoming/causal arrow placed laterally)
Relay information to cerebral cortex (outgoing/effective arrow angled vertically)
Relay information to posterior hypothalamus/heat gain centre (outgoing/effective arrow placed vertically)

c. 4
By cerebral cortex
From cold receptors
Negative feedback from blood temperature
Inhibition from heat loss centre

d. Relay information/impulse to cerebral cortex
Relay information/impulse to posterior hypothalamus

e. 1. shivering
2. skin arterioles constrict
3. hairs raised
4. adrenaline released
5. thyroxine released (4 + 5 = metabolic rate increase)
6. inhibits heat loss centre

2.

Arrow number	Statement
1.	causes/results in
2.	stimulates/affects ('monitored by' implies wrong direction)
3.	stimulate/activate/impulses to (message to)/informs
4.	as for 3
5.	result in/cause (result accepted as poor expression; effect not accepted)

APPENDIX 1.5
Probe set 5: Interviews on the Thermoregulation flowchart (Figure 6.3)

Suggested questions to guide the interview in order to further probe suspected difficulties and allow unexpected difficulties to emerge.

Look carefully at this diagram. I am going to ask you about it. I want you to answer as fully as you can. However, remember that there are no right and wrong answers ....
What is the topic of this diagram?
How did you decide on this topic?

Just now you practised using a pointer to show me your path of search. I want you to do the same with this diagram. As your eye moves across the diagram, move the pointer. When you talk about a feature, point to it. Okay?

What does the diagram tell you?
You started describing the diagram at -----Why did you start at this point?
Clarify points not fully discussed: Why do you say that? e.g. You mentioned ----- Can you tell me more about it?

Let's look at some of the features you have used [to further probe the questions used in Probe set 4]. Again, point to the area you are referring to.
What effect does a low temperature have on skin temperature?
What is the function of the cold receptors in thermoregulation?
In what ways can the heat gain centre be stimulated?
Give the changes that are directly caused by the heat gain centre

I am going to point to certain arrows. Please give a word or phrase that you could use instead of the arrow. Write them on the diagram so that we can refer to them later if you need to.
What do the following arrows mean?
Arrow 1
Arrow 2
Arrow 3
Arrow 4
Arrow 5
Now use each of the words/phrases to explain what each arrow is showing: Arrow 1, 2, 3, 4, 5

If for some reason, the arrow between ----- and ---- was removed,

a. What would this possibly indicate?
b. How would it affect the interpretation of the diagram?

Let's look at a few of the words used in the diagram.
What does the word 'inhibition' mean?
Which arrows show inhibition?
Explain what the arrows (labelled inhibition) tell you.
PROMPT: Why do the arrows marked 'inhibition' go in opposite directions?
Which arrow/s show negative feedback? Use the diagram to explain the role of negative feedback and inhibition in the diagram.

What parts of the body are involved in thermoregulation? What is the role of each?

Now we'll look at the way the arrows are drawn.
Which arrows have a special style (appearance)?
Why is this arrow (negative feedback) drawn differently?
Comment on the format of the arrow to the box with the words 'blood temperature'.
PROMPT: Why is it different?
Some arrowheads are drawn differently. Which are they?
In your opinion, why are they different?

Is it possible to divide the diagram into subsections or categories? Try it. Explain why you used those subdivisions.
Now that you have worked through the diagram, what is your opinion of this type of format? PROMPT: Is the information arranged in a suitable way? Why or why not?

Criteria to guide the analysis of interview transcripts, videos and student-modified diagrams using the thermoregulation flowchart.

Perceptual criteria
Spatial organisation of diagram (involving the strategies of observation - detection, selection and organisation)

1. Plan of search
2. Global pattern recognition
3. Partitioning of diagram

Grouping within diagram

4. Observation, selection and organisation of arrow groups and patterns

Individual arrows within and between perceptual units

5. Observation of arrow positions relative to referents
6. Observation of arrow features relative to referents

Style of arrow symbolism

7. Comment on arrow format

Conceptual criteria
Conceptual understanding of theoretical concepts

1. Method of establishing the topic of the diagram
2. Use of prior knowledge in answers with/without referring to the diagram
3. Transfer of knowledge from another topic to this one
4. Relevant knowledge of the structures noted in process
5. Meaning of terminology used in the diagram e.g. inhibition

Conceptual understanding of arrow symbolism

Reasoning criteria

1. Allocation of meaning to arrows based on the position within the diagram
2. Reasoning with the style of arrow symbolism
3. Reasoning ability with arrows in questions requiring integration of information (such as the effect of removing an arrow on the interpretation of the diagram)

Students'opinions to guide remediation

1. Opinion of diagram
2. Proposed improvements for presentation of diagram to other students

APPENDIX 1.6

Probe set 6: Multiple-choice probes on the Thermoregulation flowchart (Figure 6.3)

Selected examples of multiple-choice questions on the thermoregulation process. The focus of each question is explained as well as the propositional statement and possible difficulties for other selected choices. However, the nature of the difficulty would need to be confirmed from the student's justification.

PART 1 (Probe set 6)

Examples from part 1 of the multiple-choice probes using the Thermoregulation flowchart (Figure 6.3)

Questions 1 and 2 (perceptual probes) require the causal arrow to be accessed to create the correct link between the appropriate referents. In addition, question 1 requires the precise origin of the arrow to be detected.

QUESTION 1 Circle the letter(s) of your choice and give a reason for each choice of answer.
According to the diagram, what causes skin temperature to increase?

A. environmental temperature (Poor observation of precise origin)
B. skin warm receptors (Reverse cause and effect)
C. high environmental temperature (Propositional statement)
D. increased blood temperature (Incorrect perceptual unit in spatial organisation accessed)
E. none of the above

Reason for your answer

QUESTION 2 Circle the letter(s) of your choice and give a reason for each choice of answer.
According to the diagram, skin warm receptors are stimulated by (or react to):

A. an increase in blood temperature (Incorrect perceptual unit in spatial organisation accessed)
B. an increase in skin temperature (Propositional statement)
C. the cerebral cortex (Reverse cause and effect)
D. the heat loss centre (Reverse cause and effect)
E. none of the above

Reason for your answer

Questions 3, 4 and 5 (reasoning and conceptual probes) probe the understanding of alternative pathways. In each case the justification should be analysed to understand students' reasoning.

QUESTION 3 Circle the letter(s) of your choice and give a reason for each choice of answer.
The arrows in the diagram show the following two pathways from the skin warm receptors to the heat loss centre:

1. Directly from the skin warm receptors to the heat loss centre
2. From the skin warm receptors to the cerebral cortex and then to the heat loss centre.

The arrows of the pathway numbered 2 show:

A. a pathway that may be followed INSTEAD of the other one (Recognised as an alternative, but not dual pathway)
B. a slower pathway (A conceptual difficulty with impulse transmission)
C. a pathway that only happens when the person thinks about the heat (A conceptual difficulty with the function of the cerebrum)
D. a pathway that happens at the same time as the other one (Propositional statement)
E. a faster pathway (A conceptual difficulty with impulse transmission)
F. none of the above

Reason for your answer

QUESTION 4 Circle the letter(s) of your choice and give a reason for each choice of answer.
According to the diagram, if there were no connection or stimulation, and therefore no arrow, between the skin cold receptors and the cerebral cortex:

A. the person would not feel cold (Propositional statement – depends on knowledge of the function of cerebrum)
B. the heat gain centre would not be stimulated and therefore the blood temperature of the person could not be adjusted (Ignore effects of alternative causal arrow)
C. heat gain centre would be stimulated faster and therefore the temperature of the person could be adjusted more quickly (Conceptual difficulty with impulse transmission)
D. there would be no difference in the process of thermoregulation as shown on the diagram (Conceptual difficulty with function of arrow symbolism)
E. none of the above

Reason for your answer

QUESTION 5 Circle the letter(s) of your choice and give a reason for each choice of answer.
According to the diagram, if there were no connection or stimulation, and therefore no arrow, between the skin cold receptors and the heat gain centre:

A. the heat gain centre would not be stimulated (Ignore alternative causal arrow)
B. the heat gain centre would be stimulated by the cerebral cortex (Propositional statement)
C. the person would not feel cold (Perceptual difficulty of alternative pathway or conceptual difficulty with function of cerebral cortex)
D. the skin warm receptors would relay the information to the heat loss centre instead (Perceptual difficulty of with spatial organisation)
E. the skin temperature would remain cold (Perceptual difficulty with alternate pathway)
F. none of the above

Reason for your answer

Question 8 probes the concept of inhibition as part of the feedback mechanism.

QUESTION 8 Circle the letter(s) of your choice and give a reason for each choice of answer.
In the diagram, the arrows marked 'inhibition' between the heat gain and heat loss centres tell you that the heat gain and heat loss centres:

A. function at the same time (Misunderstood inhibition, sees links)
B. function one at a time (Propositional statement)
C. have the same function (do the same thing) (Do not read functions, do not reason)
D. will only work if stimulated by the cerebral cortex (Miss the pattern)
E. work according to the Law of Mass Action (from the highest to the lowest concentration) (Incorrect transfer)
F. none of the above

Reason for your answer selected

PART 2 (Probe set 6)

Examples from part 2 of the multiple-choice probes using the Thermoregulation flowchart (Figure 6.3)

Questions 1 - 4 probe aspects of the spatial organisation of the diagram

QUESTION 1 Circle the letter(s) of your choice and give a reason for each choice of answer.
Which of the following parts of the body does a LOW environmental temperature affect?
Circle ALL of the parts that are affected.
Also give a reason for EACH option selected.

A. skin receptors
B. the cerebral cortex
C. the skin arterioles
D. the skin hairs
E. the blood
F. some hormonal glands
G. liver
H. muscles
I. sweat glands
J. none of the above

Reason for each answer

QUESTION 2 Circle the letter(s) of your choice and give a reason for each choice of answer.
Which of the following options DIRECTLY affect the functioning of the heat loss centre.
Circle ALL of the ones that do.
Also give a reason for EACH option selected. N.B. WRITE DOWN THE LETTER OF EACH SELECTED ANSWER WITH THE REASON WHY YOU SELECTED THAT ANSWER.

A. an increase in environmental temperature
B. a decrease in environmental temperature
C. heat gain centre
D. an increase in blood temperature
E. a decrease in blood temperature
F. sweating
G. stimulation of skin warm receptors
H. cerebral cortex
I. stimulation of skin cold receptors
J. dilated skin arterioles
K. shivering
L. none of the above

The Propositional statements are: C, G, H

Reason for each answer

QUESTION 3 Circle the letter(s) of your choice and give a reason for each choice of answer.
Circle the letter/s of your choice and give a reason for EACH choice.
Stimulation of the skin warm receptors has the following effects(s):

A. the skin temperature increases (Reverse cause & effect)
B. the heat loss centre functions (Propositional statement)
C. the environmental temperature lowers (Reverse cause & effect)
D. the heat gain centre functions (incorrect access to sp. organisation)
E. none of the above

Reason for each answer

QUESTION 4 Circle the letter(s) of your choice and give a reason for each choice of answer.
Circle the letter/s of your choice and give a reason for EACH choice.
Stimulation of the heat loss centre has the following effect(s):

A. the heat gain centre is inhibited (Propositional statement)
B. the cerebral cortex and skin warm receptors are inhibited (Reverse cause & effect)
C. the heat gain centre is stimulated (Incorrect concept of inhibition/feedback mechanism)
D. the cerebral cortex and skin warm receptors are stimulated (Reverse cause & effect)
E. the blood temperature increases (Incorrect access to sp. organisation)
F. none of the above

Reason for each answer

Questions 5 - 7 probe application of meaning to arrows in the context of the diagram.

QUESTION 5

Choose the most correct answer. If you choose option I, give your own word or short phrase.
If the arrow from the skin temperature 'box' to the skin warm receptors 'box' is replaced by a word or short phrase, the wording would be as follows:

A. heat
B. conducts to
C. detects
D. receives
E. causes
F. therefore
G. stimulates
H. increases
I. none of the above

Reason for your choice of answer

QUESTION 6

Choose the most correct answer. If you choose option G, give your own word or short phrase.
If the arrow from the skin warm receptors 'box' to the heat centre 'box' is replaced by a word or short phrase, the wording would be as follows:

A. reacts to
B. are controlled by
C. controls
D. moves to
E. a nerve
F. sends impulses to
G. one of the above

Reason for your choice of answer

QUESTION 7

Choose the most correct answer. If you choose option G, give your own word or short phrase.
If the arrow from the bracket around the words 'sweating, skin arterioles dilate and metabolic rate decreases' to the blood temperature 'box' is replaced by a word or short phrase, the wording would be as follows:

A. maintain a
B. causing a
C. stabilising a
D. combining to form a
E. react with
F. allows a
G. none of the above

Reason for your choice of answer

Appendix 2
Previous papers (SAARMSTE, 2002; 2003; ERIDOB, 2002)

SAARMSTE 2002
Content analysis of arrow symbolism in biology textbooks

Lynn du Plessis[1], Trevor R. Anderson[1], Diane J. Grayson[2]
University of Natal, Pietermaritzburg[1], University of South Africa, Pretoria[2] South Africa
e-mail: anderson@nu.ac.za

ABSTRACT

A content analysis of six popular South African biology textbooks was undertaken to ascertain the prevalence of visual displays, of each type of visual display (realistic, stylised and abstract) and of arrow symbolism within each visual type. The formats and purposes of arrow symbolism in the textbooks were categorised and a set of criteria developed by which to critically evaluate the presentation of arrow symbolism in visual displays. The subsequent evaluation revealed several areas of potentially confusing presentations that could have a negative impact on the interpretation of diagrams.

INTRODUCTION

Textbooks are used in most schools as a source of visual displays. Visual displays, which include diagrams, can be divided into realistic, stylised or abstract types, all of which play important roles in the teaching and learning of biology and other sciences. In general terms, the function of realistic displays (few of which are diagrams) is to show mainly or only, structure. Stylised displays are diagrams that show structure, function or both. Abstract displays or diagrams tend to emphasise relationships in a process or sequence. Stylised and abstract diagrams are often viewed as instructionally superior to realistic displays as they provide explanations. To accomplish their specific focus however, conventions and symbolism such as arrows are often used.

Arrows, like many other symbolic representations, may take many formats and have a wide variety of purposes. Arrows essentially represent links between nodes, clusters, elements, areas, points, independent and dependent variables and so on, indicating direction, creating meaning and specifying relationships (often cause and effect relationships) between two parts (Waller, 1981; Fisher 1990). Arrow notation, particularly when used in diagrams is therefore dependent on the other features, in the diagram. Arrows therefore, cannot be interpreted independently of other features in visual displays.

Extensive research on scientific visual displays or science diagrams has shown that they can improve text comprehension and the understanding of concepts (e.g. Mayer & Gallini, 1990; Winn *et al.*, 1991; Phillips & Quinn, 1993; Moore, *et al.*, 1993). However, these positive results are often accompanied by a proviso that the student be familiar with the type of visual display and conventions used (or be given relevant instruction); or that the construction of the visual display be instructively effective and relevant to the representation of the information and to the task. A shortfall in one or more of these areas may result in students showing difficulties with the interpretation of visual displays (e.g. Henderson, 1999; Wheeler and Hill, 1990; Reid, 1990a; Hill, 1988; Lowe, 1996). Some of these difficulties have been attributed to the incorrect, misleading or confusing presentation of arrows in diagrams, which can result in scientific reasoning and conceptual difficulties (e.g. Schollum, 1983; Jiminez-Valdares and Perales-Palacios, 2001).

Despite various articles on arrows in general, there appears to be no rigorous study reported on the evaluation of the use of arrows in scientific diagrams per se, let alone in biology diagrams. The aim of this study was to investigate the prevalence, and appropriate or misleading use, of arrow symbolism in textbooks currently used for Grade 11 and 12 biology in KwaZulu-Natal schools. This involved using content analysis to, in sequence, select suitable textbooks for analysis, determine the prevalence of the visual displays in the textbooks, categorise the visual displays into visual types, determine the prevalence, format and purpose of arrow symbolism in the visual types and, finally, evaluate the arrow symbolism according to specific criteria developed by us.

METHODOLOGY

Selection of textbooks for content analysis

Information obtained from a convenient survey of 50 teachers in 35 schools and various publishing houses was used to select three popular series of South African textbooks, from three different publishing houses, that are currently being used to teach Grade 11 and 12 biology in KwaZulu-Natal schools. Each series consisted of two books, one for Grade 11 and one for Grade 12 pupils (Ayerst, *et al.,* 2000a and 2000b; Ashwell, *et al.,* 1999a and 1999b; Degenaar, *et al.,* 1999 and 2000). These six books were then subjected to content analysis (Cohen, *et al.,* 2000; Lowe, 1993; Hunter, *et al.,*1987) to obtain the various information described below.

Analysis of visual displays in the textbooks

For the purposes of this study, a visual display was classed as any illustration, including formulae, but excluding tables of data. Stages within a display and displays of more than one entity, but with a composite caption, were included as single illustrations. The prevalence of visual displays in each of the six textbooks was ascertained by content analysis and the results expressed as average number of visual displays per page, and as percentage of pages with visual displays. Several types of displays were found in our sample, necessitating a categorisation of visual displays into three types, namely realistic, stylised or abstract (modified from Alesandrini 1987).

Analysis of arrow symbolism in visual displays and types

1. Content analysis was used to ascertain the occurrence and prevalence of arrow symbolism in visual displays and in each type of visual display. The results were expressed as percentages of displays with arrow symbolism.
2. The various arrow symbols used in the selected textbooks were then categorised according to differences in arrow format and purpose (e.g. Schollum, 1983; Kress and van Leeuwen, 1996).
3. A set of criteria, based on the work of previous researchers (e.g. Kosslyn, 1989; Winn, 1993; Kress and van Leeuwen, 1996; Goldsmith, 1987; Lowe, 1993; Reid, 1990), was developed for objectively evaluating and comparing the use and presentation of arrow symbolism in the three visual types. This set of criteria was then applied to 614 diagrams in the six selected Grade 11 and 12 biology textbooks. To establish reliability, random diagrams were presented to students for comment on presentation and interpretation of the arrow symbolism.

RESULTS AND DISCUSSION

The prevalence of visual displays in biology textbooks

This ranged from a minimum average of 0,57 visual displays per page (or 49% of pages with displays) in Degenaar, *et al.*(2000) to a maximum average of 1,31 visual displays per page (or 84% pages with displays) in Ashwell, *et al.*(1999a). The overall average shows 0,86 displays per page or that 66% of the pages in a textbook contain visual displays. These findings are consistent with the findings of other researchers (Reid and Miller,1980). Visual displays are therefore an important consideration in using textbooks.

Textbook	Total diags	No. *	% *	Diagram type Realistic				Diagram type Stylised				Diagram type Abstract			
				No #	% #	No **	% **	No #	% #	No **	% **	No #	% #	No **	% **
Ayerst, *et al.* (2000a)	366	63	17	173	47	2	1	174	48	48	28	19	5	13	68
Ayerst, *et al* *(2000b)*	291	117	40	48	16	0	0	174	60	77	44	69	24	40	58
Ashwell, *et al.* *(1999* a)	379	93	25	161	42	2	1	182	48	69	38	36	9	22	61
Ashwell, *et al.* (1999b)	402	179	45	91	23	0	0	222	55	116	52	89	22	63	71
Degenaar, *et al.* (1999)	220	57	26	25	11	1	4	184	84	49	27	11	5	7	64
Degenaar, *et al.* (2000)	212	105	50	1	0	0	0	149	70	58	39	62	29	47	76
Total	1870	614		499		5		1085		417		286		192	
Average per book	312	102	33	83	27	1	1	181	58	70	38	48	15	32	67

* Number or % of total diagrams with arrows
# Number or % of diagrams in each diagram type
** Number or % of diagrams in each diagram type with arrows

Table 1. The prevalence of arrow symbolism in visual displays and in each visual type (realistic, stylised and abstract) in the six selected textbooks.

Categorisation of visual displays into visual types

The results shown in Table 1 indicate a predominance of stylised diagrams (58%) over realistic (27%) and abstract (15%) visual types. In each series of book there is a marked shift in emphasis from Grade 11 to Grade 12, of realistic to stylised and abstract visual types. Presumably, this also indicates a shift in emphasis from structure to process and explanation. This in turn presupposes a shift toward the greater use of symbolism.

Prevalence of arrow symbolism in visual displays and visual types

The results of the analysis for arrow symbolism (also shown in Table 1) indicate that between 17% and 50% (with an average of 33%) of visual diagrams have arrow symbolism, and also bears out the expected shift in emphasis from Grade 11 to Grade 12 textbooks. Considering only the stylised and abstract categories of visual types (on average, only 1% of realistic displays employ arrow symbolism), the prevalence of arrows rises to an average of 45%. As there are more stylised diagrams than abstract diagrams, most arrow symbolism (68%) occurs in the former. However, proportionately, arrows are used in, on average, 67% of abstract diagrams to 38% of stylised diagrams. These results indicate the widespread use of arrow symbolism in diagrams and highlight the importance of a clear understanding of arrow symbolism for both presentation and interpretation.

Classification of arrow formats and purposes

Not only were arrows used in different types of displays over a wide range of contexts but the presentational format and purpose of the arrows varied considerably, both between and within diagram types. The categories of arrow format formulated by Schollum (1983) and Henderson (1999) were extended to eight categories. There occurred, within each category, a variety of arrow formats such as shape, size, width, length, colour, style, directions and ways of joining, overlapping, intercepting, and so on. Within the eight categories of formats, 24 categories of arrow purpose were identified. The purposes of the arrows included, among other more specific functions, directing attention to structures, indicating direction, magnitude and magnification, and specifying stages or relationships within a process or sequence. Hardin (1993) identified various groups of conjunctions to express relations between propositions. However, the meaning of the arrow was in many cases even more specific to, and was governed by, the context of the diagram, the position of the arrow/s in the diagram and its relative connectives. The wide range of formats and purpose of the arrow symbolism, even within one diagram, required that the intended meaning of every arrow in a diagram be determined in context. This diversity of presentation could be perceived as confusing, but not necessarily misleading. However, inconsistent or inappropriate presentation of arrow symbolism could have a negative impact on interpretation.

Evaluation of arrow presentation

The presentation of arrow symbolism in the selected textbooks was evaluated using the twelve devised criteria. The main categories of criteria and results of the evaluation are listed in Table 2. The results for each criterion were expressed as the total number and percentage of diagrams showing some form of inappropriate use of arrow symbolism. In many cases, the form of presentation could be improved by a small adjustment, and was not considered misleading to the interpretation of the diagram. However, a final cumulative assessment of all criteria for each diagram indicated that, on average, 30% of diagrams were potentially confusing or misleading.

Perceptual difficulties could result if arrows were small relative to the proportions of the diagram, too small to be readily discernable, or inappropriately grouped. In fourteen percent of diagrams, interpretation was compromised if diagrams were not carefully scrutinised for arrow presence. Inappropriate grouping of arrows could lead the eye in an unintended direction. For example, diagram B in Fig. 1 implies a linear connection between ATP and H. Careless grouping could also result in a false cue. In Fig. 1 diag. O, Pi appears to be more associated with NAD than the ADP/ATP conversion. Such illusionary or distortion effects were noted in nine percent of diagrams. The continuity effect, used to show progression, sequence or direction of flow was poorly presented in 9% of diagrams and the proximity effect (used largely to link associated elements in hierarchies) was unclear in 4% of diagrams. Few diagrams used similarity and frequency effects.

Difficulties with decoding and therefore the interpretation of arrow symbolism could result from the inappropriate presentation of several factors, including pattern formation (pattern of grouping, positions of individual arrows and connections between arrows), number and format of arrows, conformity or variation in format, the use of conventions and the quality of other supporting information.

If arrows within a group, or groups of arrows within a diagram, were not well positioned, the implicit and/or explicit boundaries of the diagram were compromised, sometimes resulting in unintentional emergent properties (as found in 12% of the evaluated diagrams). In 9% of diagrams, arrows were inaccurately placed. In Fig 2. diag. R, hydrogen and carbon dioxide should merge prior to the formation of glucose. Arrows could not be interpreted literally in their allocated position in 17% of diagrams. For example, in Fig 2 diag. S, the arrows imply the destination of the gases as the nucleus. Arrows were not easily discernable from the background detail (or labels) in 15% of diagrams. Where the origin of the arrow shaft and the point of the arrow were not precisely positioned, correct interpretation of the symbolism depended on conceptual understanding (Fig. 2 diag. T) or content knowledge (Fig. 1 diag. T), as the symbolism could not be relied on for meaning. For example, the arrowheads in diagram T should touch both the outer and midline to justify diffusion distance. In 6% of diagrams, the intention (Fig. 1 diag. B) or sequence (Fig. 2 diag. R) of the merge or split of arrows was unclear.

An inappropriate number of arrows for effective interpretation was found in 144 (12%) diagrams. The connective role of arrows was obscured with unnecessary arrows (Fig.1 diag. C, where three arrows showed the ATP/ADP conversion and diagram K, where seven arrows showed the same reaction), or with arrows not linked specifically to two discernable elements. Cohesion was lost where arrows were widely spaced (as in Fig. 1, diags. J and O), or sparse. Four percent of diagrams, mainly abstract diagrams of plant life cycles and biochemical pathways included too many arrows for information processing at Grade 11 and 12 levels.

CRITERIA FOR ANALYSIS OF ARROW SYMBOLISM	Total /614	Av %
1. Spatial arrangement of arrows in diagram including 3 categories of effective diagram type, spatial frequency and conventional read (where applicable)	33	2
2. Size of arrow features proportionate to diagram	89	14
3. Pattern formation of arrows (Grouping, positioning, connecting)		
a. Grouping for unit binding (explicit & implicit boundaries & emergent properties)	71	12
b. Grouping for continuity, proximity, similarity, frequency effect (4 categories)	44	2
c. Presentation of arrows to avoid illusion or distortion effect	57	9
d. Positioning of individual arrows within elements:		
i) relevant connections for interpretation of data	54	9
ii) optimal positioning for meaning within diagram	102	17
iii) suitable positioning for visibility, distinct from background	91	15
e. Precise connections including origin, pathway & point (3 categories)	247	13
f. Appropriate connections between merging arrows	40	6
4. Number of arrows in diagram		
a. Suitable number of arrows/groups of arrows (no gaps/no extras)	144	12
b. Suitability for information processing at relevant level	24	4
c. Consistent number within group for repeated, similar process	5	1
5. Format of arrow		
a. Suitable format for intended meaning (12 categories)	352	5
b. Variation/consistency in format, for different/within purpose (3 categories)	124	7
c. Suitability of arrow format for the focus of diagram	104	17
b. Correct use of arrow 'conventions' (where applicable)	65	11
6. Clarity of meaning of arrow/s		
a. Unambiguous interpretation of individual/groups of arrows within the diagram	135	22
b. Method/position/consistency of labelling for arrow interpretation (2 categories)	191	16
c. Suitable key (where necessary)	100	16
7. Goal of search defined/clear for appropriate interpretation of arrows	106	17
8. Conformity of arrow format within diagrams, context and textbook	161	26
9. Level of presentation relative to age, learning level, text and culture	71	4
10. Layout and linkage of entities within displays and proximity to relevant text	97	5
11. Use of arrows as label lines, with other arrow symbolism or other label lines	50	8
12. Cumulative assessment of arrow symbolism (relative to student level)	185	30

Table 2. The results of the evaluation for inappropriate presentation of arrow symbolism in the visual displays of the six selected textbooks, using the devised criteria.

Twelve formats of arrow presentation were identified as being pertinent to the meaning of the symbolism. Formats were misleading in 17% of diagrams. Notably, the presentation of change of magnification and magnitude was confusing, as the arrow shaft often tapered in contradiction to the change. The conversion of ADP to ATP as shown in Fig.1 diag. A, indicates relative energy levels, but despite being in close proximity in the textbook, the taper of the arrows in diagrams B, C and D ignore or contradict this presentation. The purpose of a particular arrow format was potentially ambiguous if the format, including size, was not consistent within the purpose. Conversely, variation in arrow format that could facilitate interpretation in different purposes, was sometimes lacking. Furthermore, the format of arrows was not suitable for the focus of the diagram in 17% of diagrams. Inappropriate format could therefore have a marked impact on the interpretation of the diagram.

Expected conventions (such as the broken line depiction for inhibition and the parallel process of the ADP/ATP reaction) were not adhered to in 11% of diagrams. For example, a broken arrow was used in Fig. 1 diags. J and O, to show a reaction pathway, (unless the intention of the change from dotted to solid line, as shown only in diagram O, was intended to show relative energy levels). Conformity of particular arrow formats within diagrams, contexts and textbooks was ignored in 26% of diagrams. In Ayerst, *et al.* (2000b) eleven different depictions of the ADP/ATP conversion were given. A further five novel presentations occurred in the other two series of textbook. Some examples of the styles of presentation of this reaction are given in Fig. 1

The clarity of meaning of arrows within the diagram is important for conceptual understanding and reasoning. Some degree of ambiguity with one or more arrow occurred in 22% of diagrams (examples include diags. B, C, D, J, K and O in Fig. 1, and the diagrams in Fig. 2). Labelling of arrows (or other cues to meaning) was not provided in 16% of diagrams. Sixteen percent of diagrams would also have benefited from a key to explain the arrow symbolism. Some diagram captions or annotations ignored the presence of arrow symbolism in the diagrams, thereby denying a specified goal of search to the interpreter. Presentation of information was at a level that was too advanced for the age or learning level of the student or to the supporting text, in 4% of diagrams.

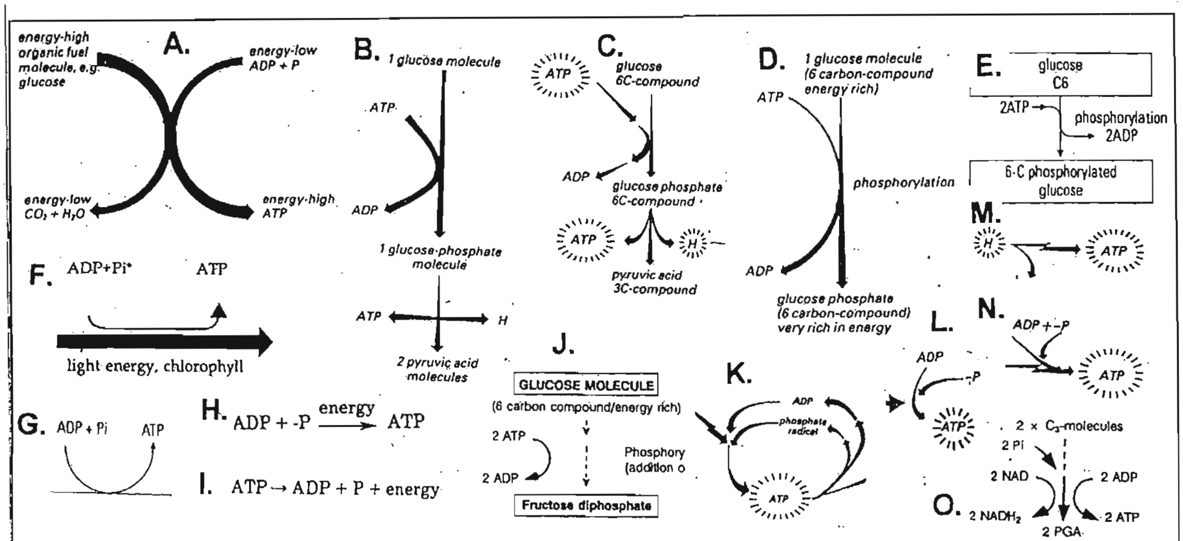


Fig.1. Diagrams (or portions of diagrams) illustrating a range of presentations of ADP/ATP conversions in respiration and photosynthesis. Diagrams A, B, C, D, H, I, K, L, M, N (Ayerst, et al., *2000b); Diagrams E and G (Ashwell,* et al., *1999b); Diagrams F, J and O (Degenaar,* et al., *2000).*

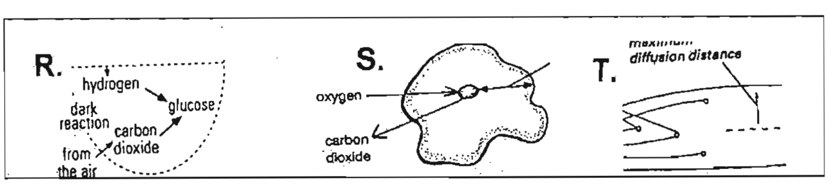


Fig. 2. Diagrams (or portions of diagrams) showing misleading use of arrow symbolism. Diagram R (Ashwell,* et al., *1999b); Diagrams S and T (Degenaar,* et al., *1999).

CONCLUSIONS

This study has shown that a wide range of arrow symbolism is used extensively, and often inappropriately, in diagrams. This suggests that it is wrong to include arrows in diagrams, on the assumption that they will necessarily aid student understanding of scientific concepts. A systematic study, of any difficulties experienced by students in the interpretation of arrow symbolism in diagrams, needs to be performed. In this regard, preliminary research has yielded evidence for numerous conceptual and reasoning difficulties with arrow symbolism among Grade 11 and 12 biology students. Future research will focus on the elaboration of such difficulties and the devising of strategies for the remediation of the difficulties through improved teaching approaches and diagram design (e.g. Mayer *et al.,* 1995; Lowe 1993).

Diagrams comprise a large part of a textbook and it is therefore essential that students understand their intention and how to interpret them in order to optimise learning. It is also of the utmost importance that textbook editors pay careful attention to the presentation of diagrams and in particular to arrow symbolism to ensure that the intended communication of the author is accurately portrayed. Beck (1984) stated: *"When designing combined and interrelated visual cues, careful consideration must be given to the necessity, prominence and reciprocity of the cues. Once the cues (visual) are embedded in the materials, learners may need special training in how to effectively process these signalling devices." P215*

This research was supported by financial grants from the National Research Foundation (NRF) and the University of Natal Research Fund (URF).

REFERENCES

Alesandrini, K.L.: 1987, 'Computer graphics in learning and instruction' *Psychology of Illustration Volume 2 Instructional Issues*, Houghton, H.A.and Willows, D.M.(Eds) Springer-Verlag N.Y. 175 - 179

Ashwell, A., Clitheroe, F., Dilley, L., Doidge, M., Marsden, S., Mtombeni, G.: 1999a, *Focus on Biology Grade 11,* Maskew Miller Longman (Pty) Ltd S.A.

Ashwell, A., Clitheroe, F., Dilley, L., Doidge, M., Marsden, S., Mtombeni, G.: 1999b, *Focus on Biology Grade 12*, Maskew Miller Longman (Pty) Ltd S.A.

Ayerst, P.W., Green-Thompson, A.L., Pellew, V.W. & Thienal, A. in collaboration with van Rensburg, N.P.J., van Rensburg, C.A.J. & Roux, J.S. : 2000a 10th impression, *Discovering Biology Grade 11,* Shuter and Shooter (Pty) Ltd Pietermaritzburg S.A.

Ayerst, P.W., Green-Thompson, A.L., Pellew, V.W. & Thienal, A. in collaboration with van Rensburg, N.P.J., van Rensburg, C.A.J. & Roux, J.S.: 2000b 4th impression, *Discovering Biology Grade 12*, Shuter and Shooter (Pty) Ltd Pietermaritzburg S.A.

Beck, C.R.:1984 Visual cueing strategies: Pictorial, textual and combination effects. *Educational Communication and Technology Journal* **32**, 207 - 216

Cohen, L., Manion, L. & Morrison, K.: 2000 *Research Methods in Education. 5th ed.* Routledge- Falmer London & New York 164-165

Degenaar, J.P., Scholtz, D.A., Thomas, A.M.L., Kuhn, M.S.F.: 1999 2nd impression, *Active Biology Standard 9,* Kagiso Publishers Pretoria S.A.

Degenaar, J.P., Scholtz, D.A., Thomas, A.M.L., Kuhn, M.S.F.: 2000 7th impression, *Active Biology Standard 10,* Kagiso Publishers Pretoria S.A.

Fisher, K.M.: 1990, 'Semantic networking: The new kid on the block', *Journal of Research in Science Teaching*, **27**(10), 1001 – 1018

Goldsmith, E., 1987: 'The Analysis of Illustration in Theory and Practice', In *Psychology of Illustration Volume 2 Instructional Issues,* Houghton, H.A.and Willows, D.M.(Eds) Springer-Verlag N.Y. 51-85

Henderson, G.: 1999, 'Learning with diagrams', *Australian Science Teachers' Association* **15**(2), 17 – 25

Hardin, P.: 1993, 'A theoretical Framework for diagrams and Information Graphics in Research and Education', *Visual Literacy in the Digital Age*: Selected readings from the annual conference of the International Visual Literacy Association October 13 – 17) 20-25

Hill, D. M.: 1988, 'Difficulties with diagrams'. *Journal of Science and Mathematics in S. E. Asia*, **11**(2), 32 – 40 Hunter, B., Crismore, A. & Pearson, P.D. :1987, 'Visual displays in basal readers and social studies textbooks', *Psychology of Illustration Volume 2 Instructional Issues,* Houghton, H.A.and Willows, D.M.(Eds) Springer-Verlag N.Y. 117-135

Jiminez-Valladares, J de Dios & Perales-Palacios, F.J.: 2001, 'Graphic representation of force in secondary education: analysis and alternative educational proposals', *Physics Education*, **36**, 227 – 235

Kosslyn, S.M. : 1989, ' Understanding charts and graphs', *Applied Cognitive Psychology* **3**, 185 - 226

Kress G. & van Leeuwen, T.: 1996, *Reading Images The grammar of visual design* Routledge London 43-118

Lowe, R.K.: 1993, '*Successful Instructional Diagrams',* Kogan Page Ltd London

Lowe, R. K.: 1996, 'Background knowledge and the construction of a situational representation from a diagram', *European Journal of Psychology of Education*, **11**(4), 377 – 397

Mayer, R.E. & Gallini, J.K.: 1990, 'When is an illustration worth ten thousand words?' *Educational Psychology*, **82**, 715 – 726

Mayer, R.E., Steinhoff, K., Bower, G. & Mars, R.: 1995 'A generative theory of textbook design: Using annotated illustrations to foster meaningful learning of science text', *Educational Technology Research and Development*, **43**(1), 31 - 43

Moore, P.J., Chan, L.K.S., & Wing, K.A.: 1993, 'High school students' use of diagrams during reading', *Research in Reading* **16**(1), 57 - 71

Phillips, T.I. & Quinn, J.: 1993, 'The effects of alternative flowcharting techniques on performance of procedural Tasks', *Performance Improvement Quarterly*, **6**(1), 54 - 66

Reid D., 1990, ' The role of pictures in learning biology: Part 1, perception and observation', *Journal of Biological Education*, **24** (3) 161 – 172

Reid, D.J. & Miller, G.J.A.: 1980'Pupils' perceptions of biological pictures and its implications for readability studies of biological textbooks', *Biological Education* 14(1) 59-69

Schollum, B.: 1983, 'Arrows in Science Diagrams: Help or hindrance for pupils', *Research in Science Education*, **13**, 45 - 59

Waller, R.: 1981, 'Understanding Network Diagrams', (Paper presented at the Annual meeting of the American Educational Research Association Los Angeles C.A. April) 1-17

Wheeler, A.E. & Hill, D.: 1990, 'Diagram-ease: Why students misinterpret diagrams', *The Science Teacher*, **57**(5), 59 – 63

Winn, W.: 1993, 'An account of how readers search for information in diagrams', *Contemporary Educational Psychology* **18**, 162 – 185

Winn, W.D., Li, T.Z. & Schill, D.E.: 1991,' Diagrams as aids to problem solving: Their role in facilitating search and computation', *Educational Technology Research and Development*, **39**, 17 – 30

SAARMSTE 2003
Students' perceptual difficulties with the graphical presentation of arrow symbolism in biological diagrams

Lynn du Plessis[1], Trevor R. Anderson[1], and Diane J. Grayson[2]
University of Natal, Pietermaritzburg[1], University of South Africa, Pretoria[2]
Email: anderson@nu.ac.za

Abstract
Students' perceptual difficulties with the graphical presentation of arrow symbolism were investigated using examples of stylised and abstract biology diagrams. The diagrams were first analysed for potential misleading or confusing presentation according to a set of criteria. Difficulties with the interpretation of the diagrams were investigated, using a series of free-response, multiple-choice and interview probes. These were followed by inductive analysis of the student responses. Several categories of difficulties, resulting from poor observation (search and detection), selection, sequential and organisational skills emerged and were classified according to the four-level framework of Grayson *et al.* (2001).

Context
Extensive research on diagrams has shown that they can improve student understanding of scientific concepts if the construction of the diagram is instructively effective (Lowe, 1993; Lowe, 1996; Kosslyn, 1989; Henderson, 1999; Wheeler & Hill, 1990; Reid, 1990; Hill, 1988; Fleming, 1987; Mayer & Gallini, 1990; Mayer, *et al.*, 1995). In this regard, a possible source of difficulty lies with the presentation of the physical (how features are drawn) and perceptual (how features are discerned) characteristics of the diagram. If graphic principles are violated, the relevant cues, such as those designated by arrows, will not be extracted or suitably organised. Consequently, the significance of the relationships between elements will not be grasped, and the process of scientific reasoning and the subsequent formation of a mental model, will be compromised (Kosslyn, 1989). In addition, acquisition of the intended information will be facilitated only if the reader also understands the parameters of the display type (spatial organisation) and the conventions or 'language' of the graphic devices used in the diagram (Fleming, 1987; Lowe, 1993; Henderson, 1999).

Graphic or design principles (Kosslyn, 1989; MacEachren, 1995, Kress and van Leeuwen, 1996; Goldsmith, 1987), include the principles of:
a. Perceptual apprehension (detection of lines, colours and regions);
b. Perceptual organisation (grouping or pattern formation) including the Gestalt laws of continuity (marks suggesting a continuous line tend to be interpreted as such), proximity (marks near each other tend to form perceptual units or discrete areas of focus within the diagram), similarity (similar marks tend to be grouped), good form (regular enclosed shapes are seen as single units) and repetition;
c. Between and within-level mapping (positioning of connectors between and within elements);
d. Congruity (the appearance of connectors should be compatible with meaning); and,
e. Acceptability (presentation or spatial organisation should be compatible with purpose).

Analysis of diagrams in biology textbooks by the above authors has shown that in many instances, the presentation of arrow symbolism is potentially misleading and confusing, causing students to show a wide range of difficulties. Although various general articles have been written on difficulties with arrow symbolism in the fields of physics and chemistry (Schollum, 1983; Jiminez-Valdares and Perales-Palacios, 2001), there appears to be no rigorous study reported on the evaluation of the use of, and difficulties with, arrows in scientific diagrams per se, let alone in biology diagrams, the focus of the present study.

Aim of research
The aim of our investigation was to assess students' perceptual skills with the graphical presentation of arrow symbolism in biology diagrams in order to identify difficulties with the interpretation of biology diagrams.

Research design and method
The study was performed, post-instruction, on three populations of Grade 11 and 12 biology students. A stylised diagram (Fig. 1) of the cardiac cycle (Wright, 1989) and an abstract flow chart (Fig. 2) of the thermoregulation process (Independent Examinations Board, South Africa, Senior Certificate examination paper, 1994) were

selected for investigating student difficulties. These diagrams were selected as being typical of what South African educators expect Grade 11 and 12 students to be able to understand and use for learning. The diagrams were also selected for their different styles (stylised and abstract) and the following range of cueing strategies that they possess:

1. Arrows indicating sequence and/or direction;
2. Single, diverging, converging and groups of arrows;
3. Vertical, horizontal and opposite foci;
4. Repetition; and,
5. Arrow style: Fig. 1, showing the cardiac cycle has one style of arrow, and Fig. 2 has several styles of arrow, representing different concepts.

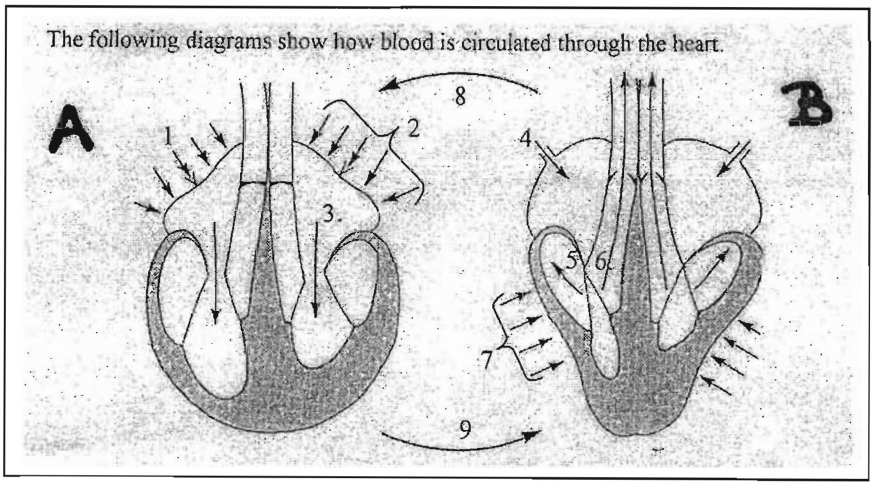


Fig. 1. A stylised diagram of the cardiac cycle (Wright, 1989).

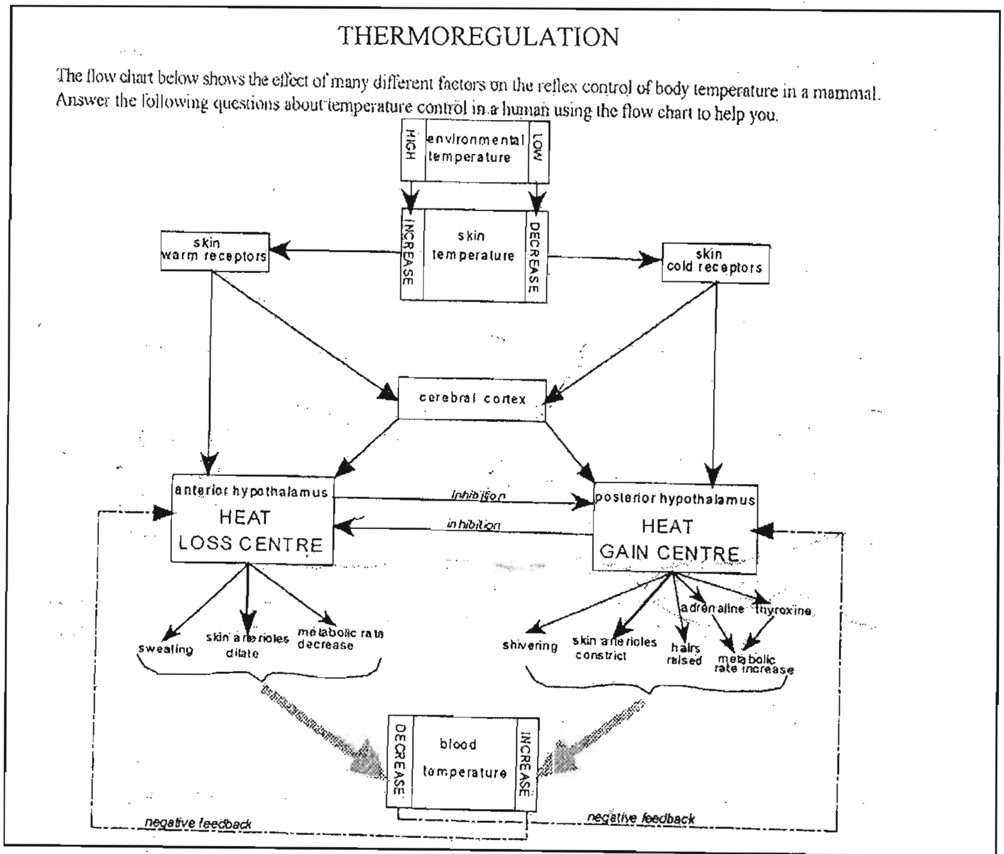


Fig. 2. An abstract diagram of a flow chart showing the process of thermoregulation (Independent Examination Board, South Africa, Senior Certificate examination paper 1994).

The presentation of arrow symbolism in each diagram was analysed according to design criteria (Kosslyn, 1989; Kress and van Leeuwen, 1996, MacEachren, 1995; Goldsmith, 1987; Collier, 2001; Bell, 2001), developed by us, from which possible student difficulties were identified. This information was used to inform the design of free-response, multiple-choice (Haslam & Treagust, 1987; Treagust, *et al.,* 1988) and interview questions (Posner and Gertzog, 1982; Cohen, *et al*., 2000) for investigating these possible difficulties. Inductive analysis (McMillan and Schumacher, 1993) of the student response data allowed the categories of difficulties (Table 1) to emerge, which were then classified on the 4-level framework of Grayson *et al.* (2001) according to the amount of insight into the nature of each difficulty.

Results and Discussion

Figs. 1 and 2 are composed of several perceptual units and were therefore, according to the results of our analysis, classed as complex for school level biology. This is supported by the following quote, relating to Fig. 2, from a student interview:

> *I think it's a good way of showing thermoregulation... but umm....I think its quite confusing because there are so many arrows and you really need to take a lot of time to look at it and try to understand it.*

In addition, Fig. 1 has one style of arrow representing several concepts and an inconsistent number of arrows in groups 2 and 7. These possibly misleading features, and other features of the diagrams, resulted in difficulties with the interpretation of the arrow symbolism.

The perceptual difficulties with arrow symbolism encountered by students, were categorised and classified at level 3 on the 4-level framework of Grayson *et al.* (2001). The difficulties are summarised in Table 1. Incidence of difficulties is presented as the average % of students showing the difficulty for related questions in the multiple-choice probes. Quotes refer to data from these probes and interviews.

	DESCRIPTION OF PERCEPTUAL DIFFICULTY resulting from poor observation (search and detection), selection, sequential and organisational skills.	Fig	Av %
1	The spatial organisation of the diagram is not established.		
a	The spatial organisation (layout) is partially identified.	2	50
b	The spatial organisation (layout) is incorrectly identified. Unexpected perceptual patterns, that use irrelevant or unintended features, emerge.	1	18
2	Poor perceptual strategies hinder the selection of relevant information and thus the formation of perceptual units.		
a	A universal answer is provided, such as explaining the overall process or layout of the diagram, instead of only the relevant elements being selected.	—	—
b	Absence of, or poor search patterns preclude grouping of appropriate information into elements within the diagram.	2	20
c	Poor perceptual strategies exclude relevant information from a perceptual unit. One or more arrows in a pair or group of arrows are ignored.	1 & 2	41
d	Poor sequential logic may preclude the correct pathway being traced.	2	11
e	A local rather than a global focus limits the value of supporting cues.	1	90
3	The relevant feature or cue is not distinguished from other information.	1	48
4	The position of the arrow relative to supporting information is poorly identified.	1	26
5	The position of the arrowhead, origin and shaft relative to supporting information is not identified.	2	11

Table 1. Descriptions of student difficulties with the perception of arrow symbolism in diagrams (Figs.1 and 2), classified at level 3 on the 4-level framework (Grayson *et al.* 2001). Incidence of difficulties is presented as the average % of students showing the difficulty over a series of related questions in the multiple-choice probes.

Fifty-percent of students had some difficulty (Difficulty 1a; Table 1) combining all elements in the diagram showing the process of thermoregulation (Fig. 2). For example, 11% of students explained only the effects of environmental temperature on blood temperature, while another 11% explained only the internal feedback mechanism. Further probing during interviews, showed a preference for the vertical pattern initiating from environmental temperature, illustrated by the following quote:

> *Interviewer: The layout of the diagram, is it arranged in a suitable way?....*

Student: Like everything else goes straight down except the blood temperature, but that's obviously, the most obvious because that's where it ends, where the whole diagram ends.

Cues contrary to this vertical line were overlooked. In selecting features affected in the thermoregulation process, 48% of students stopped short of the centrally situated frame representing blood temperature. Horizontally placed cues were not readily accessed. This is supported by the following typical student quote:

Interviewer: Alright. Just now when you described the process to me you didn't actually mention those two arrows (the inhibition arrows). Can you give me a reason for that?
Student: Umm.......No, I just sort of really noticed them now talking about these two – it just then struck me.

The complex nature of the diagram could hinder the establishment of the spatial organisation of the diagram. However, despite methodical probing, this difficulty persisted during interviews. This suggests that students' poor observational and organisation skills are also a consideration. As a consequence of this difficulty, a holistic interpretation is precluded.

Emergent patterns may result from distortions, illusions or unintended perceptual organisation not anticipated at the time the image was initially formed. Emergent patterns resulted in an average of 18% of students incorrectly identifying the spatial organisation of the diagram (Difficulty 1b). For example in determining the sequence of flow of blood in the cardiac cycle (Fig. 1), students attempted to create the continuity effect, ignoring the intentions of other symbolism. The positioning of, and similarity in the style of, arrows, probably contributed to this tendency. Fourteen-percent of students found arrows 8 and 9 strongly suggestive of a circular pattern indicating the pathway of blood flow. Other erroneous flow patterns included continuity from arrows 1 and 2 through 3, 9, 7, 6 and 8, and a sequence from arrow 4 to arrow 6 despite the closed valve. The latter example is illustrated in the following student quotation.

Interviewer: Okay. Look at diagram B. What does diagram B tell you?
Student: It shows the contraction of the ventricles and the dilation of the atria and blood coming in through 4 going up to the top of the ventricles and out through the aorta and pulmonary artery.

In this explanation, the closed valve is ignored, illustrating probable dominancy of the continuity effect over the good form principle of closure. However, the effect of closure prompted 22% of students to note arrow 6 but ignore arrow 4 when probed about the functions of part B of the cardiac cycle.

Distortions occur if parts of the diagram appear more, or less, prominent than intended. In the thermoregulation flowchart (Fig. 2), some students considered criteria such as the size of text or text frame, position of information or symbolism and the number of arrows in a group, important. However, the style of presentation, or position of these criteria proved misleading, resulting in an incorrect focus or emphasis. This difficulty (1b) is illustrated by the following quotes.

Interviewer: Okay, you started interpreting the diagram at heat gain centre. Why did you start there?
Student 1: Because the letters are so big that they emphasised upon you and you picked that up first.

And:

Student 2: ...I think the cerebral cortex, the way that that's put there (student indicates middle position of diagram) makes it look as though its not that important.

Thus in summary, emergent patterns may thwart the identification of correct relationships between elements, resulting in incorrect foci or emphases being applied during reasoning. The presentation of arrow symbolism within the diagram should therefore be explicit.

A universal answer such as an overall explanation of a process (Difficulty 2a), instead of the selection of relevant information, could result in key elements within the diagram being overlooked. This difficulty was apparent in interviews and open-ended questions about both Figs.1 and 2. The nature of multiple-choice answers precluded it. The following quote from an interview illustrates this difficulty.

Interviewer: Okay. What is the function of the cold receptors in thermoregulation?

Student: Umm... ummm to generate umm body heat.

In Fig. 2, an average of 20% of students showed evidence of poor search patterns (Difficulty 2b), by not grouping appropriate information into elements. Relationships within, and between, elements would thereby be compromised. Twenty-eight percent of students interpreted the arrows from environmental temperature, and increase in skin temperature, as having a direct effect (with no intermediate step) on the heat loss centre although neither is adjacent to the heat loss centre frame. The sweat glands were identified by 11% of students as the targets of LOW environmental temperature, despite it being on the wrong side of the diagram. The following quote from an interview illustrates the same difficulty:

Interviewer: ...what effect does a LOW temperature have on skin temperature?
Student: (moves pointer to heat LOSS centre) It decreases the blood temperature...and....ja, no, decreases the blood temperature.
Interviewer: And what makes you decide that it (indicates low environmental temperature) decreases the blood temperature?
Student: Because the heat loss causes the sweating and the metabolic rate to decrease and umm.... Then there's an arrow pointing to the blood temperature, but on the other side where it says decrease.

Due to poor perceptual strategies, relevant information is excluded from perceptual units (Difficulty 2c), thereby hindering a holistic interpretation. This suggests that a greater awareness of the significance of arrow symbolism should be promoted. Within elements, arrows, particularly those horizontally placed or placed contrary to constant direction, are ignored or not detected. An average of 41% of students showed this difficulty. In Fig. 2, 70% of students omitted to identify at least one of the four arrows pointing to the heat loss/gain centres. Fifty-three percent omitted the inhibition arrow, 38% the negative feedback arrow, 25% the arrow from the cerebral cortex and 18% the vertical arrow. As illustrated for difficulty 1a, a top downward focus again appears stronger than a horizontal cue. Thirty-four percent of students selected one branch of the divergent arrow from the receptors in the thermoregulation flowchart, interpreting it as an alternative and not as bi-directional. This was substantiated during interviews by the following typical quotation:

It goes specific ways depending on how heat needs to be lost, and
Ummm...ja well, I think the skin cold receptors obviously have an effect on the cerebral cortex which in turn has an effect on the heat um, gain receptors, but......ummm.......I think that's just a long way round. So I took the short way. Straight to the heat gain centres.

In Fig. 1, 29% of students did not associate arrow 5 (in opposite direction to the main flow of blood) with direction of blood flow, until specifically prompted.

Several students (11%) had difficulty (2d) maintaining a constant direction and included incorrect features when tracing a sequential pathway through the flow chart (Fig. 2).

Strong repetition was evident in both diagrams. However a local rather than a global focus, (Difficulty 2e), limited the value of the repetitive and other supporting cues. For example, the cue value of arrow 4 was not used by 90% of students, to either substantiate the function of arrow 1 or separate it from its perceptual unit. It may be argued that the complexity of the diagram exceeded the perceiver's cognitive abilities (Kosslyn, 1989) or scope of vision. However, specific probing during interviews for comparison between aspects of the diagrams, still resulted in repetitive cues being ignored. Adequate access demands active search patterns.

An average of 48% of students, in response to the proximity principle, had difficulty decomposing perceptual units (Difficulty 3). In Fig. 1, arrow 1 is drawn as part of, and in similar style to, the group of arrows labelled 2. Consistently over five questions, 57% of students did not isolate arrow 1 from the group of arrows. Specific probing for the function of this arrow in its singular form still resulted in 39% of students grouping it, thus denying a comparison of the functions of arrows 1 and 4. The strength of the proximity cue suggests that different styles of arrow are necessary to clarify the intention of the symbolism.

An average of 26% of students did not identify the position of the arrow precisely (Difficulty 4). The relevance of the position of the arrow was, therefore, compromised as the connection (arrow or line) between elements specifies meaning. Despite arrow 5 in Fig.1 being entirely within the ventricle, 24% of students interpreted it as indicating flow of blood leaving the heart. Arrow 1 was interpreted by 39% of students as showing blood entering the atrium despite it being positioned entirely outside the atrium. Quotes about arrow 1 state: "*blood through into atrium*" and "*blood going into (atrium)*". Fourteen-percent of students interpreted arrow 4 as indicating the opening, despite the arrow passing through the opening and into the atrium. Thus observation of the precise position of arrows is essential for the interpretation of meaning.

The precise position of the features of the arrow (Difficulty 5) was not identified by an average of 11% of students. In Fig. 2, 13% of students did not observe the precise origin of the arrow shaft at the 'increased temperature' portion of the 'environment' frame. By not noting the position of the arrowhead, 6% of students reversed the intentioned cause – effect direction between skin temperature and skin warm receptors. Similarly 13% of students included sweating or dilated arterioles as affecting the heat loss centre. This suggests that a greater awareness of the properties of arrow symbolism could alleviate this difficulty.

Implications

Student difficulties with the interpretation of diagrams resulted from the misleading and confusing presentation of the arrow symbolism in diagrams. In order to minimise these difficulties, and the possible formation of alternative conceptions, we suggest that textbook authors and artists ensure that arrow presentation is in accordance with graphical principles. Educators should also select diagrams in accordance with these principles and obtain appropriate training where competency is a problem. To minimise the effects of complexity, educators should also choose diagrams consistent with the level of maturity of their students, allow sufficient time for analysis, and provide guided instructions to facilitate interpretation.

Student difficulties with the interpretation of the arrow symbolism also resulted from a lack of understanding of the intentions of the graphic devices and poor perceptual skills. Educators should, therefore, ensure that students are aware of the implications or 'cue value' of graphical devices and are trained in the relevant perceptual skills. Perceptual skills involve observational skills required to search for and detect cues and patterns, selection skills for isolating relevant information and features of the symbolism either to form or decompose perceptual units, sequential skills for following a continuous pattern, and the organisation skills required to construct patterns such as for spatial organisation, perceptual units and relationships.

Future research will focus on the elaboration of student difficulties with the interpretation of arrow symbolism and the development of strategies for the remediation of the difficulties through improved teaching approaches and diagram design.

Acknowledgements

This research was supported by financial grants from the National Research Foundation (NRF) and the University of Natal Research Fund (URF).

References

Bell, P.: 2001, 'Content analysis of visual images', T. van Leeuwen & C. Jewitt (Eds.), *Handbook of Visual Analysis* (pp.10-34) Sage Publications Ltd., London.

Cohen, L., Manion, L. & Morrison, K.: 2000, *Research Methods in Education* 5th ed. 161 – 165, Routledge-Falmer, London & New York.

Collier, M.: 2001, 'Approaches to analysis in visual anthropology'. *Handbook of visual analysis.* Van Leeuwen, T & Jewitt, C.(Eds) Sage London.

Fleming, M.L.: 1987, 'Designing Pictorial/Verbal Instruction: Some speculative extensions from research to practice', *The Psychology of Illustration Volume 2: Instructional Issues* H.A. Houghton & D.M. Willows,136-158. Springer-Verlag Inc., New York.

Goldsmith, E.: 1987, 'The Analysis of Illustration in Theory and Practice', *Psychology of Illustration Volume 2 Instructional Issues,* H.A. Houghton & D.M. Willows, 51-85 Springer-Verlag, New York.

Grayson, D. J., Anderson, T. R. & Crossley, L. G.: 2001, 'A four-level framework for identifying and classifying students conceptual and reasoning difficulties', *International Journal of Science Education* **23**, 611-622.

Haslam, F., & Treagust, D.F.: 1987, 'Diagnosing secondary students' misconceptions of photosynthesis and respiration in plants using a two tier multiple- choice instrument' , *Journal of Biological Education* **21** (3) 203-211

Henderson, G.: 1999, 'Learning with diagrams', *Australian Science Teachers' Association* **15**, 17 – 25

Hill, D.M.: 1988, 'Difficulties with diagrams', *Journal of Science and Mathematics in S. E. Asia* **11** (2), 32-40.

Jiminez-Valladares, J de Dios & Perales-Palacios, F.J.: 2001, 'Graphic representation of force in secondary education: analysis and alternative educational proposals', *Physics Education* **36**, 227-235.

Kosslyn, S.M. : 1989, 'Understanding charts and graphs', *Applied Cognitive Psychology* **3**, 185 - 226

Kress G. & van Leeuwen, T.: 1996, 'Reading images', *The grammar of visual design*, 43-118, Routledge.

Independent Examinations Board, South Africa. *Senior Certificate examination paper* 1994.

Lowe, R.K.: 1993, *Successful Instructional Diagrams*, Kogan Page Ltd, London.

Lowe, R. K.: 1996, 'Background knowledge and the construction of a situational representation from a diagram', *European Journal of Psychology of Education* **11**(4), 377 – 397MacEachren, A.M.: 1995, *How maps work. Representation, Visualization, and Design.* The Guildford Press, New York.

Mayer, R.E. & Gallini, J.K.: 1990, 'When is an illustration worth ten thousand words'? *Educational Psychology* **82**, 715-726.

Mayer, R.E., Steinhoff, K., Bower, G. & Mars, R.: 1995, 'A generative theory of textbook design: Using annotated illustrations to foster meaningful learning of science text', *Educational Technology Research and Development* **43** (1), 31- 43.

McMillan, J.H. & Schumacher, S.: 1993, *Research in Education: A conceptual introduction* (3rd), Harper Collins, New York.

Posner, G.J. and Gertzog, W.A.: 1982, 'The Clinical Interview and the measurement of conceptual change', *Science Education* **66**(2), 195-209.

Reid D.: 1990, 'The role of pictures in learning biology: Part 1, perception and observation', *Journal of Biological Education* **24** (3), 161-172.

Schollum, B.: 1983, 'Arrows in Science Diagrams: Help or hindrance for pupils'. *Research in Science Education* **13**, 45-59.Treagust, D.F.: 1988, 'Development and use of diagnostic tests to evaluate students' misconceptions in science', In*ternational Journal of Science Education* **10** (2), 159-169.

Wheeler, A.E., & Hill, D.M.: 1990,'Diagram-Ease Why students misinterpret diagrams'. *The Science Teacher* **57**(5) 59 – 63.

Wright, D.:1989, *Human Biology,* Heinemann Educational, Oxford.

ERIDOB 2002
STUDENT DIFFICULTIES WITH THE USE OF ARROW SYMBOLISM IN BIOLOGICAL DIAGRAMS

Lynn du Plessis[1], Trevor R. Anderson[1], Diane J. Grayson[2]
University of Natal [1], University of South Africa [2], South Africa
email: anderson@nu.ac.za

Abstract

Students experience difficulties with the interpretation of arrow symbolism in biology diagrams. The source of difficulties could be attributed to the misleading use of graphic principles in presentations or to student difficulties with the interpretation and intention of the symbolism. To investigate the extent of the problem, a content analysis of six popular South African biology textbooks was undertaken to ascertain the prevalence of visual presentations, of each type of visual presentation (realistic, stylised and abstract) and of arrow symbolism within each visual type. The styles and purposes of arrow symbolism in the textbooks were categorised and a set of criteria developed by which to critically evaluate the presentation of arrow symbolism in visual displays. Several areas of potentially confusing presentations were revealed. A series of probes and interviews, using stylised and abstract diagrams, were designed and the results analysed to expose difficulties experienced by students in the interpretation of arrow symbolism. Several perceptual, reasoning and conceptual difficulties were revealed and classified at level 3 on the framework of Grayson *et al.* (2001). Presentation of arrow symbolism in diagrams that was contrary to the principles of graphic design contributed to difficulties.

1. Introduction

Textbooks are used in most schools as a source of visual displays (presentations). Visual displays are divided into realistic representations and stylised or abstract diagrams, all of which play important roles in the teaching and learning of science including biology. In general terms, realistic representations show structure while stylised and abstract diagrams enhance aspects of structure or function and emphasise relationships between elements of the diagram. To accomplish their particular focus, graphic devices such as arrows are used.

Extensive research on stylised and abstract science diagrams, has shown that they can improve student understanding of scientific concepts (e.g. Mayer & Gallini, 1990; Mayer, *et al.*, 1995; Winn, *et al.,* 1991; Sterner, 1998; Phillips & Quinn, 1993; Moore, *et al.*, 1993). However, to be instructively effective, the construction of the diagram should comply with graphic (design) principles (Kosslyn, 1989), and be relevant to the representation of the information or content and to the task. A shortfall in one or more of these areas may result in students showing difficulties with the interpretation of the diagram (e.g. Henderson, 1999; Wheeler and Hill, 1990; Reid, 1990; Hill, 1988; Lowe, 1993; Fleming, 1987).

Arrows, like many other symbolic representations, can be presented in a variety of patterns, take many styles and have a wide range of functions and meaning (Schollum, 1983; Henderson, 1999; Hardin, 1993; Geva, 1983). Lack of objective during the interpretive process or a misunderstanding of the intention of the symbolism relative to the context of the diagram could generate confusion or misinterpretation. To aid interpretation of diagrams, students should therefore be instructed in the relevant content knowledge, in the process of interpretation of diagrams (Kindfield, 1994; Lowe, 1996) and in the conventions and symbolism, including graphic devices such as arrows, used in diagrams (Henderson, 1999; Kress & van Leeuwen, 1996). An understanding of potential difficulties would allow appropriate strategies for such training to be designed.

Various general articles have been written on difficulties with arrow symbolism, mostly in the fields of physics and chemistry (Schollum, 1983; Jiminez-Valdares & Perales-Palacios, 2001; Amettler & Pinto, 2002). However, despite their significance as specifiers of function and relationships and their integral role in directing meaning, there appears to be no rigorous study reported on the evaluation of the use of, presentation of, and difficulties with, arrows in scientific diagrams per se, let alone in biology diagrams, the focus of the present study.

2. Aims of research

The aims of this study were two-fold:
a) To investigate the prevalence, and appropriate or misleading use of arrow symbolism in textbooks currently used for Grade 11 and 12 biology studies in South African schools.
b) To assess students' skills with the interpretation of arrow symbolism in biology diagrams in order to investigate students' understanding and identify difficulties.

3. Research design and Method

The above aims were respectively addressed according to the methods described in sections 3.1 and 3.2 below.

3.1 Prevalence of arrow symbolism and the quality of its presentation.

3.1.1 Information obtained from a convenient survey of 50 teachers in 35 schools was used to select three popular series of South African textbooks, from three different publishing houses, that are currently being used to teach Grade 11 and 12 biology in schools in the KwaZulu-Natal region of South Africa. Each series consisted of two books, one for Grade 11 and one for Grade 12 pupils (Ayerst, *et al.*, 2000a and 2000b; Ashwell, *et al.*, 1999a and 1999b; Degenaar, *et al.*, 1999 and 2000). These six books were then subjected to content analysis (Cohen, *et al.*, 2000; Bell, 2001) to obtain the following information:

a) The prevalence of visual displays in each of the six textbooks;

b) The categorisation of visual displays into realistic representations, and stylised and abstract diagram types (modified from Alesandrini, 1987; Hunter, *et al.*, 1987);

c) The occurrence, and prevalence, of arrow symbolism in visual displays and in each type of visual display; and,

d) The classification of the arrow symbols, used in the selected textbooks, according to differences in arrow style and purpose (Schollum, 1983; Kress and van Leeuwen, 1996).

3.1.2 A set of 12 criteria (Table 1), based on the work of previous researchers (Kosslyn, 1989; Kress and van Leeuwen, 1996; Goldsmith, 1987; MacEachren, 1995), was developed for evaluating the use and presentation of arrow symbolism in the realistic, stylised and abstract displays. The criteria were applied to 614 displays in the six selected Grade 11 and 12 biology textbooks. Possible areas of difficulty with interpretation of the displays were identified and used to inform the design of probes for student understanding and difficulties (See 3.2.1).

3.2 Identification of student difficulties with arrow symbolism.

The study was performed, post-instruction, on three populations (average number 50) of Grade 11 and 12 biology students. For investigating student difficulties, a stylised diagram (Fig. 1) of the cardiac cycle (Wright, 1989) and an abstract diagram of a flow chart (Fig. 2) of

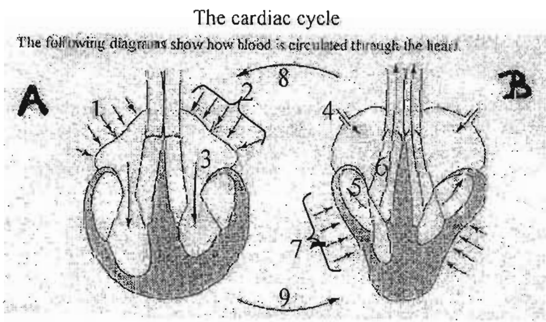


Fig. 1. A stylised diagram of the cardiac cycle (Wright, 1989 p55).

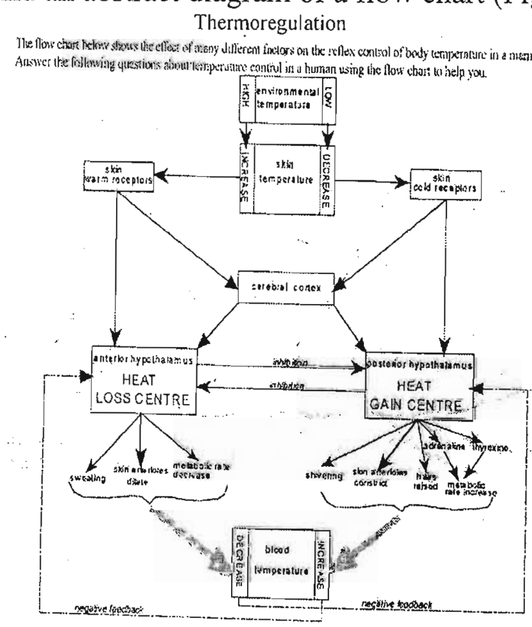


Fig. 2. An abstract diagram of a flow chart showing the process of thermoregulation (Independent Examination Board, South Africa, Senior Certificate examination paper 1994).

the thermoregulation process (Independent Examinations Board, South Africa, Senior Certificate examination paper, 1994) were selected as being typical of what South African educators expect Grade 11 and 12 students to be able to understand and use for learning.

These diagrams were also selected for their different styles (stylised and abstract) and the following range of visual cues that they possess:
a) Arrows indicating sequence and/or direction;
b) Single, diverging, converging and groups of arrows;
c) Vertical, horizontal and opposite foci;
d) Repetition; and,
e) Arrow style: Fig. 1, showing the cardiac cycle has one style of arrow, and Fig. 2 has several styles of arrow, representing different concepts.

3.2.1 The presentation of arrow symbolism in each diagram (Figs. 1 & 2) was analysed according to the design criteria in Table 1, from which possible student difficulties were identified. This information was used to inform the design of free-response, multiple-choice with justification (Haslam & Treagust, 1987; Treagust, *et al.,* 1988) and interview questions (Posner and Gertzog, 1982; Cohen, *et al.*, 2000; White & Gunstone, 2000) to establish whether these possible difficulties actually occurred among the students. Examples of typical probes are included in the appendix.

The multiple-choice probes (see examples in the appendix), included a correct answer (or propositional knowledge statement), several distractors and, in some instances, a possibility for students' suggestions. Justifications allowed clarification of students' perceptual and reasoning skills and conceptual understanding. Answers to related questions in probes were compared for constancy of interpretation. For the interviews, a series of questions from general, free-response questions at a superficial level to more specific and targeted questions at a deeper level, was designed to lay the foundation of, and guide the interview. However, flexibility allowed deeper investigation into difficulties specific to individual students. Respondents were encouraged to think aloud and point out features of the diagram being discussed, and where appropriate, draw markings on the diagram. In addition to notes made by the interviewer, the interviews were also audio-, and, in some cases, video-taped, and transcribed. To allow for any aberrant or 'invented' answers given on the spur of the moment (Hills, 1989), difficulties with incidences of less than 8% were disregarded. Incidences of related questions, designed to probe the same difficulty, were combined and averaged.

3.2.2 Inductive analysis (McMillan and Schumacher, 1993; Johnson & Gott, 1996) of the student responses to written and interview questions allowed the categories of difficulties to emerge. The identity, nature and description of each difficulty was honed by:
a) Comparing student responses with propositional knowledge statements based on scientifically acceptable answers to the questions and sound graphic principles (Kosslyn, 1989); and,
b) Using the 4-level framework of Grayson *et al.*, (2001) to guide the process of progressively gaining greater insight into the nature of each difficulty. Using this framework, difficulties emerging unexpectedly from free-response probes were classified on the framework at level 1, while difficulties suspected on the basis of teaching experience or following analysis of the diagrams according to the above criteria (section 3.2.1), were classified at level 2. More specific probing into the nature of the level 1 and 2 difficulties, including with interviews, yielded greater insight into the nature of the difficulties, allowing them to be classified at higher levels on the framework, namely at level 3 (partially established) or level 4 (fully established), at which stage stable descriptions of the difficulties were obtained. Only difficulties established at level 3 are reported in this paper (Table 2).

4. Results and Discussion

4.1 Prevalence of arrow symbolism and the quality of its presentation.

4.1.1 The prevalence of visual displays in the selected biology textbooks range from a minimum average of 0,57 visual displays per page (or 49% of pages with displays) in Degenaar, *et al.,* (2000) to a maximum average of 1,31 visual displays per page (or 84% pages with displays) in Ashwell, *et al.,* (1999a), with an overall average of 0,86 displays per page or 66%. These findings are consistent with the findings of other researchers (Reid and Miller, 1980). Visual presentations are, therefore, an important consideration in using textbooks. The results also indicate a predominance of stylised diagrams (58%) over realistic (27%) and abstract (15%) visual types, with a shift in emphasis from Grade 11 to Grade 12, of realistic representations to stylised and abstract diagrams. Presumably, this also indicates a shift in emphasis from structure to more cognitively-demanding considerations of process and explanation. This in turn presupposes a shift toward the greater use of symbolism.

The results of the analysis for arrow symbolism indicate that between 17% and 50% (with an average of 33%) of visual displays have arrow symbolism, and also bears out the expected shift in emphasis from Grade 11 to Grade 12. The average percentage increases to 45% if realistic representations, which seldom use arrow symbolism, are disregarded. Arrows are used in, on average, 67% of abstract diagrams and 38% of stylised diagrams. These results indicate the widespread use of arrow symbolism in diagrams and highlight the importance of a clear understanding of arrow symbolism for both presentation and interpretation.

Not only were arrows used in different types of displays over a wide range of contexts but the presentational style and purpose of the arrows varied considerably, both between and within diagram types. Eight categories of style, presented in a variety of groupings and pattern formations, and 26 categories of arrow purpose, were identified. The meaning of the arrow was in many cases specific to, and governed by, the context of the diagram, the position of the arrow/s in the diagram and the relative connections. The wide range of styles and purpose of the arrow symbolism required that the intended meaning of every arrow in a diagram be determined in context. This diversity of presentation could be perceived as confusing, but not necessarily misleading. However, since inconsistent or inappropriate presentation of arrow symbolism could have a negative impact on interpretation this was further evaluated.

4.1.2 The presentation of arrow symbolism in the selected textbooks was evaluated using twelve devised criteria (Table 1). The results revealed that, on average, 30% of diagrams were potentially confusing or misleading, particularly to students unfamiliar with the context or visual style. Incorrect interpretation could ensue. In view of limited space we will illustrate the results in Table 1 using selected examples of diagrams (see Fig. 3 and 4).

Perceptual skills are required to search for, detect, select and organise relevant features and related elements in diagrams (Winn, 1993). Perceptual difficulties can result if arrows are small relative to the proportions of the diagram, too small to be readily discernable, or inappropriately grouped. In fourteen percent of diagrams (Table 1; Criterion 2), interpretation was compromised as arrows were too small to be readily detected. Inappropriate pattern formation or grouping of arrows (Criterion 3) can inhibit the formation of perceptual units (groups) or lead the eye in unintended directions (e.g. in Fig 3 diagram B, the horizontal arrows imply a linear link between ATP and H, thus minimising their association with glucose-phosphate. Such illusionary or distortion effects, noted in nine percent of diagrams

(Criterion 3c), could lead to poor student mental models of the metabolic pathway chemistry.

Table 1. Evaluation of inappropriate presentation of arrow symbolism in visual presentations of six selected textbooks. The results for each criterion are expressed as the total number and percentage of diagrams showing some form of inappropriate use of arrow symbolism.

CRITERIA FOR ANALYSIS OF ARROW SYMBOLISM	Inapprop. Presentation	
	Total /614	Av %
1.Spatial organisation of arrows in diagram including 3 categories of effective diagram type, spatial frequency and conventional read	33	2
2.Size of arrow features proportionate to diagram	89	14
3.Pattern formation of arrows (Grouping, positioning, connecting)		
a. Grouping/unit binding (explicit, implicit boundaries & emergent properties)	71	12
b. Grouping for continuity, proximity, similarity, frequency (4 categories)	176	7
c. Presentation of arrows to avoid illusion or distortion effect	57	9
d. Positioning of individual arrows within elements:		
i) relevant connections for interpretation of data	54	9
ii) optimal positioning for meaning within diagram	102	17
iii) suitable positioning for visibility, distinct from background	91	15
e. Precise connections including origin, pathway & point (3 categories)	247	13
f. Appropriate connections between merging arrows	40	6
4. Number of arrows in diagram for effective processing		
a. Suitable number of arrows/groups of arrows (no gaps/no extras)	144	12
b. Suitability for information processing (meaning) at relevant level (no overload)	24	4
c. Consistent number in repeated group intending similar interpretation	5	1
5. Style of arrow		
a. Suitable style for intended meaning (12 categories)	352	5
b. Variation/consistency in style, for different/within purpose (3 categories)	124	7
c. Suitability of arrow style for the focus of diagram	104	17
d. Correct use of arrow 'conventions' (where applicable)	65	11
6. Clarity of meaning of arrow/s		
a. Unambiguous interpretation of individual/groups of arrows	135	22
b. Method/position/consistency of labelling for interpretation (2 categories)	191	16
c. Suitable key (where necessary)	100	16
7. Goal of search defined/clear for appropriate interpretation of arrows	106	17
8. Conformity of arrow style within diagrams, context and textbook	161	26
9. Level of presentation relative to age, learning level, text and culture	71	4
10. Layout & linkage of entities in displays and proximity to relevant text	97	5
11. Use of arrows as label lines, with other arrow symbolism or label lines	50	8
12. Cumulative assessment of arrow symbolism (relative to student level)	185	30

The continuity effect (a continuous line of marks tends to be grouped), was poorly presented in 9% of diagrams and, the proximity effect (marks near to each other tend to be interpreted as a unit), was unclear in 4% of diagrams. Few diagrams repeated arrows for the similarity (similar marks tend to be associated), and frequency (the size of the group indicates meaning) effects, thereby reducing the overall percentage given for Criterion 3b. In 12% of diagrams, arrows within a group, or groups of arrows within a diagram, were not well positioned, thereby compromising the implicit or explicit boundaries (formation of discernable units) (Criterion 3a), sometimes resulting in unintended emergent properties (unexpected patterns).

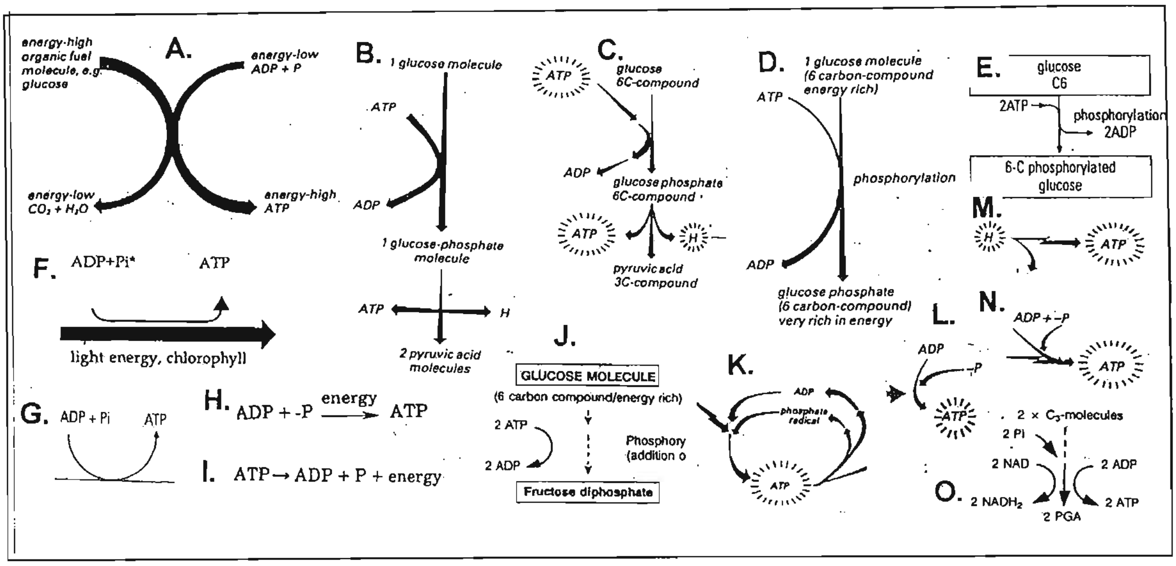


Fig. 3. A selection of diagrams (or portions of diagrams) illustrating ADP/ATP conversions in respiration and photosynthesis. Diagrams A, B, C, D, F, G, H, I, K and L (Ayerst, *et al.*, 2000b); E and J (Ashwell, *et al.*, 1999b); M, N and O (Degenaar, *et al.*, 2000).

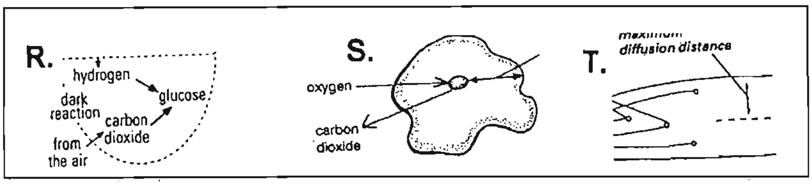


Fig. 4. Diagrams showing misleading use of arrow symbolism. Diagram R. (Ashwell, et al., 1999b); S and T (Degenaar, et al., 1999). Diagram R presents part of the process of photosynthesis. Diagrams S and T indicate the diffusion distance during gaseous exchange.

Arrows were not readily discernable from the background detail (or labels) of the diagram in 15% of diagrams (Criterion 3diii). Cohesion was lost (Criterion 3dii) where arrows were widely spaced (e.g. as in case of curved and straight arrows in Fig. 3, diagram J and O), or with arrows not linked specifically to discernable elements. An inappropriate number of arrows (Criterion 4a) was found in 12% of diagrams. The connective role of the arrows was compromised in the case of too few arrow links, or when obscured by unnecessary arrows (e.g. in Fig. 3 diagrams C and K, multiple arrows connect ATP and ADP). Four percent of diagrams, mainly abstract diagrams of life cycles and biochemical pathways, included too many arrows for information processing at Grade 11 and 12 levels (Criterion 9).

During processing, significance (for meaning) should be assigned to the position of the arrow, arrow features and style. In 9% of diagrams (Criterion 3di), arrows were not placed between the relevant connections (e.g. in Fig. 4. diagram R, hydrogen and carbon dioxide should join prior to the formation of glucose, which again could mislead students regarding the correct chemistry). The position of the arrow did not allow meaningful interpretation (Criterion 3dii) in 17% of diagrams (e.g. in Fig. 4 diagram S, the arrows incorrectly imply the destination of gases as the nucleus). Where the origin of the arrow shaft and the position of the point of the arrow were not precise (Criterion 3e), correct interpretation of the symbolism depended on prior knowledge (e.g. in Fig. 4 diagram T, the arrow heads stop short of both the exchange surface and midline, thereby not indicating the external source and destination of gases). In

6% of diagrams (Criterion 3f), the intention, or the sequence, of the merge or split of arrows was not clear (as in Fig. 3 diagram B, where ATP appears to be connected to H).
The clarity of meaning of arrows within the diagram is important for sound diagrammatic reasoning, leading to conceptual understanding. Twelve styles of arrow presentation were identified (Criterion 5a). In 5% of diagrams, arrow style was inappropriately presented for meaning in context. For example, the conversion of ADP to ATP shown in Fig. 3 diagram A, indicates relative energy levels, but despite being in close proximity in the textbook, the taper of the arrows in diagrams B, C and D ignore or contradict this. This could impact on the interpretation of students, alerted to the significance of the taper, thereby affecting their conceptual understanding. Some degree of ambiguity (Criterion 6a) with one or more arrows occurred in 22% of diagrams. Expected conventions (such as the broken line depiction for inhibition, the zigzag of energy and the parallel process of the ADP/ATP reaction) were not adhered to in 11% of diagrams (Criterion 5d) in which they were used (as in diagrams J and O in Fig. 3). In addition, conformity of particular arrow styles within diagrams, contexts and textbooks (Criterion 8) was ignored in 26% of diagrams. In Ayerst, *et al.* (2000b) eleven different depictions of the ADP to ATP transformation occurred. A further five novel presentations occurred in the other two series of textbook. Some examples of the styles of presentation of this reaction, given in Fig. 3, illustrate non-conformity as a potential source of confusion, especially to novices in the field. Further confusion could result from lack of direction in presentations. Labelling (Criterion 6b) of arrows, keys (Criterion 6c) or other cues for interpretation, were absent in 16% of diagrams. Some diagram captions or annotations ignored the presence of arrow symbolism in the diagram, thereby denying a specified goal of search to the interpreter (Criterion 7).

This analysis shows that inappropriately presented arrows can result in, or influence, perceptual, reasoning and conceptual difficulties, thus prompting the following investigation.

4.2 Identification of student difficulties with arrow symbolism.
4.2.1 Analysis of the diagrams in Figs. 1 and 2, selected to investigate students' understanding and difficulties with the interpretation of arrow symbolism, showed possible sources of confusing or misleading symbolism that may result in difficulties. Both diagrams are composed of several perceptual units and are therefore, according to the results of our analysis, classed as complex for school level biology. This is supported by the following quote, relating to Fig. 2, from a student interview:

> I think it's a good way of showing thermoregulation... but umm....I think its quite confusing because there are so many arrows and you really need to take a lot of time to look at it and try to understand it.

Fig. 1 has only one style of arrow representing several concepts (Criterion 5b), namely flow of blood (arrows 1, 3, 4, 5 and 6), the amount of pressure (or alternatively, degree of contraction or change in size), (arrows 2 and 7), and alternating processes (arrows 8 and 9). The frequency effect (Criterion 3b) shown by the number of arrows in groups 2 and 7 may, depending on the interpretation of the group size, influence syntactic emphasis. According to the analysis, there is no misleading use of arrow symbolism in Fig. 2.

4.2.2 Analysis of student responses to the various probes (see appendix) revealed several categories and subcategories of perceptual, reasoning and conceptual difficulties with various features of Figs. 1 and 2. These difficulties, all classified at level 3 on the 4-level framework, are summarised in Table 2. Since a detailed discussion of all these difficulties is beyond the scope of this paper, we will illustrate key difficulties with specific examples. In some cases we will give specific incidences of difficulties rather than the average values given in the table.

Table 2. Descriptions of student difficulties with the interpretation of arrow symbolism in the diagrams in Figs.1 and 2, classified at level 3 on the 4-level framework (Grayson, *et al.* 2001). Incidence of difficulties is presented as the average % of students showing the difficulty over a series of related questions in the multiple choice probes. # = Incidence not given in the case of interview evidence only.

	DESCRIPTION OF DIFFICULTY	Fig	Av %
	PERCEPTUAL DIFFICULTIES from inadequate observation (search and detection), selection, sequential and organisational skills.		
1	The spatial organisation of the diagram is not established.		
A	The spatial organisation (layout) is partially identified.	2	50
B	The spatial organisation (layout) is incorrectly identified. Unexpected perceptual patterns, that use irrelevant or unintended features, emerge.	1	18
2	Inadequate perceptual strategies hinder the selection of relevant information and thus the formation of perceptual units.		
A	A universal answer is provided, such as explaining the overall layout of the diagram, instead of only the relevant elements being selected.	#	#
B	Absence of, or inadequate search patterns preclude grouping of appropriate information into elements within the diagram.	2	20
C	Inadequate perceptual strategies exclude relevant information from a perceptual unit. One or more arrows in a pair or group of arrows are ignored.	1 & 2	41
D	Inadequate sequential logic may preclude tracing of the correct pathway.	2	11
E	A local rather than a global focus limits the value of supporting cues.	1	90
3	The relevant feature or cue is not distinguished from other information.	1	48
4	The position of the arrow relative to supporting information is poorly identified.	1	26
5	The position of the arrowhead, origin and shaft relative to supporting information is not identified.	2	19
	REASONING DIFFICULTIES (from inadequate processing skills)		
6	The syntactic emphasis of cueing strategies is misunderstood or not considered.		
A	Differing intentions of arrows presented in similar style is misunderstood or not considered.	1	59
B	Syntactic emphasis presented by the size and number of arrows in a group is misunderstood or not considered.	2	20
C	Significance is not afforded the position of the arrow or its features, relative to surrounding information.	#	#
7	The intention of arrow style is misunderstood or not considered.	2	14
8	The role of arrow symbolism as the link in the cause – effect relationship is not given significance.	1	18
9	Meaning in context cannot be attributed to arrows.	2	13
	CONCEPTUAL DIFFICULTIES		
10	Integration of information is limited by poor prior knowledge of the relevant concept.	2	17
11	Integration of information is limited by the use of prior knowledge without accessing layout.	#	#

The results suggested that some difficulties could be attributable to the misleading or confusing use of graphic principles in the diagram presentation. For example, difficulties may be influenced by the complexity (Table 1; Criterion 9) of the diagrams, particularly of Fig. 2. The spatial organisation or layout (Criterion 1) of Fig. 2 was partially identified (Table 2; Difficulty 1A), with crucial elements of the diagram being overlooked, by 50% of students. For example, 11% of students explained only the effects of external temperature on blood temperature, while another 11% selected or explained only the effects of the internal feedback mechanism (Appendix; Question B3). Further probing during interviews, showed a preference for the vertical pattern (Criterion 1) initiating from environmental temperature. This preference is illustrated by the following quote:

> Interviewer: The layout of the diagram, is it arranged in a suitable way?....
> Student: Like everything else goes straight down except the blood temperature, but that's obviously, the most obvious because that's where it ends, where the whole diagram ends.

However, despite methodical probing, this difficulty persisted during interviews. This suggests that students' poor observational and organisational skills are also a consideration.

Complexity will compound inadequate perceptual strategies required during diagram processing, resulting in difficulties with the selection of the relevant information needed to form perceptual units (Difficulty 2). For example, in Fig. 2, 70% of students omitted to identify (Difficulty 2C) at least one of the four arrows pointing to the heat loss/gain centres (Question B4).

The singular style of arrow presentation (Criterion 9) in Fig. 1 may have influenced the interpretation of the diagram. For example, the layout of the diagram was incorrectly identified as a result of unintended emergent properties (Difficulty 1B) by an average of 18% of students. In determining the sequence of flow of blood, 14% of students found arrows 8 and 9 strongly suggestive of a circular pattern (Criterion 3b) and indicated the pathway of blood flow between diagrams A and B, from arrows 1 and 2 through 3, 9, 7, 6 and 8. The positioning of arrows 8 and 9 in close proximity (Criterion 3b) to other arrows of similar style in the diagram contributed to the tendency to create a continuity effect. In addition, the combined effects of poor perceptual discrimination and similarity of presentation caused 59% of students to have some difficulty interpreting the intentions of arrows 1, 2, 4 and 7 (Difficulty 6A). Arrow 1 is drawn as part of, and in similar style to, the group of arrows labelled 2. Consistently over five questions, 39% of students did not isolate arrow 1 from the group of arrows labelled 2 (Difficulty 3), despite specific probing for the function of arrow 1 in its singular form. Twelve percent of the students interpreted arrows 2 and 7 as indicative of the path of blood flow.

In addition to difficulties related to problems with diagram presentation, several other perceptual, reasoning and conceptual difficulties emerged. The position and features of arrows require careful observation and identification in order to determine the relationship between the communicant information (Criterion 3d). Failure to access this vital information (Difficulties 4 and 5) and, using reasoning ability, afford it significance (Difficulty 6), will compromise the meaning of the arrow as a connector. Despite the position (Difficulty 4) of arrow 5 in Fig. 1 being entirely within the ventricle, 24% of students interpreted it as indicating flow of blood leaving the heart (Question B1). Arrow 1 was interpreted by 39% of students as showing blood entering the atrium despite it being positioned entirely outside the atrium. This is substantiated by the quotes: "blood through into atrium" and "blood going into (atrium)". Fourteen percent of students interpreted arrow 4 as indicating the opening, and not blood flow, despite the arrow passing through the opening and into the atrium (Question B2). In Fig. 2, an average of 19% of students did not detect the position of the arrowhead and recognise its significance (Difficulty 5). One consequence was the reversal of cause and effect. This is illustrated by the following responses:

Question: Stimulation of the skin warm receptors has the following effect(s):
Response 1: Skin warm receptors increases the skin temperature.
Response 2: Skin temp. increases because environmental temp. has increased.

And:

Question: Stimulation of the heat loss centre has the following effect(s):
Response 1: B occurs (the cerebral cortex and skin warm receptors are inhibited) so that there is no more heat being produced/stimulated .: allowing the heat loss process to take place.
Response 2: The skin warm receptors and the cerebral cortex are stimulated to cause a decrease in blood temperature, keeping the body at a constant equilibrium.
Response 3: The blood temperature has to increase for the stimulation of heat loss centre.

Inadequate reasoning ability, resulted in some of the several different styles of arrow used in Fig. 2, proving confusing (Difficulty 7) to an average of 14% of students. Interpretations of the dashed shaft of the arrow (Question C5) representing negative feedback included:

Student 1: not permanent or they don't always happen.
Student 2: because its not going anywhere as such its just umm......
Student 3: maybe because their function is prolonged ..umm......ja.
Student 4: ummm... well the part here with the blood temperature and the negative feedback mechanism, the line was dotted so makes you think that its not umm very clear or important.

Arrow 4, evoked this response:

Student: ....and number 4 has a longer tail.
I: Okay. Any reason for the longer tail?
S: Um, I think maybe because blood is slowly coming into the... or maybe blood has ...has a lot of
blood has come in and its sort of closing and its getting less.

Further, students without a sound prior knowledge base experienced difficulty interpreting aspects of the arrow symbolism (Difficulty 10). As a result of poor conceptual understanding of the terms 'cause' and 'effect', 41% of students chose the alternative "Pressure causes contraction" as the function of arrow 1 in Fig. 1, the reverse of the intended relationship. In questions specifically probing understanding of either cause or effect at various points of the diagram in Fig. 1, 35% could not identify the effects, and 29% had difficulty with the cause, of blood flow. Seventeen percent of students not conversant with the meaning of the term 'inhibition', were unable to link the left and right sides of the diagram effectively in order to interpret the role of the feedback mechanism in Fig. 2.

This investigation showed that students have various difficulties when interpreting diagrams, and that these difficulties may be aggravated by presentations contrary to graphic principles.

5. Conclusions

The content analysis of biology textbooks has shown that arrow symbolism is used extensively in diagrams and is, therefore, an important consideration in the interpretation of biology diagrams. Not only is there a wide range of pattern, style and purpose of arrow symbolism, but there is also little conformity of presentations between, and sometimes even within, diagrams. These factors can all contribute to difficulties with the interpretation of arrow symbolism. In addition, the graphic principles used in the creation of diagrams using arrow symbolism may not be adhered to. Presentation of arrow symbolism that is not in accordance with graphic principles may be inappropriate to the purpose of the diagram and may therefore impact negatively on its interpretation.

Several student difficulties were found to be influenced by poorly presented graphic principles. The complex nature of both diagrams and the similarity in style of the arrows in the cardiac cycle diagram (Fig. 1) may have negatively influenced the interpretation of the diagrams. In addition, several perceptual, reasoning and conceptual difficulties emerged. Perceptual difficulties were evidenced by inadequate organisation skills, poor detection, selection and sequential skills and difficulty distinguishing relevant features and related elements within a diagram. Inadequate processing skills inhibit significance being assigned to the position of the arrow, to arrow features relative to other information in the diagram and to arrow style. As a result of these difficulties, the process of reasoning is hampered and meaningful new knowledge is then not extracted from the diagram. In addition, limited prior knowledge and conceptual understanding may preclude interpretation.

6. Implications

In order to minimise difficulties with the interpretation of diagrams, and the possible formation of alternative conceptions, we suggest that authors and editors should be obligated to ensure that arrow presentation in textbook diagrams is in accordance with sound graphic principles. Furthermore, educators need to be aware of the implications of graphical devices when selecting textbooks and diagrams that include arrow symbolism to use as teaching tools. They should also not presume an understanding of arrow symbolism in novel diagrams, or diagrams being used as teaching tools. Educators should therefore ensure that students are aware of the potential role of arrow symbolism in different types of diagrams, that they have knowledge of graphic principles and are competent in the skills necessary for interpreting diagrams. Strategies need to be designed for teaching students how to read, interpret and learn from diagrams effectively. As there appears to be no standardised style for the presentation of arrow symbolism, conventions should be introduced.

Future research will focus on the elaboration of student difficulties with the interpretation of arrow symbolism, the development of a guide for the teaching and learning with diagrams using arrow symbolism, and the design of strategies for the remediation of the difficulties through improved teaching approaches and diagram design.

This research was supported by financial grants from the National Research Foundation (NRF) and the University of Natal Research Fund (URF).

REFERENCES

Amettler, J. & Pinto, R. (2002). Students' reading of innovative images of energy at secondary school level. *International Journal of Science Education,* 24 (3) 285-312.

Alesandrini, K.L. (1987). Computer graphics in learning and instruction. In H.A.Houghton & D.M. Willows (Eds.), *Psychology of Illustration Volume 2 Instructional Issues* (pp.175-179). New York: Springer-Verlag.

Ashwell, A., Clitheroe, F., Dilley, L., Doidge, M., Marsden, S., Mtombeni, G. (1999a). *Focus on Biology Grade 11*, South Africa: Maskew Miller Longman (Pty) Ltd.

Ashwell, A., Clitheroe, F., Dilley, L., Doidge, M., Marsden, S., Mtombeni, G. (1999b). *Focus on Biology Grade 12,* South Africa: Maskew Miller Longman (Pty) Ltd.

Ayerst, P.W., Green-Thompson, A.L., Pellew, V.W. & Thienal, A. in collaboration with van Rensburg, N.P.J., van Rensburg, C.A.J. & Roux, J.S. (2000a). *Discovering Biology Grade 11* (10th). Pietermaritzburg, South Africa: Shuter and Shooter (Pty) Ltd.

Ayerst, P.W., Green-Thompson, A.L., Pellew, V.W. & Thienal, A. in collaboration with van Rensburg, N.P.J., van Rensburg, C.A.J. & Roux, J.S. (2000b). *Discovering Biology Grade 12* (4th). Pietermaritzburg, South Africa: Shuter and Shooter (Pty) Ltd.

Bell, P. (2001). Content analysis of visual images. In T. van Leeuwen & C. Jewitt (Eds.), *Handbook of Visual Analysis* (pp.10-34) London: Sage Publications Ltd.

Cohen, L., Manion, L. & Morrison, K. (2000). *Research Methods in Education* (5th). (pp.164-165). London & New York: Routledge-Falmer.

Degenaar, J.P., Scholtz, D.A., Thomas, A.M.L. & Kuhn, M.S.F. (1999). *Active Biology Standard 9* (2nd). Pretoria, South Africa: Kagiso Publishers.

Degenaar, J.P., Scholtz, D.A., Thomas, A.M.L. & Kuhn, M.S.F. (2000). *Active Biology Standard 10* (7th). Pretoria, South Africa: Kagiso Publishers.

Fleming, M.L. (1987). Designing Pictorial/Verbal Instruction: Some speculative extensions from research to practice. In H.A. Houghton & D.M. Willows (Eds.), *The Psychology of Illustration Volume 2: Instructional Issues* (pp. 136-158). New York: Springer-Verlag Inc.

Geva, E. (1983). Facilitating reading comprehension through flowcharting. *Reading Research Quarterly,* 18 (4), 384-405.

Goldsmith, E. (1987). The Analysis of Illustration in Theory and Practice, In H.A. Houghton & D.M. Willows (Eds.), *Psychology of Illustration Volume 2 Instructional Issues* (pp.51-85). New York, Springer-Verlag.

Grayson, D.J., Anderson, T.R. & Crossley, L.G. (2001). A four-level framework for identifying and classifying students conceptual and reasoning difficulties. *International Journal of Science Education*, 23, 611-622.

Haslam, F. & Treagust, D.F. (1987). Diagnosing secondary students' misconceptions of photosynthesis and respiration in plants using a two tier multiple-choice instrument. *Journal of Biological Education,* 21 (3), 203-211.

Hardin, P. (1993). A theoretical framework for diagrams and information graphics in research and education. Visual literacy in the digital age. *Selected readings from the annual conference of the International Visual Literacy Association (October 13 – 17)* (pp.20-25).

Henderson, G. (1999). Learning with diagrams. *Australian Science Teachers' Association,* 15 (2), 17-25.

Hill, D.M. (1988). Difficulties with diagrams. *Journal of Science and Mathematics in S. E. Asia*, 11 (2), 32-40.

Hills, G.L.C. (1989). Student "untutored" beliefs about natural phenomena: Primitive science or common sense? *Science Education*, 73, 155-186, cited in Johnson, & Gott, (1996).

Hunter, B., Crismore, A. & Pearson, P.D. (1987). Visual displays in basal readers and social studies textbooks. In H.A.Houghton & D.M. Willows (Eds.), *Psychology of Illustration Volume 2 Instructional Issues* (pp.117-135). New York: Springer-Verlag.

Jiminez-Valladares, J de Dios & Perales-Palacios, F.J. (2001). Graphic representation of force in secondary education: analysis and alternative educational proposals. *Physics Education,* 36, 227-235.

Johnson, P. & Gott, R. (1996). Constructivism and evidence from children's ideas. *Science Education,* 80 (5), 561- 577.

Kindfield, A.C.H. (1994). Biology Diagrams: Tools to Think With. *The Journal of the Learning Sciences*, 3 (1), 1-36.

Kosslyn, S.M. (1989). Understanding charts and graphs. *Applied Cognitive Psychology*, 3, 185-226.

Kress G. & van Leeuwen, T. (1996). *Reading Images. The grammar of visual design* (pp.43-118) London: Routledge.

Independent Examinations Board, South Africa. Senior Certificate examination paper (1994).

Lowe, R.K. (1993). *Successful Instructional Diagrams*. London: Kogan Page Ltd.

Lowe, R.K. (1996). Background knowledge and the construction of a situational representation from a diagram. *European Journal of Psychology of Education*, 11 (4), 377-397.

MacEachren, A.M. (1995). *How maps work. Representation, Visualization, and Design.* New York: The Guildford Press.

Mayer, R.E. & Gallini, J.K. (1990). When is an illustration worth ten thousand words? *Educational Psychology*, 82, 715-726.

Mayer, R.E., Steinhoff, K., Bower, G. & Mars, R. (1995). A generative theory of textbook design: Using annotated illustrations to foster meaningful learning of science text. *Educational Technology Research and Development,* 43 (1), 31- 43.

McMillan, J.H. & Schumacher, S. (1993). *Research in Education: A conceptual introduction* (3rd). New York: Harper Collins.

Moore, P.J., Chan, L.K.S. & Wing, K.A. (1993). High school students' use of diagrams during reading. *Research in Reading,* 16 (1), 57-71.

Phillips, T.I. & Quinn, J. (1993). The effects of alternative flowcharting techniques on performance of procedural Tasks. *Performance Improvement Quarterly*, 6 (1), 54-66.

Posner, G.J. and Gertzog, W.A. (1982). The Clinical Interview and the measurement of conceptual change. *Science Education*, 66 (2), 195-209.

Reid D. (1990). The role of pictures in learning biology: Part 1, perception and observation. *Journal of Biological Education*, 24 (3), 161-172.

Reid, D.J. & Miller, G.J.A. (1980). Pupils' perceptions of biological pictures and its implications for readability studies of biological textbooks. *Biological Education*, 14 (1), 59-69.

Schollum, B. (1983). Arrows in Science Diagrams: Help or hindrance for pupils. *Research in Science Education*, 13, 45-59.

Sterner, R.T. (1998). The Scientific Method: An instructor's flow chart. *The American Biology Teacher*, 60 (5), 374-378.

Treagust, D.F. (1988). Development and use of diagnostic tests to evaluate students' misconceptions in science. *International Journal of Science Education*, 10 (2), 159-169.

Wheeler, A.E. & Hill, D. (1990). Diagram-ease: Why students misinterpret diagrams. *The Science Teacher*, 57 (5), 59-63.

White, R. & Gunstone, R. (2000). *Probing Understanding* (5th). Great Britain: Falmer Press.

Winn, W. (1993) An account of how readers search for information in diagrams. *Contemporary Educational Psychology,* 18, 162-185.

Winn, W.D., Li, T.Z. & Schill, D.E. (1991). Diagrams as aids to problem solving: Their role in facilitating search and computation. *Educational Technology Research and Development*, 39, 17-30.

Wright, D. (1989). *Human Biology*. Oxford: Heinemann Educational.

APPENDIX

A. Free-response questions referring to Fig. 1.

Instructions were to: Note features shown in the diagram to account for your reasoning.

1. Refer to diagram A - Explain what is happening in this diagram.
2. Refer to diagram B - Explain what is happening in this diagram.
3. Explain the flow of blood as shown in these diagrams.
4. Why are arrows drawn between the diagrams A and B?

B. Examples of multiple-choice questions. Every multiple-choice question carried the instructions to: Circle the correct answer(s) and give a reason for each choice of answer.

Examples of multiple-choice questions referring to Fig. 1. (* = Propositional statement)

1. In diagram A, the arrow labelled number 1:

Shows blood surrounding the atrium

A. Represents contraction of the muscles around the atrium
B. Shows that pressure is exerted onto the atrium so that it contracts
C. Shows the direction of flow of blood leading to the atrium *
D. Shows blood entering the atrium
E. None of the above

2. In diagram B, arrow 4 indicates:

A. The opening (entrance) to the atrium
B. An open valve into the atrium
C. Inward pressure
D. The direction of flow of blood *
E. The relaxation of the atrium
F. None of the above

Examples of multiple-choice questions referring to Fig.2. (* = Propositional statement)

3. The blood temperature will be increased:

A. If the environmental temperature decreases ONLY
B. If the blood temperature decreases ONLY
C. If EITHER the environmental temperature OR the blood temperature decrease *
D. If BOTH the environmental temperature AND the blood temperature decrease at the same time
E. None of the above

4. Which of the following options DIRECTLY (with no intermediate steps) affect the functioning of the heat loss centre:

A. An increase in environmental temperature
B. A decrease in environmental temperature
C. Stimulation of the heat gain centre *
D. An increase in blood temperature *
E. A decrease in blood temperature
F. Sweating
G. Stimulation of skin warm receptors *

H. Cerebral cortex *
I. Stimulation of skin cold receptors
J. Dilated skin arterioles
K. Shivering
L. None of the above

C. Examples of interview questions, referring to Fig. 2.
1. What is the topic of this diagram?
2. What does the diagram tell you? Explain it to me.
3. What does this portion of the diagram tell you? (depending on response to question 2).
4. What does this arrow, in this particular position, tell you? What does it mean?
5. Why is this arrow (as indicated), drawn in this style?