## Methods to determine the role of external representations in developing understanding in biochemistry

### **1** Introduction

The last two decades have witnessed increased trends in the use of external representations (ERs) for learning and teaching biochemistry. There is no doubt that ERs such as diagrams, pictures, graphs and animations are invaluable resources within textbooks, on computer screens and as part of educators' instructional visual tools. It follows, that students of biochemistry have to continuously process, interpret and interact with a diversity of ERs that depict biochemical concepts, processes and principles in *multiple* ways, at different levels of *abstraction* and in differing aesthetic formats (e.g. Schönborn & Anderson, 2006; Ainsworth & Van Labeke, 2004). In this regard, it is essential to consider that much science education research (e.g. Pintó & Ametller, 2002; Schönborn, Anderson & Grayson, 2002) has demonstrated that ERs are not always effective tools for providing the intended learning outcomes for students. Often, graphic artists, textbook authors and teachers simply assume that students' interpretation of ERs will automatically lead to the desired conceptual understanding and reasoning proficiency (e.g. Lowe, 2003). However, the literature shows that such assumptions are often naïve conjecture which is not in agreement with science education research (e.g. Scaife & Rogers, 1996). Therefore, given the increased exposure of students to ERs in biochemistry, and the rapidly expanding body of biological knowledge, it is logical to argue that urgent research is required to evaluate the effectiveness of ERs for learning in order to measure whether certain ERs may actually be doing more harm than good. Based on this argument, the current paper responds to the research question, what methodological instruments can be used to evaluate the effectiveness of ERs for teaching and learning biochemistry?

Since 2000, we have developed a range of qualitative instruments (e.g. Schönborn, 2005; Schönborn et al., 2002) to investigate students' conceptual and reasoning difficulties associated with the interpretation of ERs in biochemistry, as well as the effect of the ER itself on the interpretation process. Moreover, we are also currently developing tasks (e.g. Mnguni, Anderson & Schönborn, 2006) for investigating students' visualisation of ERs in the biomolecular sciences at large. In the current paper we present applications of these previously designed methods which we believe could contribute, in part, to alleviating the lack of specialised instruments available to education researchers for evaluating the effectiveness of ERs for teaching and learning in biochemistry.

## 2 Methods

Several research methods for gathering data on student interpretation of ERs in the learning and teaching of biochemistry were used in four separate studies (Mnguni et al., 2006; Schönborn, 2005; Schönborn & Anderson, submitted) conducted since 2000 at the University of KwaZulu-Natal, South Africa. An overall description of the methodological paradigm employed to collect data is provided below.

### 2.1 Participants and ERs used in the studies

Data on student interpretation of biochemical ERs was obtained from a total of 272 second and third-year undergraduate biochemistry students. Amongst others, the ERs that were provided to students during data collection consisted mainly of protein and amino acid structure and function. More specifically, the ERs displayed structures of glutamic acid and glycine as well as enzyme and antibody structure and their respective primary interactions with substrate and antigen. The latter ERs represented one or more levels of protein structure, including primary amino acid structure, secondary, tertiary and quaternary protein structure and, enzyme-substrate interaction. The ERs of relevance to this study are presented in the appropriate sections of the results.

### 2.2 Collection of data on students' interpretation of ERs

The overall methodological framework used to collect data on student interpretation of the ERs followed a post-positivistic philosophy that was characterised by inductive (Lincoln & Guba, 1985), interpretive and qualitative research methods (e.g. Gall, Borg & Gall, 1996). Data was collected from students by means of a multi-method approach that consisted of combinations of written probes (e.g. Stylianidou, Ormerod & Ogborn, 2002), audio- and video-taped clinical interviews (e.g. Pavlinic, Buckley, Davies & Wright, 2001), and student-generated diagrams (e.g. Glynn, 1997). Each of these three methods that we have developed in earlier work, and that have proved useful for collecting data on students' interpretation of ERs in biochemistry, are outlined below.

### 2.2.1 Written probes

Gathering written verbal outputs is one way in which the processing of ERs can be investigated. In this regard, written questions that are "free response" in nature allow the learner to write "what comes to mind" without being forced into a particular way of thinking (e.g. Stylianidou et al., 2002). In our earlier work (e.g. Schönborn et al., 2002), we initially used free-response type questions (also termed "probes" as we use the questions to probe for student understanding) to collect data during written tests. This ensured that students were free to respond spontaneously

and reveal their understanding and interpretation of the ER, without being led into giving a particular answer. In naturalistic research designs (e.g. Gall et al., 1996; Lincoln & Guba, 1985), such as the one reported here, as more insight was gained into the nature of each response pattern, the probes became increasingly more focused, and more specific for each pattern of interpretation that emerged from the data (e.g. Schönborn et al., 2002).

### 2.2.2 Clinical interviews

The *clinical* element of interview instruments in science education research is born out of Piaget's approach (e.g. Bukatko & Daehler, 1992) to gathering data from individuals where, while the learner speaks *freely*, the interviewer probes progressively deeper into the learner's understanding of a concept of interest. In this respect, clinical interviews have the general objective of gathering information about the nature and extent of a person's cognitive structure and knowledge about a certain idea (e.g. Posner & Gertzog, 1982). Based on this premise, our earlier work (Schönborn & Anderson, submitted; Schönborn, 2005) involved the development of a specially designed instrument termed the Three-Phase Single Interview Technique (3P-SIT) to gather data on students' interpretation of ERs. The overall structure and protocol of the instrument is that it consists of three phases for the collection of data. The objective of Phase 1 is to use free response probes to gather information about a students' conceptual knowledge of a particular phenomenon of interest before exposure to any ER. Upon exposure of a student to an ER of interest, Phase 2 uses semi-structured probes to measure a student's ability to reason with the ER and with their own conceptual knowledge. In Phase 3, students respond to semi-structured probes about the ER of interest in order for the researcher to measure the effect of the actual mode of representation on student interpretation processes.

### 2.2.3 Student-generated diagrams (SGDs)

Modern science education research suggests that one useful technique for investigating how learners process ERs in science is to get them to construct or generate their own diagrams (e.g. Beilfuss, Dickerson, Libarkin & Boone, 2004). Such methods enable workers to trace and probe students' mental models of scientific ERs (Gobert & Clement, 1999). As noted by Glynn (1997), when students draw diagrams of their mental representations, they are essentially sketching their mental models of a particular concept. Hence, methods that incorporate the "drawing" of mental models can be seen as a diagnostic tool that can help researchers isolate conceptual and reasoning difficulties and alternative models that students may possess (e.g. Glynn, 1997; Kindfield, 1993/1994). The use of student-generated diagrams (SGDs) is a technique that we are currently employing (e.g. Mnguni et al., 2006) to trace students' interpretation and processing of ERs in biochemistry.

#### 2.3 Data analysis

The data collected were subjected to analytic induction (e.g. Mouton, 2001; Gall et al., 1996). This approach to data analysis is concerned with "inducing" (Gall et al., 1996, p. 25) common themes from the data as a process of discovery rather than subjecting previously enforced themes to the data before any analysis (e.g. Bell, 1999). Such inductive analysis of the data constitutes a research process where patterns are uncovered and "made explicit" from "embedded" information that resides in the data (Lincoln & Guba, 1985, p. 203).

During inductive analysis of the data, patterns of meaning and evidence were allowed to emerge from the data themselves (e.g. Anderson & Aresenault, 1998; Lincoln & Guba, 1985) without being previously enforced (McMillan & Schumacher, 1993). In addition, interpretations were drawn and described once all information was gathered (e.g. Verma & Mallick, 1999). Such an inductive approach is also often viewed as a "descriptive synthesis" of the data rather than a process of data reduction (McMillan & Schumacher, 1993, p. 480). In this regard, the current study was concerned with providing a natural and detailed description of the patterns that emerged from the data (Gall et al., 1996). Furthermore, the method of data analysis employed in the study was viewed as being *grounded* in theory (e.g. Gall et al., 1996; Miles & Huberman, 1994; McMillan & Schumacher, 1993; Lincoln & Guba, 1985). This was because descriptions and explanations of phenomena came from the data themselves rather than with a view to an already pre-existing theory. This approach to data analysis is in contrast with other solely deductive forms of analysis often associated with positivistic designs (e.g. Verma & Mallick, 1999).

In addition to being used to obtain specific data on students' interpretation of ERs alone, we argue that the developed methods described above can also be adapted to yield empirical data about the actual effectiveness of ERs in developing students' understanding of biochemistry.

# **3** Testing of instruments for investigating the effectiveness of ERs in biochemistry

In response to the research question raised in this paper, we provide data to show how our previously developed methods can be adapted for the evaluation of the effectiveness of ERs in developing students' understanding in biochemistry. We also show how these adapted methodological instruments can inform us of the role of the graphical features contained within ERs and, therefore, of the effectiveness of ERs for successful interpretation of biochemical knowledge.

### 3.1 Using written instruments to evaluate the effectiveness of ERs

In one aspect of the research, we wished to obtain student responses to the following three ERs of antibody-antigen interaction (Fig. 1 A, B & C).



Fig.  $1^1$ : Three ERs showing the three-dimensional structure of an antibody (IgG) molecule. (A): Tertiary structure showing Variable (V) and Constant (C) regions. The two V regions are represented by the two 'halves' of the spherically-shaded areas to which antigen binds (from Bohinski, 1987); (B): Tertiary structure in chain form (from Bohinski, 1987); (C): Three-dimensional structure showing the two Heavy (H) chains (heavily shaded) and two Light (L) chains (lightly shaded). A carbohydrate unit is attached to the protein (from Stryer, 1995).

<sup>1</sup> The three original ERs that were used in the study were provided in colour. Fig. 1 (A) depicted antigen in dark red, the Variable (V) domains were coloured light red and Constant (C) regions in grey. Fig. 1 (B) depicted the arrows and text, "binding specificity for antigen" in dark red. Fig. 1 (C) depicted one of the Heavy (H) chains in dark red and the other in dark blue. One of the Light (L) chains was shown in light red and the other in light blue. The carbohydrate chain attached to the protein molecule was shown in yellow.

Examples of written instruments that were used to investigate students' interpretation of the ERs (Fig. 1) and that we found could also be adapted to evaluate the effectiveness of the above ERs are presented in Fig. 2 below.

Describe everything you think this diagram represents or shows. (Fig. 1 A, B & C)

Use the diagram to explain what happens to the antigen (i.e. what does it do?) after it has bound to the antibody. (Fig. 1 A & B)

What do the circles and lines represent? (Fig. 1 B)

Where and how does antigen bind to the antibody? (Fig. 1 A & B)

Fig. 2: Examples of four written instruments that were used to obtain student responses to three ERs. The respective ERs that correspond to each probe are shown in brackets.

Upon analysis of students' written responses to the probes (Fig. 2), we identified three general categories of difficulty with students' interpretation of the three ERs (Fig. 1). The three general categories that emerged were classified as the process-type (P), structural-type (S) and DNA-related (D) difficulties. Students demonstrating the general process-type difficulty (P) thought that the three IgG antibody ERs (Fig. 1) represented various complex processes, rather than a simple non-covalent binding interaction between antibody and antigen molecules. Students who showed the structural-type difficulties (S) when interpreting the three ERs (Fig. 1) incorrectly interpreted the way in which various structural features of IgG are visually represented on the ERs. In the DNA-related difficulties (D), some students interpreted the three ERs (Fig. 1) as representing a form of DNA structure and/or DNA processing.

When incidences of the three categories of difficulty were calculated, relative to *each ER* used in the study, it was shown that different ERs played a greater role in causing a particular difficulty given that the conceptual knowledge required to interpret all the ERs was assumed to be highly similar. For instance, Fig. 1 A induced the highest incidence for the P category at 70% followed by Fig. 1 B at 50% and Fig. 1 C at 7%. By contrast, Fig. 1 B and Fig. 1 A caused the highest incidence of 19%. Lastly, Fig. 1 A caused most students to reveal the D category difficulty at 40% incidence followed by Fig. 1 C (10%) and Fig. 1 B (4%). Thus, with respect to the aims of the current paper, these incidences provide an indication of the degree in which the nature of the graphical markings represented within each ER contributed towards a particular category of difficulty and therefore, serve as a measurement of the effectiveness of a particular ER on students' interpretation. In this regard, it is clear from the above incidences that the visual markings in Fig. 1 A and Fig. 1 B caused the most problems for students,

with Fig. 1 A having the most negative influence out of the three, across all three categories of difficulty.

In further inspection of the above incidences relative to each ER (Fig. 1), analysis of the data suggested that the *nature of the ER* and its graphical markings played a major role in students' ability to successfully interpret them. Again, such analyses suggest that the above instruments (e.g. Fig. 2) could be used to measure the effectiveness of ERs (e.g. Fig. 1) in a biochemical context, albeit in qualitative terms. A demonstration of such a qualitative measurement of ER-effectiveness is as follows. For Fig. 1 A, the arrow-like depiction of antigen as both pointing at the space between the light and heavy chains and being of the same width as the space; the "ball-like" graphical means used to depict V and C regions of heavy and light chains; the use of a red-like colouring to represent variable regions of the antibody; and, the black "lines" used to denote polypeptide chains as well as disulfide bonds, could have all contributed to categories of difficulty. For Fig. 1 B and C, the graphical nature of the arrows used to indicate possible areas for antigen-antibody interaction often caused induced difficulties when students interpreted them as indicating a point of entry for the antigen molecule. Furthermore, the graphical marks used to represent amino acids on Fig. 1 B and C were often misinterpreted, while the "supercoiled" arrangement representing the heavy and light chains in ERs Fig. 1 B and C also misled some students. Lastly, across all three ERs (Fig. 1), students often struggled to resolve the function of the arrow symbolism used to graphically represent the antigen and its binding *location* on the antibody structure. As a result, students struggled to discriminate between those graphical markings that showed antibody components and those that showed possible sites for interaction between antigen and antibody. All of these analyses are examples that demonstrate how the effectiveness of ERs for learning biochemistry can be evaluated.

# **3.2** Using clinical interview instruments to evaluate the effectiveness of ERs

As described in the methods section above, Phase 3 of the 3P-SIT method described by Schönborn and Anderson (submitted) can be used to measure the role and effect of the graphical markings and features of the ER such as conventions, icons, colour, artistic devices, labels and captions on students' reasoning processes. In other words, data revealed in Phase 3 of 3P-SIT helps the researcher measure the nature or influence *of the ER* on students' reasoning processes. Therefore, with respect to the current study, Phase 3 serves as a means with which to evaluate the effectiveness of the ER during interpretation. For instance, consider Fig. 3 below, which presents examples of typical interview questions that are given to students during Phase 3 of 3P-SIT. Is there anything on the ER in particular that you don't understand or find confusing?

What do you think this ER is not showing? Explain your answer.

Consider yourself a diagram designer or textbook author. If you could change this ER in any way, what would you do to improve it, if anything?

### Fig. 3: Examples of interview questions used in Phase 3 of 3P-SIT.

In an example of how data generated in Phase 3 of 3P-SIT can be used to measure what graphical property of an ER may or may not be effective for students, consider the following interview extract that was generated by one student upon interpretation of the ER shown in Fig. 4 below:

Interviewer: Is there anything that you don't understand or find confusing on this representation [Fig. 4]?

Student: ... The only thing is like... where the bonds form between the different antibodies.



Fig. 4: ER depicting electron micrograph (x 1 000 000) of complexes formed on mixing divalent antigen with antibodies. The antigen links together three Y-shaped antibody molecules to form a trimer-shaped complex (from Roitt, 1997).

It is evident from the above interview datum that the student thought that the Y-shaped antibodies were somehow joined together, rather than being bonded to small antigens present in between the antibodies. Such data generated from the 3P-SIT instrument demonstrates a means with which researchers can measure how specific graphical features within an ER can influence students' interpretation. Therefore, such analysis assists researchers in evaluating the relative effectiveness of ERs for learning biochemistry.

# **3.3** Using student-generated diagrams (SGDs) to evaluate the effectiveness of ERs

In one example where we employed an application of methods concerned with students generating their own diagrams to measure interpretation of ERs in biochemistry, they were asked to, "Draw a simple amino acid of their choice". Upon responding to the task, we found that a range of different representations of the concept were generated. Two examples of such student-generated diagrams (SGDs), obtained from two students, are provided below in Figure 5.



Fig. 5: Two SGDs obtained from two different students that represent the amino acids glutamic acid and glycine, respectively.

Although the sample of students produced quite a variety of SGDs (e.g. Fig. 5), we observed that individual students preferred to only generate the amino acid representation which they felt most comfortable with. In addition, when more than one SGD was generated by the students, not only did they find it very challenging to relate one representation to the other but they also struggled to relate their drawings to actual ERs of the concept, i.e. to those in textbooks. This finding suggests that due to the multitude of different graphical features and ERs that are available to students for depicting even simple concepts, such as amino acid structure, students find it difficult to form a single and integrated mental model of the concept (e.g. Schönborn & Anderson, 2006). Instead, students often tend to exhibit a 'piecewise' understanding of a concept and struggle to link, and translate, between different ERs which represent the same phenomenon, a difficulty that also seems to vary from one student to another. In this regard, data such as those revealed by instruments which require students to generate their own diagrams (e.g. Fig. 5), researchers can measure whether certain ERs are effective in developing students understanding or not. In the current example, we propose that the sheer diversity in graphical form and markings used to depict even 'simple' biochemical concepts such as amino acid structure may sometimes 'overwhelm' students and cause a surface-level understanding of the concept understudy (e.g. Lowe, 2003).

### 4 Concluding remarks

This paper has demonstrated how three methodological instruments can be used to determine the role of ERs in developing students' understanding in biochemistry. In particular, we have shown that application of our previously developed written, clinical interview and student-generated diagram methods are useful for yielding empirical data that sheds light on the actual effectiveness of the graphical features on students' interpretation of ERs in a biochemical context. The written instruments can be used to measure the effectiveness of ERs, albeit in qualitative terms. The development of accompanying quantitative analytic methods in addition to the

qualitative written methods could serve to strengthen the findings attributed to the use of the written instruments presented in this paper. In terms of the interview instrument, we have shown that the instrument can be used to yield useful information as to the role of an ER for developing understanding in biochemistry. The instrument is simple, easy to use and potentially extremely versatile in that it could potentially be applied to all types of ERs. However, given this claim, the current methods have been developed and applied to the use of ERs that depict limited concepts in biochemistry. Nevertheless, given the general lack of specialised instruments for measuring the actual effectiveness of ERs for learning biochemistry (e.g. Richardson & Richardson, 2002), these methods could be viewed as useful instruments in this area of research.

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