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Some cognitive perspectives related to students' interaction with external representations in biochemistry

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Abstract

External representations (ERs) like diagrams are considered essential vehicles for communicating scientific concepts and for the construction and integration of knowledge. In recent years, the focus in diagram research has shifted away from merely identifying the benefits and pitfalls of using ERs for teaching and learning science to that of investigating students' *interaction* with them. That is to say, recent theorists (e.g. Zhang and Norman, 1994; Scaife & Rogers, 1996; Cheng *et al*., 2001) view interaction with an ER as a *system* of representation governed by the relationship between, and the distribution of, both internal and external characteristics during processing. This study identifies some of the cognitive perspectives that are related to students' interaction with ERs in biochemistry and suggests how investigation of these can aid both the design of, and teaching and learning with, ERs in science.

Introduction

No educator or learner would deny the usefulness of diagrams and other visual displays in the learning and teaching of science. Research on the effectiveness of diagrammatic representations (DRs), and other external representations (ERs), in the learning of science is a rapidly developing field (e.g. Sanders, 2002; Brna *et al*., 2001) which, these days, takes both the educational and cognitive science perspectives into consideration (e.g. Scaife & Rogers, 1996; Cheng *et al*., 2001). This approach is particularly valuable for understanding the role of ERs in 'abstract' sciences such as biochemistry which make extensive use of visual ERs like space-filling representations, computer models, graphical plots, schematic displays, and symbolic notations to help students *see* and interact with the sub-microscopic environment (e.g. Hoffmann & Laszlo, 1991). For students to learn effectively from ERs they not only have to understand multiple and often idiosyncratic external depictions of the same phenomenon (see Stryer, 1995), they also have to deal with formulating and using the required conceptual knowledge that is implied by each ER. In the science of biochemistry, ERs rarely exist in isolation, and the *way* students *interact* with and *use* them is of particular educational relevance (e.g. Cheng *et al*., 2001). This is the focus of this paper. In our previous work (Schönborn *et al*., 2002a) the research framework of Grayson *et al*. (2001) was used to identify and classify student difficulties with the interpretation of ERs used in biochemistry. Using these difficulties, the aim of the present study was to extract and elaborate on some of the cognitive variables rooted to these difficulties, compare them to the current literature, and use this knowledge to inform guidelines for ER design and the use of ERs for teaching and learning in biochemistry, and science in general.

Methods and Rationale

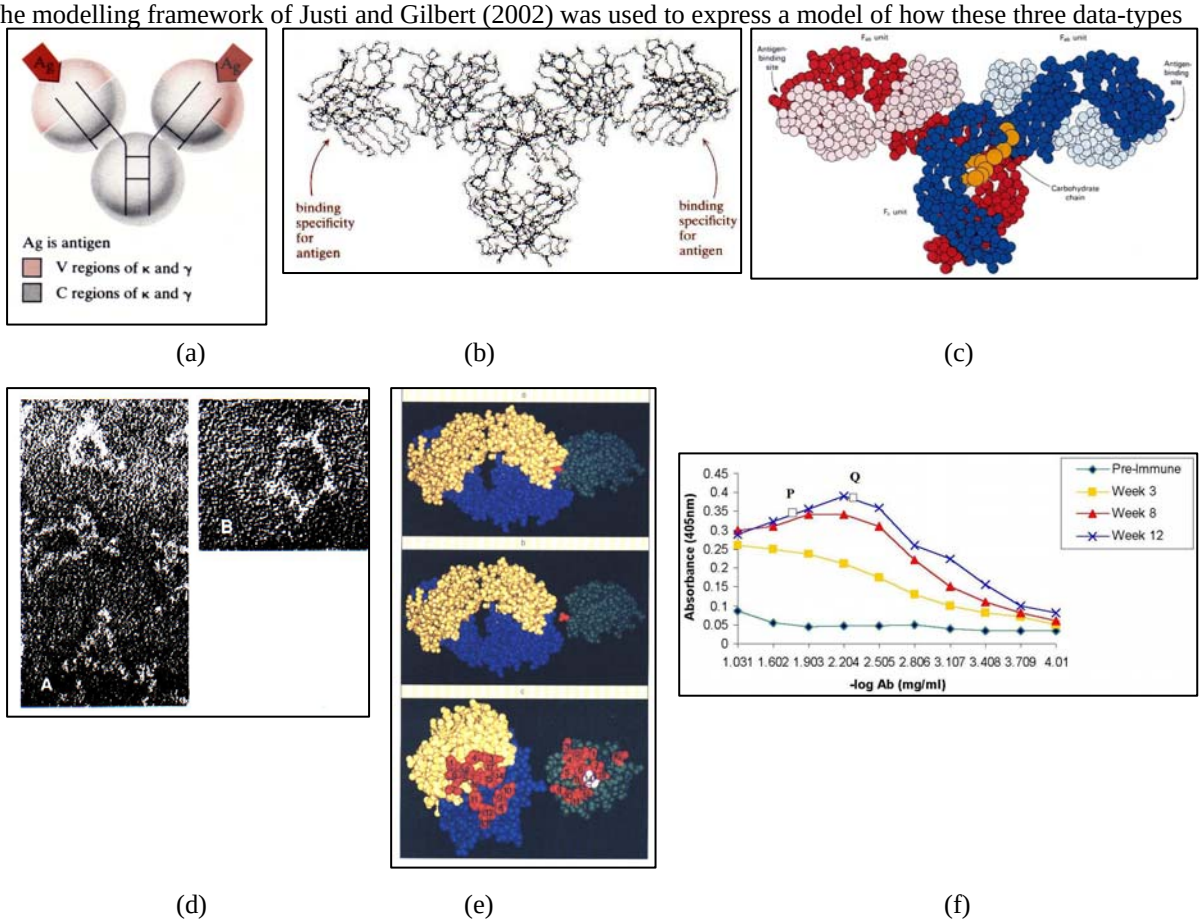
Student samples and external representations under study

The study was done from 2000 to 2002 and investigated 166 biochemistry students' interaction with six multiple ERs which all, in varying degrees of abstraction (e.g. Sumfleth & Telgenbüscher, 2001), depicted the structure of immunoglobulin G (IgG) and its primary interaction with antigen (Fig 1). The participants consisted of the following samples. One hundred and thirty were second-year biochemistry students who had studied a module on immunology and 21 were third-year students who had studied the same course the previous year. All of these students responded to written probes and ten second-year students participated in interviews. Furthermore, 6 students with varying domain-specific knowledge in different years of study and a further 9 third-year biochemistry majors participated in interviews only.

Designing instruments to gather information about students interaction with the ERs

Student interaction, and difficulties, with the ERs (Fig 1) was initially investigated with free-response type written probes. As more insight was gained into the nature of each difficulty the probes became increasingly more specific for each difficulty. Subsequently we designed a three-phase single interview technique (3P-SIT) for the isolation of three types of data: students' diagrammatic reasoning processes, their related conceptual understanding, and the role of the representation mode itself (Schönborn *et al*., 2002b). In short, the instrument gathered information through 'think-aloud' tasks (Lowe, 1993; Bowen, 1994), student-generated diagramming (e.g. Gobert & Clement, 1999) and diagram-related observable behaviours (Kindfield, 1993/1994) such as

beginning, modifying, annotating and completing a diagram or pointing, indicating and alluding to a diagram. The modelling framework of Justi and Gilbert (2002) was used to express a model of how these three data-types



(a) (b) (c)

(d) (e) (f)

Fig 1 Six ERs showing the structure of an IgG antibody molecule and/or its interaction with antigen. (a) Tertiary structure showing V and C regions, (b) Tertiary structure in chain form, (c) Three-dimensional structure; one of the H chains is shown in dark red, the other in dark blue. One of the L chains is shown in light red, the other in light blue. A carbohydrate unit attached to a C_H2 domain is shown in yellow, (d) Electron micrograph (x 1 000 000) of complexes formed on mixing divalent hapten with anti-hapten antibodies. The hapten links together the Y-shaped antibody molecules to form trimers (A), and pentamers (B), (e) Space-filling model showing Fab antilysozyme and lysozyme molecules fitting snugly together. Antibody heavy chain, blue; light chain, yellow; lysozyme, green with its glutamine 121 in red. Fab and lysozyme models are also shown pulled apart in the second frame, (f) Antibody response curves obtained from an ELISA showing the relationship between Absorbance (405nm) and Antibody concentration (mg/ml). Three booster shots were administered and the antibodies collected at the weeks indicated in the text box. ((a) From Bohinski, R.C., 1987, (b) from Silverton et al., 1977 and adapted in Bohinski, R.C., 1987: Reproduced by permission of Pearson Education, Inc., Upper Saddle River, NJ 07458; (c) From Silverton et al., 1977 and adapted in Stryer L., 1995, (d) From Valentine, R.C. and Green, N.M., 1967 and reproduced in Roitt, I.M., 1997: Reproduced by permission of Academic Press, (e) From Roitt, I.M., 1997, (f) From Jackson, J, pers. comm.)

influenced each other, the nature of their relationship and the extent of their interdependence. We suggest that at the union of each exists an *interactive* zone, which if monitored, allows informing of some the cognitive perspectives relating to students' interaction with ERs used in biochemistry. In doing so, we were able to suggest possible sources for the described categories of difficulty. The interactive zones were then studied for this exact purpose.

Data Analysis

Student answers to the written probes and interview questions were analysed iteratively by inductive analysis (McMillan & Schumacher, 1993). Using this method, the categories of student difficulties emerged from the data themselves, rather than being pre-determined. As the process of sorting students' responses proceeded, the nature of the categories, and hence the underlying difficulties, became clearer and sub-categories emerged. The four-level methodological framework of Grayson *et al.* (2001) was used for the classification of difficulties according to how much information and understanding the researchers had about the nature of each difficulty. In

addition, and in an approach similar to Kindfield (1993/1994), all 3P-SIT interviews were videotaped and transcribed. The data analysed in the study consisted of written responses, videotapes, transcripts and student-generated diagrams. Transcripts were divided and subdivided into sections that corresponded to the respective segments of the 3P-SIT interview protocol. By sorting the transcripts in this way, we attempted to classify responses as belonging more to the conceptual, reasoning or representation mode factors, or to an interaction zone between these factors. Viewing videotapes of students' drawing behaviour (e.g. Kindfield, 1993/1994; Lowe, 1993) and other gestures (e.g. Sumfleth & Telgenbüscher, 2001) provided information about student processing of the ERs. Analysis of 134 student-generated diagrams served as a diagnostic tool that helped to isolate reasoning processes and extent of conceptual understanding (e.g. Glynn, 1997).

Results and Discussion

The results revealed four main categories of student difficulties termed the *process-type*, *structural-type*, *DNA-type* and *binding-type*, with incidences of 70%, 70%, 40% and 67%, respectively. The *process-type* difficulty was characterised by students viewing the ERs (Fig 1) as representing various complex processes (e.g. secondary responses of the immune system), rather than a simple non-covalent binding interaction between antibody and antigen molecules. Students who showed the *structural-type* difficulty erroneously interpreted the way in which various structural features of IgG were externally represented on the ERs. These included features representing disulfide bonds, variable and constant amino-acid regions, light and heavy chains, α-carbons, antigen molecules, antigen binding sites and level of structure. Interpretation of the ERs as a form of DNA structure or processing constituted the *DNA-type* difficulty. Finally, students with the *binding-type* difficulty suggested that the IgG antibody had only *one* possible binding site for the antigen and that an antigen was accommodated within the entire V-shaped 'cleft' of the Y-shaped antibody, instead of sharing an interaction with the antibody's *two* variable binding domains.

Deeper analysis of the data from the six ERs (Fig 1) revealed distinct patterns of cognitive processing, embedded within the above four general categories of difficulties. Four of these patterns of cognition will be supported by quotations and student-generated diagrams containing two or more of the conceptual, reasoning and representation mode components, i.e. the *interaction* between components at the interactive zone of the expressed model (Schönborn et al., 2002b).

Firstly, we found that some students displayed *surface-level reasoning* (Chi *et al*., 1981), in that graphical symbols and icons were often interpreted at face value without consideration of the deeper structure of their canonical forms (e.g. Lowe, 1993). For instance, consider the following student interpretations of Figs 1(a), (b) and (e) respectively:

> *"…It [the diagram] shows where the antigens attack / go through the antibody. Shows us that antigens enter into the V regions first and then move into the C regions."*
>
> *"* *Oxygen*
> *bonds."*
>
> *I: What does this plate over here… this frame over here [c] represent [points to frame c]?*
> *S: There was probably interaction between the antibody and the lysozyme…yeah [points to c] and that interaction caused the glutamine to break down and join with the antibody [points on c]. The antibody is actually working on the glutamine [circular pointing on c]…*

Due to depiction of the antigen as an arrow-like entity, students may have thought that antigen entered the antibody structure itself when interpreting Fig 1(a). As seen in the second quote above, one student thought the circles representing α-carbons on Fig 1(b) to be indicative of oxygen atoms. Lastly, the third student thought that the glutamine 121 residue was being "broken down" by the antibody, probably due to the use of the same red colouring to designate contact regions between amino acids. As noted by Cheng et al. (2001) and Henderson (1999), overemphasis of the graphical markings on a display during processing may lead to the construction of superficial and unwarranted mental models. It follows in the present study that students' formulation and construction of ideas such as the antibody itself being responsible for elimination or digestion of the antigen may be a consequence of this. This is illustrated in the following quote obtained from interpretation of Fig 1(a):

> *"It is meant to show how the antigen Ag attack[s] the cell and how the antibody fights the antigen and get[s] rid of it. Region[s] V and C show the different parts of the antibody which are meant to destroy the antigen. The composition of chemicals released in region V are different to the one['s] in region C."*

The above results, and other data not shown in this paper, suggest that students often relied heavily on perceptual organisation during processing (e.g. Olivier, 2001). In other words, students made extensive use of perceptual cognitive operators to make sense of an ER. The result of this is an over reliance on the visual forms,

which resulted in the construction of scientifically flawed concepts and mental models. Furthermore, this reasoning was compounded when perceptual groupings were filtered by poor or flawed conceptual knowledge (e.g. Olivier, 2001; Henderson, 1999). In light of this, the current study also revealed evidence for "boot-strapping" (Cheng, *et al*., 2001), where it was shown that the manner in which an ER was processed depended largely on at least two types of knowledge that the user brought to the ER: knowledge of the actual canonical forms presented (diagrammatic conventions) and knowledge of the subject matter itself. As shown by Cheng et al (2001), we too found that reasoning with an ER was indeed modulated by this knowledge.

Secondly, the study revealed that some students displayed the cognitive process of *inappropriate analogical reasoning* (e.g. Sumfleth & Telgenbüscher, 2001) when exposing their conceptual knowledge about antibody-antigen interaction as well as during interpretation of the ERs. We shall attempt to show that this was probably due to the concrete and ingrained nature of particular conceptual schema. For example, *all* the students in this part of the study, just like some textbooks (e.g. Amit *et al*., 1986; Roitt, 1997), readily used the "lock-and-key" analogy, normally used to explain enzyme-substrate interactions, to also explain the nature of antibody-antigen interaction. Since most textbooks (e.g. Ritter, 1996) only give *single*-enzyme-*single*-substrate lock-and-key analogies, the possibility arose that students may think that a *single* immunoglobulin G molecule can only bind to a *single* antigen molecule. The student-generated diagram (Fig 2) showing interaction between IgG antibody and antigen, illustrates that this analogy was indeed erroneously understood and depicted.

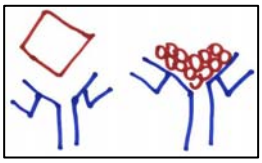


Fig 2 Student-generated diagrams displaying inappropriate analogical reasoning

The interview extract that accompanied the construction of the above diagram was as follows:

> *S: I remember we were speaking [during first interview session] mostly about the binding of the antibody to the antigen and how there was a lock-and-key method. And, yeah… it is almost like specific… the antibody binding to the antigen. They have to have similar shapes in order for the binding to take place.*

Clearly, the above served as an example of how some students thought that the entire 'V-cleft' accommodated the antigen, instead of each binding site being viewed as its own "lock-and-key" system. Note also the student's inclusion in Fig 2 of *two* binding sites on the antibody, but insertion of the antigen into the 'V-cleft' of the antibody.

Thirdly, and similar to the above processing, the study also revealed that some students performed *inappropriate transfer* (Salomon & Perkins, 1989) at two levels. At one level, during interpretation of the ERs, the following example of inappropriate transfer was carried out. Since a DNA replication fork, with lagging and leading strands, looks similar in appearance to the 'Y' shape of the immunoglobulin heavy and light chains (see Fig 1a) and the helical nature of DNA (see Fig 1c), it is possible that some students were inappropriately transferring their knowledge of DNA elongation or processing to the context of IgG structure. This is suggested by the following extracts obtained with the interpretation of Figs 1(a) and (c) respectively:

> *"This is meant to represent a DNA molecule, leading strands and a lagging strand of DNA…"*
> *"This represents the structure of a DNA molecule."*

We suggest that the inappropriate transfer shown above may well be a consequence of surface-level reasoning. At another level, during exposure of students' conceptual understanding it was found that some students were unable to transfer their knowledge to another domain that was conceptually identical. For example, some students were unable to explain the nature of primary antibody binding to secondary antibody in an enzyme-linked immunosorbent assay (ELISA) set up. This is suggested by the following interview extract and student-generated diagram following interaction with Fig 1(f):

> *I: Ok. Now, I need you to explain to me how the secondary antibody binds to the primary antibody.*
> *S1cp7-8: Oh… umm… I have no idea. It doesn't make any sense to me after all we have been talking about how the antigen binds to the antibody… how would an antibody bind to another antibody, I have no idea how it would bind … It is not like we have a specific binding over here [between Ab's]… because this has got nothing to do with shape.*
> *I: So, what are the similarities between that kind of binding [between Ab's] and the binding with the antigen?*

S: That both of them [types of binding] take place at the receptor site, except that the antigen will have a specific shape for the antibody molecule to bind. But, in the secondary antibody, there is no sort of specificity taking place. I think it is just because it's binding to another antibody, it doesn't need to have a specific shape.

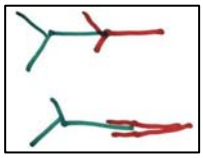


Fig 3 Student-generated diagram displaying inability to translate between two domains that are conceptually identical

The above results suggest that some students treated antibody-antibody interactions within the ELISA set-up as separate and unique situations, which were in some way different to otherwise identical "lock-and-key" antibody-antigen interactions. Related to this processing, the results suggested that some students were unable to translate between different representations depicting an identical phenomenon (e.g. between their generated diagrams and the ER under study), and that they found it difficult to map between one representation system and another, probably because each was treated, interpreted and understood differently (e.g. Ainsworth *et al*., 1998). In these cases we suggest that some students did not seem to possess a single and integrated mental model of the phenomenon. Instead, there often appeared to be many alternatives available to a student depending on the function of the task (e.g. Gobert and Clement, 1999).

Fourthly, the results showed the *inappropriate "superimposing"* of one concept upon another when students interpreted the ERs. For example, during interpretation of Fig 1 (a) and (c) students inappropriately combined distinctively separate concepts, as illustrated by the following interpretations of Fig 1 (a) and (c), respectively:

"-DNA molecule replication -Where the Ag bind[s] to the DNA molecule."
"This diagram is meant to show how DNA molecule IgG fights the antigen. It has an antigen binding site where antigen binds and will be killed after it is locked by this molecule"

It is clear form the above quotations that these students inappropriately fused immunology knowledge with DNA-related knowledge. The "superimposing" of concepts was also found during other students' explanations of Ab-Ag interaction. For instance, consider the following two student-generated diagrams, the first obtained during a student's exposure of her current knowledge and the second with a student's interpretation of Fig 1 (d):

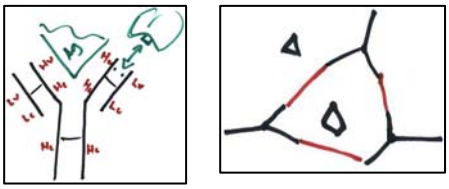


Fig 4 Two student-generated diagrams showing the inability to disentangle concepts from one another

Both these diagrams (Fig 4) demonstrated the "superimposing" of the concept of the lock-and-key binding analogy upon that of antigen binding to the variable binding domain of an antibody. It was invalid for both concepts to be represented and explained simultaneously since one actually serves the purpose of explaining the other. Like Grayson (submitted) has shown in the context of students' understanding of electric circuits in physics, it is possible that the above students were unable to *disentangle* distinctively different concepts from one-another when interpreting certain ERs or during exposure of their conceptual understanding.

In general, our results showed that firstly, processing of ERs is indeed regulated by three factors which we have expressed in a model (see Schönborn et al., 2002b) and are embedded in the categories of difficulty: the *conceptual understanding* that the user brings to the diagram, the *reasoning mechanisms* employed by the viewer and the *mode of representation* itself. Secondly and in relation to the former, our results agree with the most recent literature, which suggests that this processing is *distributed* across internal and external dimensions (Zhang & Norman, 1994; Scaife and Rogers, 1996; Cheng et al., 2001) and should not be attributed to naïve and simple statements like "a bad diagram" or, "a poor student". Therefore, understanding the processing of ERs should be done by consideration of a *representational system* consisting of interactions between factors. Our research shows that there appears to be regular shifting in the weighting of interaction between the three factors. We suggest that by investigating the intersection between factors allows for a more robust and holistic account of processing because the relationship between properties of both external and internal structures is considered *together* (e.g. Cheng *et al*., 2001). It follows that harnessing and analysing the data pertaining to cognitive

perspectives allows the researcher to gain a more fruitful and explanative account of possible sources for the difficulties.

Implications

Our results suggest that the most effective way of considering the role of cognitive perspectives in improving and studying the use of ERs is to consider both the "external cognition" standpoint of Scaife & Rogers (1996) and the "distributed cognition" standpoint of Zhang & Norman (1994). With this approach, understanding the cognitive issues surrounding interaction with ERs is important for their design (e.g. Lowe, 1993), for informing their use by students and instructors, and for understanding which ERs are perhaps more effective than others (Cheng *et al*., 2001) so that student difficulties might be prevented or remediated. The literature suggests (e.g. Brna *et al*., 2001) that in an educational context, *more* work is needed to understand how students learn from, learn to interpret, translate between, and use ERs. In this vain, further investigation into the nature of cognition will help improve teaching and learning with ERs in science.

Acknowledgements

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