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Articles

The Importance of Visual Literacy in the Education of Biochemists*

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Visualization is an essential skill for all students and biochemists studying and researching the molecular and cellular biosciences. In this study, we discuss the nature and importance of visualization in biochemistry education and argue that students should be explicitly taught visual literacy and the skills for using visualization tools as essential components of all biochemistry curricula. We suggest that, at present, very little pedagogical attention has been given to this vital component of biochemistry education, although a large diversity of static, dynamic, and multimedia visual displays continues to flood modern educational resources at an exponential rate. Based on selected research findings from other science education domains and our own research experience in biochemistry education, 10 fundamental guidelines are proposed for the promotion of visualization and visual literacy among students studying in the molecular and cellular biosciences.

Keywords: External representation, visual literacy, visualization, interpretation, teaching, learning.

All biochemists would readily agree that visualization tools are essential for understanding and researching the molecular and cellular biosciences. This is reflected by the exponential growth over the years in the number and range of visualization tools now available to the biochemist for teaching, learning, and research. These include, *inter alia*, physical and molecular models, photographs, micrographs, pictures, diagrams, illustrations, drawings, images, analogical representations, metabolic maps, symbolic pathways, genomic representations, graphs, icons, static visuals, dynamic visuals, animated visuals, multimedia, and virtual reality environments. Such tools are collectively termed external representations (ERs)[1] by cognitive psychologists [1] because they portray phenomena in the external world, contain spatial relationships, and can be distinguished from internal representations (*e.g.* mental models), which are an archetype of the mind [2]. Sound ERs therefore enable learners and researchers to construct meaningful mental models [3] of biochemical phenomena, which allows for the visualization, integration, and understanding of biochemical concepts.

The aim of this study is three-fold. Firstly, to discuss the nature and mode of the different ERs used in biochemistry education. Secondly, to argue for the importance of explicitly teaching visualization skills and visual literacy as an essential component of the modern biochemistry curriculum. Thirdly, to suggest some possible *guidelines* for promoting teaching and learning with ERs, developing students' visualization skills, minimizing visualization difficulties and, therefore, enhancing the general visual literacy of our future students.

THE (CONFUSING) NATURE OF ERs USED IN BIOCHEMISTRY EDUCATION

Biochemistry is a science that is investigated within the macroscopic (*e.g.* Fig. 1*A*), microscopic (*e.g.* Fig. 1*B*), and particularly, the submicroscopic (molecular) (*e.g.* Fig. 1, *C* and *D*) levels of organization. Thus for a holistic understanding of biochemistry, students are required to readily translate between these three levels of organization, something that can be rather difficult and confusing for them. Since we cannot physically see the submicroscopic environment, biochemists use physical and chemical data to construct theories, hypotheses, and models in an attempt to explain these abstract phenomena. These constructs, in turn, if accepted by the community of biochemists, govern how we subsequently interpret and visualize the submicroscopic environment and, therefore, what we include in educational resources (*e.g.* textbooks, lecture notes, computer software, and the Internet) and teach to students.

To facilitate the visualization of biochemical phenomena at all three levels of organization (Fig. 1), biochemists make use of a visual "language" in the form of multiple ERs and symbolism that differ both in esthetic (*e.g.* color, shape, size) appearance and in level of abstraction (*e.g.* Ref. [4]). Whereas physicists, chemists, and mathematicians make use of clear and well established symbolism, termed conventions, to represent particular phenomena (*e.g.* the convention used to represent a battery in a circuit diagram),

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[1] The abbreviations used are: ER, external representation; PCK, pedagogical content knowledge.

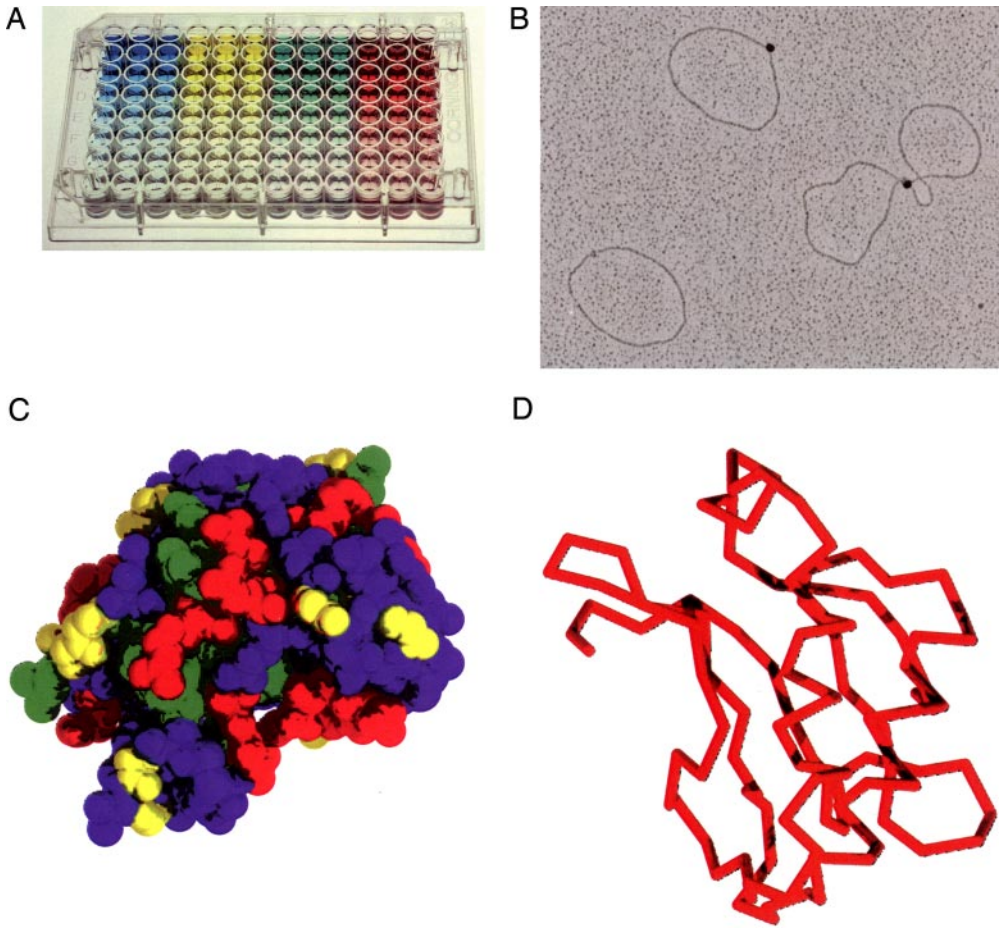

FIG. 1. **Multiple ERs showing examples of the nature of typical ERs used in biochemistry education.** *A*, a macroscopic representation of a microtiter plate containing differently colored biochemical solutions. This figure was kindly provided by *BioFX Laboratories*. *B*, a microscopic representation of a 10-nm gold particle (*black sphere*) conjugated to Z-DNA antibody that, in turn, is bound to a Z-DNA segment within plasmid DNA. This figure was courtesy of R. Inman, Institute for Molecular Virology and Department of Biochemistry, University of Wisconsin-Madison. *C*, a submicroscopic representation showing the volume of space occupied by each non-hydrogen atom making up a protein molecule. Hydrophobic amino acids are *green*, charged amino acids are *red*, polar amino acids are *blue*, and glycine is *yellow*. *D*, a submicroscopic representation of the α-carbon atoms constituting the carbon backbone "trace" of a protein molecule. Both were kindly provided by T.J. Smith, www.danforthcenter.org/smith/MolView/Over/overview.html.

biochemists often use a *range of symbolism* to represent the same phenomenon. For example, a disulfide bond in a protein ER has been represented in textbooks as –S–S– [5], as a straight black line [6], and as a yellow bar [7]. This lack of strictly adhered to conventions means that the visual language that biochemistry students have to learn is far more complex and potentially confusing than that in other disciplines. This problem stems from the fact that expert biochemists, due to their more extensive conceptual knowledge, are not generally confused by the lack of conventions and, therefore, wrongly assume that the same would hold for novices [8]. Thus there is clearly an urgent need for the International Union of Biochemistry and Molecular Biology (IUBMB) nomenclature committee, with the assistance of researchers, textbook authors, and graphic designers, to consider introducing more standardized conventions where possible.

Regarding the level of abstraction of ERs, biochemists make use of a wide range of ERs, at each level of organization (Fig. 1), which can be placed on a continuum from abstract, to more stylized, to more realistic representations of phenomena. For example, at the submicroscopic (molecular) level of organization, students might be required to translate between multiple representations of antibody-antigen binding ranging from an abstract representation such as an ELISA graph (*e.g.* Fig. 2*A*), to a stylized two-dimensional diagram or computer image (*e.g.* Fig. 2*B*), to a more realistic electron micrograph of the binding complex (*e.g.* Fig. 2*C*) (Ref. [9]). Among other things, this means that students might, for example, need to make sense of an *abstract* representation of an *abstract* (molecular) phenomenon alongside stylized and realistic representations of the same phenomenon, something which in our experience [10] students find very confusing.

Thus in summary, students are not only required to translate between the macro-, micro-, and molecular levels of organization (*e.g.* Fig. 1) but also between ERs representing phenomena at each level of abstraction (*e.g.* Fig. 2), which in combination becomes extremely cognitively challenging for students [11]. However, in essence, without these visualization tools and the accompanying human visualization mechanisms and skills used to interpret ERs (*i.e.* human visualization ability), learning, teaching, and research in the molecular world would not be possible.

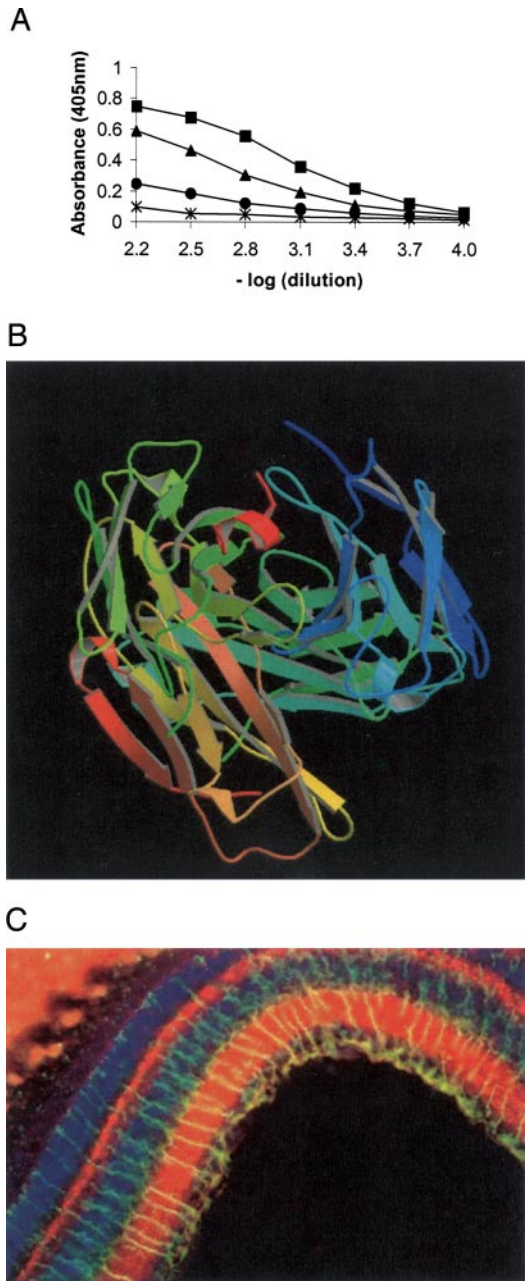

FIG. 2. **Multiple ERs of antibody-antigen binding on a continuum from abstract (*A*), to stylized (*B*), to realistic (*C*).** *A*, immune response of rabbits inoculated with 2,4-dinitrophenol-catOVA as determined by ELISA. 2,4-Dinitrophenol-lysine was coated on the microtiter plates and incubated with dilutions of sera from rabbits collected after 3 (*filled circles*), 8 (*filled triangles*), and 12 (*filled squares*) weeks and preimmune IgY (*X*). This figure was courtesy of J. G. Jackson, University of KwaZulu-Natal (Pietermaritzburg), South Africa. *B*, Fab fragment of a monoclonal antibody against human Interleukin-2 (the shades of *green*, *yellow*, *orange*, and *blue* are a color gradient used to provide a sense of the orientation of the molecule) in complex with antigenic peptide (*red*). This figure was reproduced from www.pdb.org, Protein Data Bank ID: 1F90, P. V. Afonin *et al.* [47]. *C*, a transverse section through a zebrafish retina that has been probed with anti-glial fibrillary acidic protein antibody and visualized with an alkaline phosphatase-mediated technique. Phosphatase substrate yields a yellow-green signal at the site of anti-glial fibrillary acidic protein antibody binding. The retinal section has been counterstained with Hoechst 33342, which stains all nuclei blue, and with tetramethylrhodamine wheat germ agglutinin, which stains both the inner and the outer plexiform layers as well as the photoreceptor outer segments red. This figure was reproduced with copyright permission from Molecular Probes, Inc.

In addition to the levels of organization and abstraction, a further possible source of confusion for students is that ERs also differ in terms of *mode* of representation. Abstract biochemical phenomena are represented in a range of different modes including two-dimensional and three-dimensional *static* modes, dynamic modes, and multimedia modes. A two-dimensional static ER is usually associated with a page of a textbook such as a diagram of a protein, a picture of a DNA helix, or a graph showing a colorimetric relationship, whereas a three-dimensional static ER can be a concrete or physical model such as a ball-and-stick model of an α-helix. In contrast, a dynamic visual is one that contains graphical "movement" or "transitory" information or, in simple terms, one that is animated. For example, when you manipulate a computer-generated ER of protein structure on a computer screen, you are interacting with a dynamic or animated visual. Animated visuals are also ideally suited to the representation of processes because they occur over time. The *multimedia* mode for visualizing molecular and cellular phenomena has become a buzzword in today's fast-moving and technological world. Formally, the term refers to "the combination of multiple technical resources for the purpose of presenting information represented in multiple formats . . . " [12]. Some of the *multiple formats* that are viewed by humans include text (sentences), static (still) ERs, dynamic (animated) pictures, video visuals, and sounds. When two or more of these media formats are combined, then we no longer have a single medium of communication, but a multimodal medium. There are numerous multimedia packages available for biochemical teaching and research, including *Mage*, *RasMol*, *Chime*, and *MolView*, to name a few. Of recent popularity are interactive CD-ROMs that accompany hardcopy textbooks (*e.g.* Ref. [13]) as well as interactive websites. Such software is also used particularly in the study of protein structure-function relationships, protein or drug design, and bioinformatics. Now, more than ever before, researchers, teachers, and learners are able to easily construct and manipulate ERs of biochemical molecules and processes (*e.g.* Figs. 1, *C* and *D*, and 2*B*).

The choice of mode used to represent biochemical concepts, phenomena, and processes depends on the nature of the biochemistry being represented, the pedagogical goals of the instructor, and the technology available to generate the ER. For example, the various static ERs generated from x-ray crystallography (*e.g.* Ref. [14]) (Fig. 1, *C* and *D*), the "ribbon" ERs (diagrams) of protein structure (*e.g.* Ref. [15]) (Fig. 2*B*), the physical ERs of chemical models (*e.g.* Ref. [16]), and the genomic ERs used in bioinformatics (*e.g.* Ref. [17]) are all excellent static ERs for teaching students about basic protein and genomic structure. On the other hand, to teach students about the three-dimensional and dynamic nature of biomolecules, it might be more desirable to use an animated computer image of, for example, a protein or DNA strand. Furthermore, an animated ER mode might be more useful for teaching about dynamic metabolic reactions than a static one would be, although as discussed below, research has shown that the choice of mode is not always so simple.

One major concern that has been put forward in the

recent science education literature is the automatic pedagogical superiority that has been bestowed upon animated and multimedia ERs as compared with static ERs. Since such ERs have a large esthetic appeal, many educators simply assume that they will be much more powerful teaching and learning tools than static ERs. On the contrary, recent research [18] has suggested that dynamic and multimedia ERs are not always superior to static ERs. Lowe [18] has provided two possible reasons for this notion. Firstly, he suggests that dynamic ERs can be cognitively "overwhelming" to students because of the greater amount of information that has to be processed than in the case of a static ER. Secondly, such ERs can be what he terms "underwhelming," in that the viewer may be distracted by its highly dynamic and esthetic appearance and thereby decrease their level of required engagement with the ER. What seems to be of great importance is how the ER (the actual static or dynamic picture) compares with the internal representation or mental model generated in the human mind [19]. Reports in the literature suggest that rigorously investigating this *relationship* will allow us to analyze the real differences and/or similarities between static, dynamic, and multimedia modes, and therefore, the relative advantages or disadvantages of the three for learning [12]. If we do this, we will be in a better position to suggest what, when, why, and how a particular ER should be used for achieving desired learning outcomes.

Thus given the wide diversity of potentially confusing ERs available to both learners and educators in biochemistry, it is clearly important to explicitly teach students about the nature of external representations as a component of all formal biochemistry curricula. Furthermore, if we agree with this contention, then it is also important to teach students the visualization skills required to interpret the ERs, *i.e.* we need to ensure that our graduates are visually literate. This issue is addressed in the next section.

THE IMPORTANCE OF VISUAL LITERACY IN THE BIOCHEMISTRY CURRICULUM

According to Lowe [18] and other education researchers, just as verbal literacy means to be able to *read* and *write* language, and numerical literacy involves the reading and writing of numbers, visual literacy encompasses the ability to *read* (understand or make sense of) as well as *write* (draw) ERs [20], including the ability to think, learn, and express oneself in terms of images [21]. We have three major claims for recommending that visual literacy should be explicitly taught as an essential component of all modern biochemistry curricula. Firstly, as already demonstrated in the previous section, students are being exposed to an ever increasing number of extremely diverse and potentially confusing ERs, which will require a greater level of visual literacy. Secondly, to effectively interpret and understand ERs, students need to develop their visualization skills beyond what they would normally acquire informally on their own. Thirdly, students with poor visual literacy show evidence of visualization difficulties that can seriously affect their ability to interpret and learn from ERs. In this section, we present some research evidence in support of the latter two claims.

Despite the extensive range of potentially confusing ERs available for the visualization of biochemical phenomena, there has been little or no research done to investigate the *actual effectiveness* of such packages for improving students' visualization and conceptual understanding in biochemistry. As stated by Richardson and Richardson [15], renowned for their development of *ribbon* displays (*e.g.* Fig. 2*B*) to depict three-dimensional protein structure in biochemistry, " . . . there is little experimental data on either the absolute or the relative effectiveness of these materials for teaching three-dimensional literacy and only minimal guidance about the best ways to use them . . . " The failure of biochemists to question and research the effectiveness of such packages is mainly because experts, including biochemistry educators, textbook authors, and computer graphics designers, tend to naively assume that what they perceive as being good teaching and learning tools will necessarily be good for promoting visualization and understanding among novices. On the contrary, extensive science education research (*e.g.* Ref. [8]) has shown that there are often large discrepancies between experts' and novices' abilities to interpret and learn from ERs. This is because experts tend to have greater conceptual knowledge, are more visually literate, and have more advanced visualization skills (*e.g.* image reading skills and spatial visualization skills) than novices do.

Relatively few teaching institutions explicitly teach visualization skills to their students that will enable them to, for example, read diagrams, decode symbolism, make sense of animations, etc. Instead, like other cognitive skills (*e.g.* thinking, reasoning, creativity, synthesis, metacognition), it is often assumed that visualization skills will be automatically acquired by "osmosis" during the course of learning activities that require some form of visualization or use of visualization tools. Science education research (*e.g.* Refs. [22 and 23]), however, has shown that it is wrong to make this assumption as many students do not adequately improve their visualization skills without being explicitly taught them through specially designed learning activities. Related to this skill problem, recent research (*e.g.* Refs. [24–26]) has shown that the interpretation and visualization of biochemical ERs can be extremely challenging for students and can lead to a range of conceptual (misconceptions), visualization, and reasoning difficulties that can impact negatively on their understanding of molecular and cellular phenomena. This is especially true in cases where interpretation of ERs of abstract scientific concepts is required [27], such as in the case of biochemistry. For example, Crossley *et al.* [28] have exposed students' reasoning difficulties with ERs depicting the electron transport chain in the mitochondrion. The study indicated that reasoning difficulties with the concept of uncoupling and coupling in oxidative phosphorylation might be attributed to the depiction of the mechanism in textbooks and in electronic ERs. For instance, some ERs show no apparent link between the oxidation of $FADH_2$ and NADH molecules and the *simultaneous* phosphorylation of ADP molecules. Also, due to the graphical nature of typical static ERs that depict the process (*e.g.* Fig. 3), students thought that electrons can "jump" from one carrier to the next across membranous structures instead of being transferred through collision between the carriers as in any normal

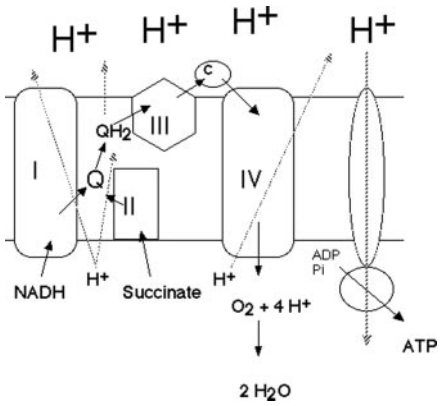

FIG. 3. **An ER representative of the static types used in educational resources to represent the process of oxidative phosphorylation.** This figure was reproduced with permission from J. Markwell and D. Brooks, dwb.unl.edu/Teacher/NSF/C11/C11Content.html.

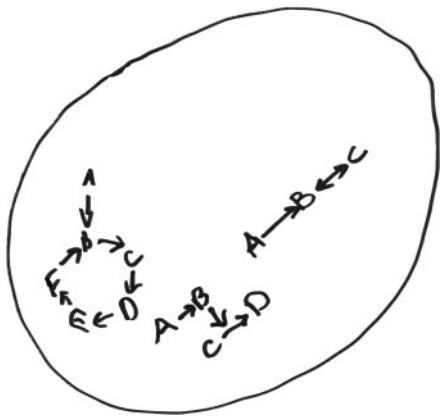

FIG. 4. **Student-generated diagram of a cell representing the citric acid cycle as a circle *in vivo*.** This figure is courtesy of T. L. Hull [25].

redox reaction. In another study that investigated students' use of diagrams for the visualization of biochemical processes, Hull [25] found that when students were asked to explain how the citric acid cycle would actually look within a cell, they interpreted textbook ERs literally by erroneously drawing the pathway as a circle (*e.g.* Fig. 4) and backing up their visualization difficulties with a corresponding verbal explanation.

Lastly, our research [10, 24, 26] on students' interpretation of ERs depicting antibody-antigen binding has exposed a range of visualization difficulties. For example, some students interpreted ERs of antibody structure as components of DNA structure or processing, whereas others thought that the antibody itself was capable of performing the cellular immune function of eliminating antigen. In addition, some students erroneously interpreted various graphical markings used in antibody ERs to depict polypeptide chains, disulfide linkages, or level of structure. For example, a black line used to denote an –S–S– bond was misinterpreted as a hydrogen bond, whereas graphical components used to show variable and constant amino acid regions were perceived as atoms and cells.

In summary, visual literacy and visualization have clearly become more important than ever for biochemistry education, especially as more and more images continue to flood educational resources. It is vital, therefore, that the international community of biochemistry educators takes appropriate steps to formally teach visualization skills and visual literacy as part of the biochemistry curriculum. Toward this end, in the next section, we briefly present various guidelines for promoting visual literacy among learners and for preventing any related student difficulties that may seriously interfere with the quality of our graduates.

GUIDELINES FOR THE TEACHING AND LEARNING OF VISUAL LITERACY

Based on the above commentary, an extensive examination of the literature, and on our own research findings, we have identified 10 fundamental guidelines [24] for teaching and learning with ERs that have arisen out of our thinking about the pedagogical implications of visualization in biochemistry education. The formulated guidelines are approaches that the international community of biochemistry instructors could consider adopting, firstly, in order to promote the teaching and learning of visual literacy and its incorporation into formal biochemical curricula, and secondly, in order to prevent (or eradicate) student difficulties with the visualization of ERs. In addition, many of the guidelines could also be the target of biochemistry education research investigations to confirm their usefulness in enhancing biochemistry students' visual literacy and visualization skills.

1. Take Cognizance of Current Theories on How Individuals Learn from, and Visualize, ERs—One of the dominant theories of how people are thought to learn science is that of *constructivism* (*e.g.* Ref. [29]). The general principle of the theory is that knowledge and images cannot be transferred passively from the teacher into the student's brain in an intact form as an identical copy [29]. Instead, each individual student actively constructs their own meaning and mental models [3], and therefore, unique knowledge structure, from the words or visual images they hear or see, interpreted within the context of their own prior scientific knowledge and life experience. In other words, as stated by Ausubel [30], "The most important single factor influencing learning is what the learner already knows." Therefore, for learners to visualize the information represented by an ER, the visual information has to be internally processed based on their already existing conceptual knowledge [31]. The process of knowledge and mental model construction has been shown to be consistently enhanced through generative [32] and active learning in which individuals make sense of the ER *themselves* (*e.g.* Ref. [33]). Thus to promote this process, and therefore, visual literacy, biochemistry instructors should encourage students to become "mentally engaged" [34] during an *active* visualization process, involving tasks such as working in groups to actively interpret an animation and critique its strengths and limitations with respect to its effectiveness in representing a particular phenomenon or concept.

Under the guise of constructivism and meaningful learning theory, Paivio's [35] *dual-coding theory* suggests that two functionally distinct systems or processes in the brain code external information. A verbal system processes textual and verbal information, leading to the construction of *verbal* mental representations, whereas a visual system processes pictorial information such as color, size, and

pattern, leading to the construction of pictorial or *image-based* mental representations [32]. *Dual* processing occurs when the brain constructs a *mental model* from a combination of the verbal and pictorial mental representations [35]. Based on dual-coding theory, Mayer's [33] *theory for multimedia learning* suggests that visualization of, and learning from, ERs is improved when learners' referential connections between verbal and pictorial representations and their conceptual knowledge are promoted. The question is, how can such connections be promoted? Mayer's *theory for multimedia learning* offers a solution to this in identifying four principles central to multimedia learning [33]. Firstly, his suggested *multimedia effect* advocates that deeper learning takes place when ERs (*e.g.* pictures, diagrams, and animations) and words (*e.g.* text or spoken) are *combined* rather than when they are presented in isolation. Secondly, his *coherence effect* suggests that learning is increased when irrelevant information is reduced. Thirdly, his *spatial contiguity effect* suggests that learning is enhanced when words are placed in close proximity to pictures. Finally, the *personalization effect* proposes that students construct more useful mental models when the accompanying text is presented in a conversational manner. Thus the above principles suggest that sound visualization and learning, and therefore, visual literacy, are significantly enhanced when students engage in an active and integrated learning process that incorporates some of the above mentioned learning activities.

2. Address the Key Factors Affecting Students' Ability to Visualize ERs—Our recent research [10, 24] has identified at least six factors that determine students' ability to visualize and interpret ERs in biochemistry. These factors include: 1) students' general reasoning skills available for interpreting an ER; 2) students' ability to *reason* with (read and make sense of) the ER and its features; 3) students' ability to *reason* with (select and retrieve) their conceptual knowledge of relevance to the ER; 4) students' understanding (or lack thereof) of the *concepts* of relevance to the ER; 5) the nature, *mode,* quality and, therefore, intelligibility of the ER itself; and, 6) the *nature* and extent (selection of) of the conceptual knowledge represented by the ER and its symbolism, markings, and esthetic content. Our research has demonstrated that all six factors are *indispensable* prerequisites for sound visualization and interpretation of ERs and that each one needs to be addressed if we wish to enhance the visual literacy of our graduates. In this regard, whereas factors 5 and 6 should be addressed by textbook authors and graphic artists, factors 1–4 can be the target of specific learning activities in the curriculum that explicitly address and endeavor to develop students' conceptual knowledge, reasoning skills [27], and general visualization skills [18]. The science education literature contains a wide range of such activities, which biochemistry instructors could consult. Since reasoning is a process, tasks aimed at developing reasoning skills (see factor 1 above) must involve reasoning with something, in this case either with the ER (factor 2) or with students' own conceptual knowledge (factor 3). Thus factor 1-type tasks will be implicit in factor 2- and 3-type tasks. Typical examples of factor 2-type tasks could simply require students to read and make sense of any ER and its features. A more complex task of this type could, for example, require students to mentally rotate a two-dimensional computer image of a biomolecule by say 90 degrees about a specific axis to establish which of several other supplied representations of the same molecule it corresponds to. In the case of factor 3-type tasks, the aim is to enhance students' ability to select and retrieve their conceptual knowledge of relevance to the ER. A suitable activity for this purpose could require students to identify and explain the meaning of, for example, any five concepts represented by a particular animation of a cellular process such as DNA replication and to indicate what symbolism is used to represent each of the concepts. Such a task would also be expected to enhance the development of students' conceptual knowledge of the topic as required for a typical factor 4-type task.

When performing tasks involving animations, such as those described above, teachers should allow students to have "control" over the animation in terms of speed of presentation, "pause" functions, and so on, so as to facilitate learning and retention of the particular conceptual knowledge represented by the ER (*e.g.* [18]). In addition, students should be shown what the teacher sees as the most useful step-by-step manner with which to make sense of the animation when viewing it [18].

3. Acknowledge the Importance of Pedagogical Content Knowledge (PCK) in Visualization—During the process of formulating strategies to improve learning and teaching in the context of ERs, it is important for instructors to take cognizance of PCK [36], which is defined as that pedagogical knowledge that *includes* not only the factual knowledge of biochemistry but also knowledge of *how* to teach each topic, concept, or phenomenon. That is, according to the proponents of PCK, the nature of the teaching approach should be dependent on the particular nature of the concept being taught. For example, the teaching approach used to teach Michaelis-Menten kinetics should require very different methods from the approaches used to teach the standard genetic code. In the context of visualization of ERs, PCK would include taking cognizance of the nature of students' (and teachers') conceptual, reasoning, and visualization difficulties and their possible sources when designing biochemistry teaching and learning activities and course curricula. This is because each conceptual or reasoning difficulty induced by an ER might require a different teaching approach to fix or prevent it. For example, a student who shows difficulty in interpreting three-dimensional spatial orientations of biochemical structures might require practice at common "mental rotation tests" to alleviate the problem, whereas a student who struggles to understand the difference between secondary and tertiary protein structure may significantly benefit from reading ERs and accompanying text that show the differences visually. Two useful strategies for predicting potential student difficulties with ERs involves instructors interpreting ERs themselves before exposing students to them and observing the manner in which students utilize such ERs [31]. Thus in summary, it is the opinion of science education researchers (*e.g.* Ref. [37]) that applying the principles of PCK to teaching and learning with ERs can lead to the improved visual literacy of our students.

4. Make the Conceptual Knowledge Depicted by ERs Explicit to Students—When teaching a biochemistry topic, teachers should always make explicit to students *what* specific conceptual knowledge will be covered [24]. When teaching with ERs, the approach should be no different; instructors should explain and clarify to students what particular conceptual knowledge the ER *is*, and is *not*, representing [18, 31]. In the classroom, teachers could also explain to students the purpose of the ER and the conceptual understanding implied by it [38]. Furthermore, due to the abstract and sometimes unfamiliar nature of biochemistry, instructors could also make use of, and contrast, various analogies (*e.g.* "lock-and-key" *versus* "induced fit") when discussing the conceptual knowledge represented by an ER [24].

5. Ensure Knowledge of the Visual Language and Conventions Used by ERs—Like written language, v*isual language* contained in ERs (*e.g.* Figs. 1–3) consists of symbolism that should be explicitly taught to learners so that they gain the necessary "visual vocabulary" and ER-processing skills [20] and thereby become more visually literate. In this regard, it is important when teaching with ERs in biochemistry that instructors actively question students about the ER and the conventions (where they exist), symbolism, and markings contained in the ER to denote conceptual knowledge [38]. For example, instructors could explicitly question students about what elements of molecular structure the ribbon (*e.g.* Fig. 2*B*), "space-fill" (*e.g.* Fig. 1*C*), and ball-and-stick representations, or any other idiosyncratic graphical markings, denote. In addition, whenever possible (*e.g.* Ref. [39]), a visualization task or activity could form part of the teaching and learning with ERs in biochemistry. This will enhance students' visualization skills and go a long way toward developing their visual literacy.

6. Make Students Aware of the Limitations of Each ER—Something that has been put forward in the science education literature with respect to other sciences, and what is crucial to learning biochemistry, is that it is necessary that educators and students alike consciously analyze, scrutinize, critique, and discuss *each* scientific ER used during a course [38]. In doing this, they should not only identify what conceptual knowledge the ER represents (see guideline 4 above) but also ascertain the *limitations* of the ER in terms of what it is not representing (*e.g.* Refs. [4, 27, and 40]). Ascertaining the limitations of an ER should be especially followed in abstract sciences such as biochemistry to avoid students thinking that the ER is an exact copy of reality, rather than only a partial *representation* of how the phenomenon really looks in reality [27, 39]. They should also realize that the real strength of a model is in its simplicity and that models that are less limited, and come closer to representing the full reality, are often too complex for students. Thus an important part of the development of visual literacy in students is to give them tasks with ERs that make them realize that ERs are just limited models of a particular phenomenon, which can vary in their usefulness for promoting learning and understanding.

7. Foster a Multiple Representations Approach to the Visualization of ERs—As discussed in guideline 6 above, a single biochemical ER lacks the "power" to show all aspects of a concept or phenomenon. In this regard, it is suggested in the literature that students should be required to interpret multiple ERs of the same phenomenon and to merge their mental models of each ER into one unifying model of reality. In this way, they would link their interpretations of the ERs to already existing knowledge to obtain different perspectives of the phenomenon, a strategy common to mathematics education (*e.g.* Ref. [41]). For instance, when learning about protein structure, students could be given a task to identify as many different representations of a particular protein as possible and to compare and critically evaluate them. This task should enable students to develop their reasoning skills by reasoning critically about the ERs and their mental model of how the protein might look in reality (*e.g.* Ref. [27]).

Interpreting and translating between a range of ERs builds powerful and integrated mental models of a biochemical phenomenon and develops a variety of cognitive strategies for visualizing the ERs [1, 4, 24]. In addition, "overloading" of a learner's mental models is minimized [8, 22]. Thus in summary, to foster a multiple representations approach to visualization, instructors should expose students to multiple ERs of the same phenomenon and get them to *practice* processing *different* ER conventions and markings that depict identical ideas (*e.g.* Fig. 2), thereby improving their translation skills between one ER and another and, therefore, their visual literacy [11, 22]

8. Empower Students with the Necessary Skills Needed to Process Biochemical ERs—As has been stressed in other areas of science education (*e.g.* Refs. [18 and 31]), biochemistry educators should be aware that little attention has been directed to actually explicitly "training" students to process ERs. Knowing how to read an abstract ER is a skill in itself, which must be learned. In addition, instructors should encourage students to adopt a strategic approach to ER processing since evidence suggests that in some cases, different skills are required to interpret different types of ERs [27, 38, 39]. For example, reading an ER portraying quaternary protein structure requires three-dimensional visualization skills, whereas an ER that depicts a genomic map requires skills for reading base sequences, etc. Furthermore, to develop sound processing skills, research results (*e.g.* Refs. [8 and 19]) suggest that students should be exposed to simpler static ERs, with which they are familiar, before having to deal with the processing constraints imposed by novel or more complex dynamic ERs. In addition to such strategies, students should also develop their transfer skills by being cued to link and transfer their conceptual knowledge between ERs representing the same phenomena (see guideline 7 above) but in different contexts (*e.g.* biology or chemistry), thus making their knowledge more flexible [34]. Thus in summary, to develop the visualization skills and visual literacy of our students, it is important that biochemistry instructors get them to perform a multitude of tasks with ERs requiring a wide range of ER-processing skills.

9. Develop Students' Metacognitive Processing Skills—As in the teaching of other sciences (*e.g.* Ref. [20]), it is important that biochemistry instructors give students tasks that stimulate their metacognitive skills, *i.e.* get them to "think about their own thinking", during exercises in-

volving the visualization of ERs. Students should ask themselves questions such as, "Am I correctly interpreting the symbolism in this ER?" or "Do I understand the conceptual knowledge represented by the ER?" By reflecting on their interpretations in this way, students build more powerful mental models and meaningful conceptual knowledge (*e.g.* Ref. [41]). Also, through acquiring such metacognitive skills, students think more like experts in that they improve their ability to think more deeply about the meanings implied by abstract ERs [18, 34]. As a further way to develop metacognitive skills, biochemistry instructors should encourage students to "take a step back" and view the ER in a critical light, asking questions such as, "What aspects of reality does this ER not show?" or "Is this a good representation of the phenomenon, or is it misleading?"

10. Use Learner-generated ERs to Help Students Visualize Biochemical Phenomena—Research has shown that students' generation of their own diagrams is a powerful method for improving scientific *visual literacy* (*e.g.* Ref. [37]). This can include getting them to produce paper-based or electronic drawings that represent cellular and molecular structures or processes. In addition, students' production of concept maps and flowcharts helps them structure, organize, and compare *concepts* graphically [42]. By planning, constructing, and refining their own ERs, students also improve their processing of other abstract ERs [43] and are stimulated to become better *metacognitive* thinkers (see guideline 9 above). Lastly, students' integration of, and reasoning with, their knowledge can be improved by drawing their own diagrams of the same phenomenon depicted by an ER [37]. As has been shown in other sciences (*e.g.* Refs. [37 and 43]), the drawing process enhances students' mental imagery and assists in making scientific concepts more concrete for them. Therefore, biochemistry educators should view students' construction of an ER as a form of *sense-making* [44] that helps students transfer their conceptual understanding to a particular task, which helps them integrate their knowledge structures in unique and powerful ways and significantly develops their visual literacy.

CONCLUDING REMARKS

It is our opinion that the pedagogical importance of visual literacy and visualization in the education of biochemists has been ignored for far too long. Given the great diversity (*e.g.* Figs. 1–3) and often confusing nature of ERs being used by biochemists, and the related visualization and conceptual difficulties identified by research, our students clearly require a high level of visual literacy to study and research biochemistry. However, since science education research has shown that students do not necessarily automatically acquire visual literacy during general instruction, we consider it essential to explicitly teach and assess this type of knowledge through specially designed instruction and assessment tasks. That is, just as practical knowledge and skills are taught in all biochemistry departments, we are proposing that the teaching of visual literacy be part of the modern biochemistry curriculum. We were encouraged to note, at the time of writing this article, that the above concerns are being addressed by other colleagues (*e.g.* Refs. [45 and 46]).

Instruction in visual literacy should inform students of the nature and modes of ERs used in biochemistry education and research and include a wide range of teaching and learning activities aimed at developing their knowledge and skills for visualizing ERs. Also, to ensure that the course curriculum is well designed, we propose that the teaching and learning activities should be informed by research into visualization, visualization difficulties, visual literacy, and related topics. Toward this end, in this study, we have proposed a far from exhaustive list of 10 guidelines that we believe could assist biochemistry educators in designing such a course. Researchers from the disciplines that specialize in visualization including science education, cognitive psychology, cognitive science, computer science, and even graphic art and media studies have generated the majority of this research. We believe that this trend will continue as the topic of visual literacy is truly interdisciplinary and concerns most of our modern world.

In addition to the guidelines for teaching and learning presented above, it is also essential that researchers investigate the *effectiveness* of ERs used in teaching and learning. In this regard, our own research [10, 24, 26] has shown that the nature of the ER itself can also have a large influence on the visualization process, and an ER that is easily interpreted by an instructor is not necessarily interpreted as easily by a learner. Thus there is an urgent need to screen all ERs for their effectiveness as teaching and learning tools in case they cause more harm than good. Therefore, formal guidelines for the *effective design* of biochemistry ERs should be given urgent attention, a topic that will be the focus of a future study.

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