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Visual Representations of DNA Replication: Middle Grades Students' Perceptions and Interpretations

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Visual representations play a critical role in the communication of science concepts for scientists and students alike. However, recent research suggests that novice students experience difficulty extracting relevant information from representations. This study examined students' interpretations of visual representations of DNA replication. Each of the four steps of DNA replication included in the instructional presentation was represented as a text slide, a simple 2D graphic, and a rich 3D graphic. Participants were middle grade girls ($n = 21$) attending a summer math and science program. Students' eye movements were measured as they viewed the representations. Participants were interviewed following instruction to assess their perceived salient features. Eye tracking fixation counts indicated that the same features (look zones) in the corresponding 2D and 3D graphics had different salience. The interviews revealed that students used different characteristics such as color, shape, and complexity to make sense of the graphics. The results of this study have implications for the design of instructional representations. Since many students have difficulty distinguishing between relevant and irrelevant information, cueing and directing student attention through the instructional representation could allow cognitive resources to be directed to the most relevant material.

KEY WORDS: cognitive load; DNA; middle school; eye tracking; instructional design.

INTRODUCTION

Visual representations play a critical role in the communication of science concepts (Ametller and Pinto, 2002; Mathewson, 1999). Numerous studies have shown that scientists use visual representations to promote their shared understanding of scientific phenomena (Kozma, 2003; Kozma and Russell, 1997). Likewise, a growing body of research has focused on the benefits of using visual representations to communicate concepts in the classroom setting (Schnotz and Kulhavy, 1994; van Sommeren *et al.*, 1998). In the science classroom, these graphics are especially helpful when representing phenomena that learners cannot observe or experience directly (Buckley, 2000; Hegarty *et al.*, 1991). Since many students depend on their senses to learn, teaching the invisible and abstract concepts in science would be difficult without visuals. For this reason, visual representations aid in making abstract concepts more concrete. Visual representations also are preferred for displaying multiple relationships and processes that are difficult to describe with text alone. These graphics provide an additional way of representing information, and when designed and selected carefully, have the potential for improving conceptual learning (Cheng, 1999).

Although a growing research base has shown the positive effects of graphics as instructional tools (Schnotz and Kulhavy, 1994; van Sommeren *et al.*, 1998), a number of studies comparing experts and novices have suggested that visual representations do not communicate understanding to all learners equally. Students with little prior knowledge focus on surface features of visuals to build an understanding of the concepts represented (Seufert, 2003). In some cases, the most salient features of a display

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(such as color, shape, labels, etc.) may not be the most relevant or important for interpreting the representation. Because novices cannot distinguish between relevant and irrelevant information, visualizations can easily confuse these learners (Hegarty *et al.*, 1991; Linn, 2003). Reliance on surface features may constrain the understanding of novices in other ways as well. Unlike experts, when working with multiple representations, novices are unable to see that representations with different surface features present the same underlying concept. In addition, novices are less able to transform representations, or provide an equivalent representation for a given concept (Kozma, 2003; Kozma and Russell, 1997). Visual representations can be powerful tools in science, but unfortunately, novice learners must surmount more obstacles in order for these graphics to facilitate their understanding of concepts (Perkins and Unger, 1994).

Schnotz and Bannert's integrative model of text and picture comprehension provides an explanation for the differences found between experts and novices. According to this model, learners comprehend graphics by constructing multiple mental representations. Initially, the learner processes the graphic at a perceptual level and creates a visual mental representation of surface structures. Then, the learner constructs a mental model that represents the subject matter on the basis of common structural features between the graphic and the content (Schnotz, 2002; Schnotz and Bannert, 2003). This mental model is more abstract than the perceptual image and irrelevant details are omitted. With little prior knowledge, novice learners often fall short of creating effective mental models; the only internal representation constructed by these learners remains at the perceptual level.

Visual representations are more likely to benefit all learners, including novices, when the design of such representations is guided by cognitive load theory. This theory is based on a cognitive architecture consisting of a limited working memory that interacts with an unlimited long-tem memory (Chandler and Sweller, 1992; Sweller *et al.*, 1998). Working memory is limited to a finite number of information items at one time (Miller, 1956); however, the load placed on working memory can be reduced by constructing cognitive schemas. Information is stored in long-term memory in schemas so that it is organized and accessible when needed (Chi *et al.*, 1982). By coding multiple items of information into one item, a schema can hold a large amount of information, even though it is processed as a single item in working memory (Kalyuga *et al.*, 1999; Kirschner, 2002).

Instruction with visual representations can place a heavy burden on the limited capacity of working memory. The load on working memory is affected by intrinsic, extraneous, and germane cognitive load. Intrinsic cognitive load is the load imposed by the nature of the subject material and element interactivity. Highly complex information, in which elements cannot be learned in isolation and must be processed simultaneously in working memory, will result in a high intrinsic load (Sweller *et al.*, 1998). Germane load is the effort required for the construction of schemas. When elements are highly interactive (high intrinsic load), more effort is required to construct adequate schemas. Extraneous load is the effort required to process poor instructional designs (Kirschner, 2002). Learning will not occur if working memory is overloaded. Any effort not directly related to the acquisition of new schemas consumes part of the working memory available and decreases the resources available for learning (Kalyuga *et al.*, 1999). Therefore, the goal of instructional designers should be to increase germane load, while decreasing extraneous load, as long as total cognitive load remains within the limits (Kirschner, 2002).

Cognitive load theory provides guidelines to assist in the design of visual representations. Using more that one modality to present information, visual and verbal, can increase the capacity of working memory. Working memory has two subcomponents that initially process visual and verbal information independently (Kirschner, 2002; Sweller *et al.*, 1998). Although it is advantageous to present material in visual and verbal modes, physical integration of these modes is required to reduce extraneous load. If cognitive effort is required to mentally integrate the two sources of information before instruction can be understood, then attention is misdirected (Chandler and Sweller, 1992). Learners should not have to allocate cognitive resources to an extraneous activity that can be avoided with proper instructional design.

Also, in congruence with cognitive load theory, cognitive effort should not be directed to a search process that is unrelated to learning. How the learner's attention is allocated is related to working memory. Visual representations are scanned both pre-attentively and attentively (Treisman and Gelade, 1980). Pre-attentive processing happens in parallel and information is initially encoded along a number of dimensions such as color, size, orientation, brightness, and direction of movement. Attentive processing requires focused attention and occurs in a serial manner, so that objects can be identified separately. To reduce extraneous cognitive load, critical features should be made salient through the use of cueing techniques. Visual representations should be designed to cue the attention of the learner using dimensions such as color and shape in such a way that search processes are reduced and cognitive resources can be directed to the most relevant material.

Reducing cognitive load associated with instructional design is critical when considering how learners are typically exposed to visual representations. More often than not, student learning from visual representations is self-directed. Textbook-oriented approaches are common in science education (National Science Resources Center, 1997; Pozzer and Roth, 2003) and modern texts are richly appointed with visual representations (Carney and Levin, 2002). More recently, computer-based multimedia materials have become more common in science classrooms (Jacobson and Kozma, 2000). The need exists for teachers to play a more pivotal role in helping students learn from visual representations. Teachers must do more than tell students to look at a graphic (Peeck, 1987); students need to be taught how to read illustrations (Stylianidou *et al*., 2002). Until teachers begin to provide explicit instructions on how to interpret visuals, features within the graphics themselves will continue to play a primary role in attracting and directing attention.

This study represents one phase in a project to examine how middle school girls interpret graphics of DNA replication, focused specifically on the characteristics that enhance the readability of these representations. The topic of DNA replication was selected for two reasons: first, public interest in DNA is widespread as evidenced in television shows, movies, and newspapers; and second, a previous DNA visualization workshop for teachers revealed that DNA is represented in a variety of ways with little thought as to how the features of these graphics affect how students interpret them. Although DNA is a novel and challenging topic for most middle school students, research has suggested that these learners have an increased ability to handle perceptual complexity (Chevrier and DeLorme, 1980; Peeck, 1987). Compared to younger children who favor pictures with simple design (Travers and Alvarado, 1970), older children experience a sudden change in preference for more complexity (Chevrier and DeLorme, 1980). In general, middle grade students have an emerging ability to engage in representational thinking (Stevenson, 1998). In addition, their potential for abstract thinking and efficient processing of information (Irving, 1997) suggests that middle school students are the most appropriate age group for research on how learners interpret visual representations.

METHODOLOGY

Background and Research Question

The subjects of this study were middle school girls ($n = 21$) participating in a 2-week mathematics and science summer camp. The participants were asked to view a PowerPoint™ presentation on DNA replication. The presentation covered four steps in the replication process with text and graphics. Specifically, for each of the four steps in the replication process, there were a text slide, a 2D simple graphic, and a 3D complex graphic. In total, the presentation consisted of 12 slides. The first set of slides provided background information about the shape of DNA (Background). The second set explained and illustrated the unzipping of DNA with special enzymes (Unzipping). The third set covered the continuous copying of the leading strand (Leading Strand), and the topic of the fourth slide set dealt with how the lagging strand is looped out and copied backwards one section at a time (Lagging Strand). Each participant viewed the 12 slides in the presentation, however the order of viewing of the 2D and 3D graphics was alternated. Half of the subjects were shown the 2D graphic in each slide set first, while the other half were shown the 3D graphic in each slide set first.

Both quantitative and qualitative data were collected to answer the following question: How will the characteristics of the DNA representations, both 2D and 3D, influence how students will respond to them? Because the first slide set on the shape of DNA was for background and the fourth slide set on copying the lagging strand was difficult for participants to interpret, analysis focused on the Unzipping (see Figs. 1 and 2) and Leading Strand slides (see Figs. 3 and 4).

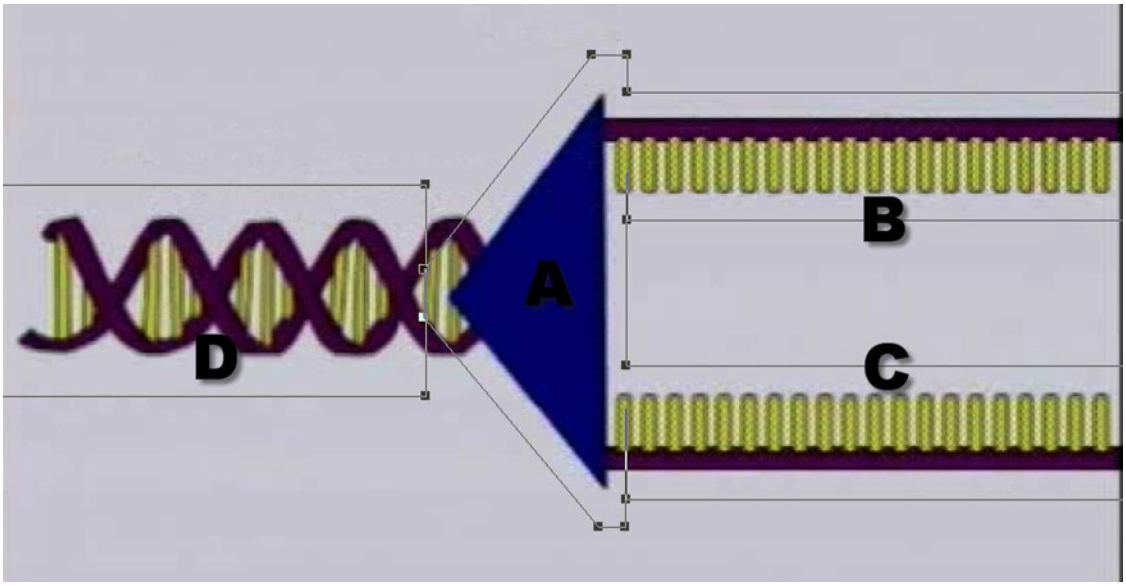

Fig. 1. 2D simple graphic illustrating the unzipping process with the following look zones defined: helicase (A), unzipped top DNA strand (B), unzipped bottom DNA strand (C), and parent DNA strand (D).

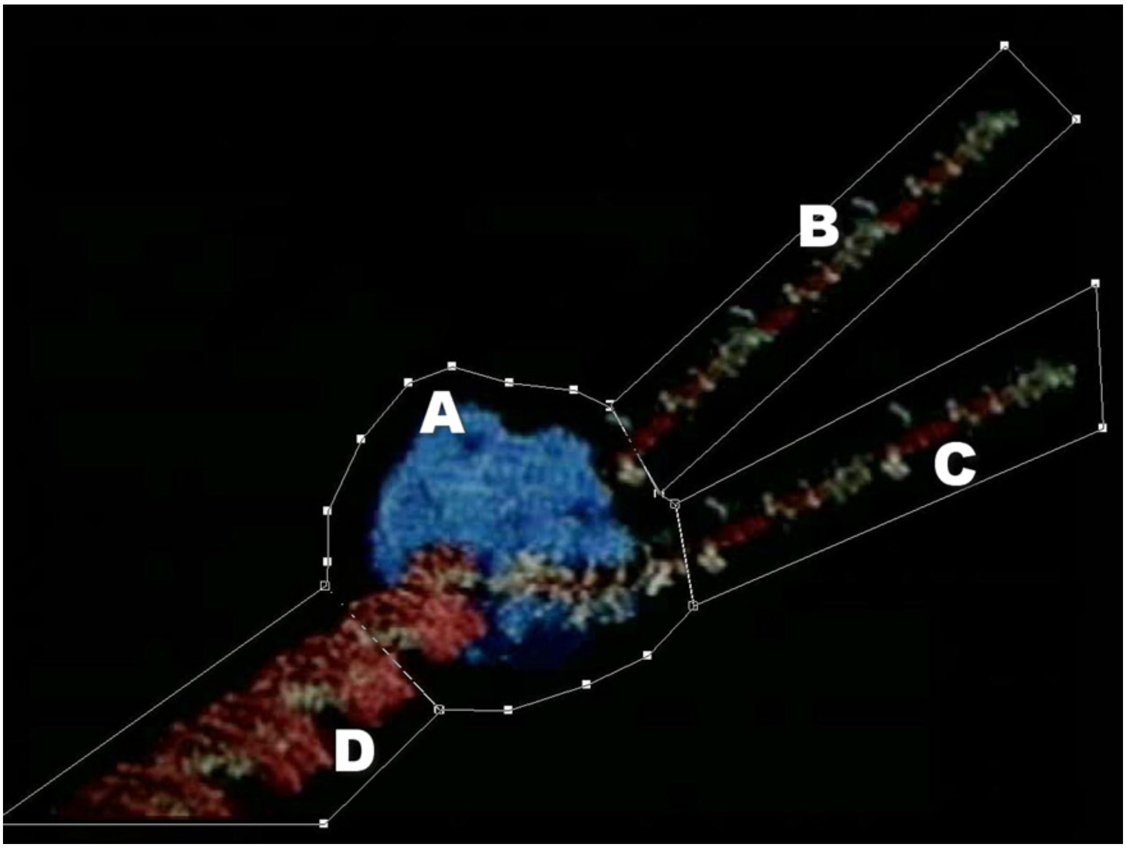

Fig. 2. 3D complex graphic illustrating unzipping process with the following look zones defined: helicase (A), unzipped top DNA strand (B), unzipped bottom DNA strand (C), and parent DNA strand (D).

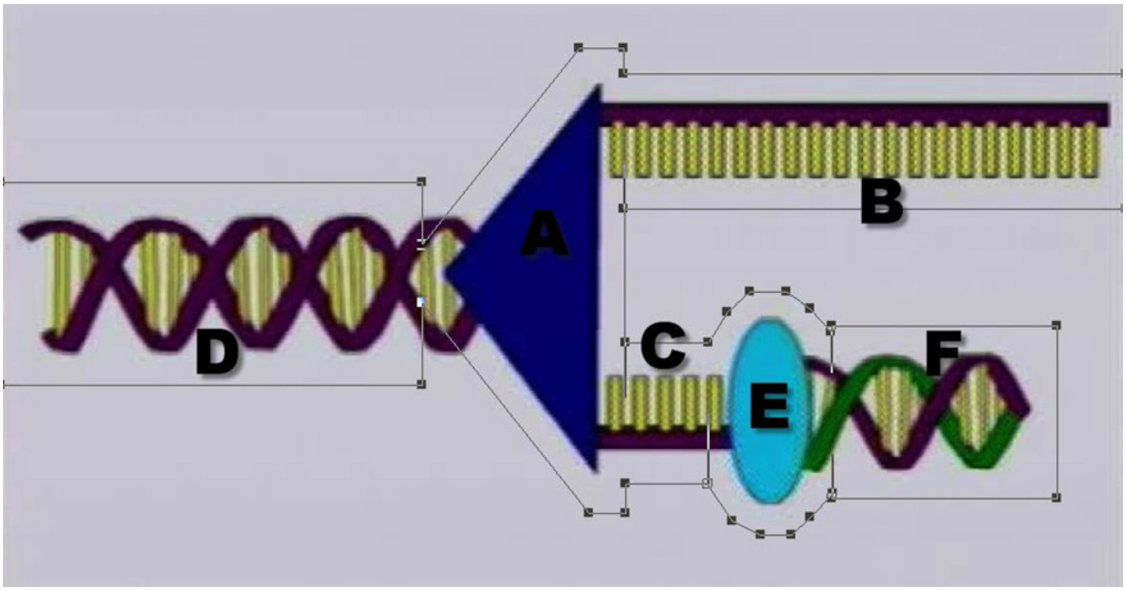

Fig. 3. 2D simple graphic illustrating the process of copying the leading strand with the following look zones defined: helicase (A), unzipped top DNA strand (B), unzipped bottom DNA strand (C), parent DNA strand (D), polymerase (E), and daughter DNA strand (F).

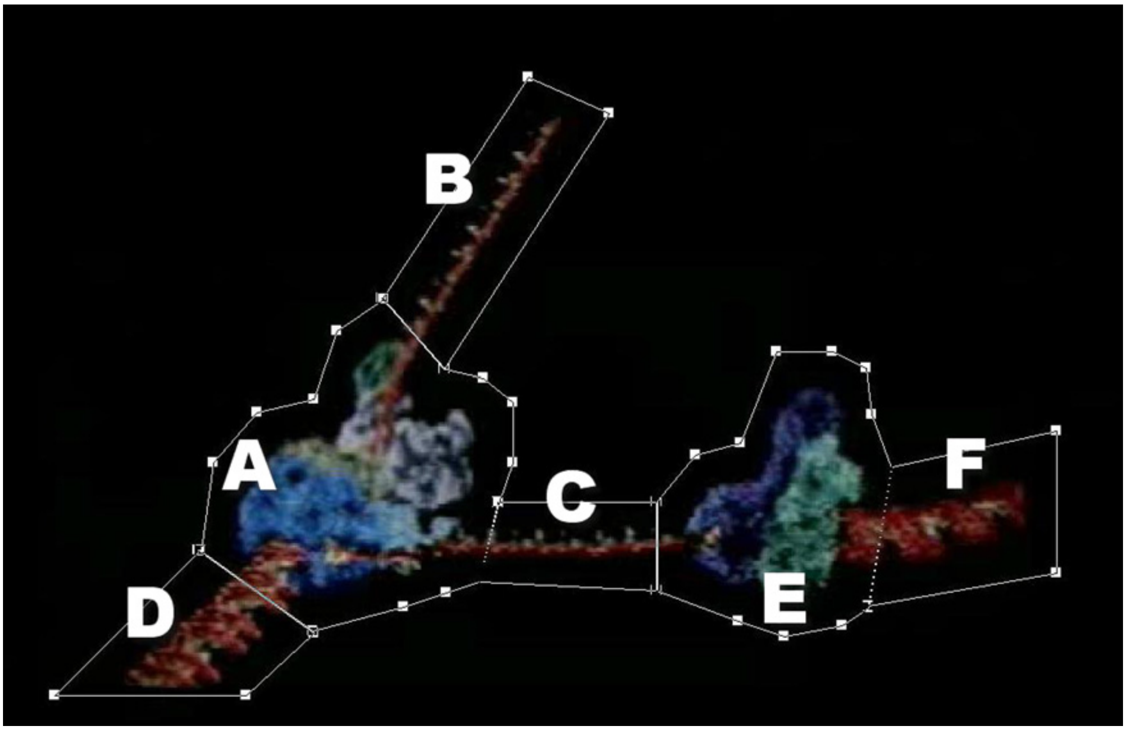

Fig. 4. 3D complex graphic illustrating the process of copying the leading strand with the following look zones defined: helicase (A), unzipped top DNA strand (B), unzipped bottom DNA strand (C), parent DNA strand (D), polymerase (E), and daughter DNA strand (F).

Eye Tracking

Eye tracking equipment was used to determine if the same features (look zones) in the corresponding 2D and 3D graphics had different salience. Comparable look zones, or outlines around important structures, were defined in the 2D and 3D graphics of each slide set, primarily driven by the science content and visual angles. A video-based combined pupil and corneal reflection eye tracker was used to measure the number of fixations occurring within the defined look zones. Fixations occur when the fovea, the area of the retina with the highest visual acuity, is stabilized over an object of interest. Graphics are scanned within fixations, normally lasting 200–300 milliseconds each, separated by saccades (Duchowski, 2002). Saccades are the "jumps" made to reposition the fovea from the current object to a new location. Where an individual fixates and how often can influence how a graphic is interpreted. Research indicates that individuals fixate on areas that are salient, surprising, interesting, or important through experience (Chang *et al.*, 1985). Initially, fixation count is related to the number of components the individual must process (Goldberg and Kotval, 1999). However, once a person finds what s/he is interested in, the number of fixations typically indicates the focus of attention, with areas receiving a high fixation count being the areas of greatest interest.

Interviews

Interviews were conducted immediately after viewing the presentation to complement the eye tracking data. Numerous studies confirm the effectiveness of combining eye tracking data with verbal protocols (Mackworth and Morandi, 1967; Von Keitz, 1988). Whereas eye tracking provides a view of how information is acquired from graphics, interviews are a more interpretive data source offering information on the usefulness and quality of the graphics, as well as affective information. In the interview portion, students were taken back through each of the four steps in DNA replication. As they reviewed each step in the process, participants were able to look at printed copies of the text slide, 2D simple slide, and 3D complex slide they viewed in the presentation. For each step of the process, the participants were probed on the salient features of the two images, similarities and differences between the corresponding 2D and 3D images, and preference for either the 2D or 3D image.

RESULTS

Salience of 3D Helicase

For both the Unzipping and Leading Strand slide sets, mean fixation count results from eye tracking indicated that more subjects fixated on the helicase in the 3D graphics compared with the 2D graphics (Unzipping, $p < .001$; Leading Strand, $p < .0001$). In the interview, many subjects indicated that the more realistic and complex shape of the 3D helicase was helpful in facilitating their understanding of the unzipping process. In the 3D graphics, an opening on the helicase allowed participants to clearly see one of the unzipped strands emerging from the enzyme. Most of the participants who found the 3D helicase helpful, did not favor the shape of the helicase in the 2D graphics. For these students, the large triangle made it difficult to imagine how the unzipped strands resulted from the parent strand. In the following quotes, participants described why the 3D helicase was more salient and offer suggestions on how to improve the 2D graphic.

Nancy: You can kind of see how it unzips (looking at 3D graphic).
Interviewer: And you can't on [the 2D graphic]?
Nancy: You can but not as much, because I see a little opening right there [on the 3D helicase] where the strand is coming out.

Amy: That one is just a triangle (pointing at 2D helicase), but this one (looking at 3D graphic) actually shows . . . you can see [the unzipped strand] coming out of [the helicase], and the other one (referring to the 2D graphic) you just don't see anything.
Kara: The arrow (referring to the 2D helicase) being as big as it is and as wide as it is, you just get this really big jump from [the zipped portion] to [the unzipped portion] and you don't really understand why until you think about it . . . Make this not so big (referring to the 2D helicase).

Lucy: [The 3D graphic] looks more realistic. Like the enzyme, it's not an arrow. I don't think that really helps—the arrow. It looks kind of weird.

Interviewer: Does this blue triangle communicate anything to you?
Rachel: Not really. I don't know why they need it there honestly. It seems sort of weird because

it blocks everything else and I thought is was supposed to be moving along the thing so it seems like a barrier . . . Maybe if you don't use a triangle. Maybe more like a circular thing. Somehow it would help me understand it more.

Cindy: I would probably move this thing (2D helicase) and show what's happening to the DNA . . . how it is unzipping.

A few students seemed to prefer the 2D, triangular helicase, interpreting direction from the shape. As the following quotes demonstrate, because these students interpreted the 2D helicase as an arrow indicating direction of movement, the lack of flow between the unzipped and zipped portions of DNA did not appear to be an issue.

Kate: This one has an arrow so you know which way it is going. You know it is unzipping, not like putting it together.

Interviewer: What does it look like [the helicase] is doing?
Nelly: It looks like it is moving forward to the left.
Interviewer: What makes it look like it is moving forward to the left?
Nelly: Because there is some behind it and it is pointing in an arrow.

Regardless of what shape they preferred, in both the 2D and 3D graphics, the helicase was brightly colored and attracted attention. Although eye movement measures indicate that more students fixated on the helicase in the 3D graphics compared to the 2D graphics, the 2D helicase was nonetheless a salient feature. For example, in the 2D graphic of the Unzipping slide set, more fixations fell on the helicase than any other look zone. As the following students explained, the helicase was salient because of its bright coloring and size.

Interviewer: What did you notice first?
Andrea: The triangle, I notice that first.
Interviewer: What made you notice that first?
Andrea: Like I said, darker colors, but it is big.

Interviewer: What stood out to you in this picture?
Tina: Probably the blue (helicase).
Interviewer: For what reason?
Tina: Because it's bright.

Salience of 2D Parent DNA Strand

There was a significant difference between the mean fixation counts for the parent DNA strand in the 2D and 3D graphics for both the Unzipping and Leading Strand slide sets. Subjects fixated more often on the parent DNA strand in the 2D graphics (Unzipping, $p < .0001$; Leading Strand, $p < .001$). In the 2D parent DNA strand, it is easier to differentiate the "rungs" of the ladder from the "sides." In the 3D graphics, this color differentiation is not as obvious. Likewise, it is easier to recognize the spiral shape of DNA from the 2D graphics than the 3D graphics. Finally, although the 2D parent DNA strand is a relatively simple representation of DNA, it is more complex than many of the other features of the 2D graphics. The following quotes illustrate students' preferences.

Amy: You can see the insides better [in the 2D graphic].
Interviewer: What is the first thing that stands out in this picture?
Amy: The purple strands (referring the to sugar-phosphate backbone) that connect the DNA rods (referring to the nitrogen bases) or whatever you want to call them.
Interviewer: What makes that stand out?
Amy: It's bigger than [in the 3D graphic] and it is colored darker.

Cindy: The yellow (referring to the nitrogen bases) with the purple (referring to the sugar-phosphate backbone), those two colors really stand out to me [in the 2D graphic] . . . I would get a clearer picture because it sort of shows everything—how they cross right here and I know there's about 3 of these in each (referring to the rods).

Tina: It looks a lot like that [3D] picture except in that [3D] picture the lines aren't very distinct—the yellow lines aren't very distinct.

Anna: This one (referring to the 2D graphic) has a better shape than I was talking about in [the 3D graphic]. It took real good form, it shows you all of the curve lines, and you saw the 3 lines [in the middle].

Nancy: I can see the spirals a little bit better (in the 2D graphic).

Sophia: It told us more of the spiral shape rather than the little, different parts of it.

Rachel: This (referring to the 3D graphic) seems like a little bunched up and you don't really know what to look at first. It just kind of looks like a lot of little dot things.

Salience of 2D Daughter DNA Strand

In the Leading Strand slide set, there was a significant difference between the mean fixation counts for the newly formed daughter DNA strand in the 2D and 3D graphics. Subjects fixated more often on the daughter strand in the 2D graphic ($p < .0001$). Many subjects revealed that the color contrast of the newly formed DNA strand in the 2D graphic aided in their interpretation of the graphic. However, in the 3D graphic, there was no color contrast and the shape of the DNA was not as easily identified. The following quotes indicate that students benefited from highlighting the new part of the strand in green in the 2D graphic.

Cindy: I noticed that was green. I think it was a different type of DNA; something happened to the DNA . . . [I liked the 2D graphic better] because I can actually see that the DNA is changing.

Kara: Maybe it's just showing you what's changing about it. It's adding a green strand to the other one so it joins and makes a double helix.

Barbara: It's sort of like another replicate of [the unzipped stand]. So like it is not really the original, but a copy. So purple is the original and green is a copy.

Interviewer: This is green. Do you think it has any significance?
Nelly: Yeah I think it has some significance because it got changed some.
Interviewer: What do you think that means then, or might mean?
Nelly: When it got unzipped and back together, it got changed somehow. Something different happened.

Sally: Like in this picture (referring to the 2D graphic), they changed the color so you could really tell, but in [the 3D graphic] it was still red

For some students, the reason behind the color change was not as obvious. As these participants indicated, they noticed the new color even though they were not able to extract meaning from it.

Emma: You have purple and yellow and then they throw the green in, and I don't know what the green is.

Linda: I'm sure there is [a reason for the green], because they want it to stand out, but I am not sure why.

Amy: I don't know what the circle meant and how the green came out of it. I knew the leading strand was being copied, but I thought that could be the purple one. I didn't know which one it was, the green or the purple.

Salience of 3D Polymerase

In the Leading Strand slide set, there were more fixations on the polymerase in the 3D graphic compared to the 2D graphic, but not to a level of significance ($p < .07$). Similar to the helicase, interest in the polymerase in the 3D graphic may be explained by its more complex shape. As they explained in the following quotes, participants were better able to see the leading strand being copied by the 3D polymerase, whereas the oval shape of the polymerase in the 2D graphic was not as helpful.

Barbara: Because I still think [the 3D graphic] is more realistic. And it shows where [the 3D polymerase] can move along that way [toward the helicase].
Interviewer: Does it do a better job of showing moving along than [the 2D graphic] does?
Barbara: Yeah.

Elizabeth: [In the 3D graphic], it looks like it is copying [the leading strand], instead of this blue thing (referring to the 2D polymerase)

Abbey: I saw that [the 3D polymerase] was making . . . I mean [the 3D polymerase] looked better than [the 2D] one, cause I could tell that it actually turned into a spiral. It was like darker colored there.

Like helicase, polymerase was brightly colored and attracted the attention of participants in both the 2D and 3D graphics. Although polymerase was more salient in the 3D graphic, the second highest number of fixations was on polymerase in the 2D graphic, indicating that it was also a salient feature in 2D.

Background and Highlighting Issues

Many subjects had more general comments to make about the 2D and 3D graphics. Several students indicated that the background was problematic. Some participants, as demonstrated by the following quotes, wanted the DNA representations to be situated in a context and others did not like the use of a black background on the 3D graphics.

Anna: [It would be more helpful] if it kind of had an area where it would be—like if it would be in the blood system, or what system it would be in . . . it's just kind of floating (referring to the 2D graphic).

Rachel: I think what's confusing about it is maybe if this was a lighter back color.
Interviewer: So is the background just distracting because it is so dark?
Rachel: Because [on the 2D graphic] my attention goes straight to the [DNA] and [on the 3D graphic] I kind of look [at the black background] and then I look at [the DNA].

Cindy: Make the background brighter [to improve picture].

Other participants offered advice on how to better direct attention to the important features of the graphics. As the following quotes indicate, students were particularly interested in highlighting the important areas and using labels and captions.

Sophia: I saw mainly this part (referring to parent strand) more than this part (referring to the unzipped strands). And [the unzipped part] was the part they were trying to focus on.
Interviewer: Because what are they trying to show in the picture?
Sophia: Unzipping
Interviewer: But you focused more on this [the parent strand]?
Sophia: Yeah, it's just brighter on the computer screen. And when they are trying to show you [the unzipped part] and it's dull and then [the parent strand] is bright, it kind of defeats the whole purpose of the picture. It kind of makes [the parent strand] seem like it is the main focus instead of [the unzipped part].
Interviewer: So what you are telling us, is that if there is something in a picture we want a middle school student to focus on, then it ought to be the brightest to get their attention?
Sophia: Or bold or something. Like if [the parent strand] was thinner or darker and [the unzipped] part was brighter and thicker you would be able to tell it was unzipping more than this picture shows you.

Sharon: [You could make this a better picture] if you could label it, somehow. If there was a way to put a small paragraph at the bottom or a sentence to say what was going on in the picture, you could probably tell a lot easier what was going on.

Rachel: It doesn't label parts and I thought it would better if it labeled parts or said like what this does or what that does because it seems just like a picture with not much there.

Cindy: I think that this should be sort of a diagram type thing where pointers would be held right here and it would say what's happening here.

Overall Preference for 2D or 3D graphics

Overall, no clear preference was found for 2D or 3D graphics in either of the two slide sets. A few participants preferred either the 2D graphics or the 3D graphics for both slide sets, however, most participants preferred the 2D graphic for one of slide set and the 3D graphic for the other. Explained by the following quotes, those students who preferred the 3D graphics cited reasons such as the high level of detail and realism and the assistance they provided in interpreting the 2D graphics.

Kara: It really captures your attention more than [the 2D graphic] . . . You can understand what's going on in the 3D better.

Barbara: It like details more into what a DNA strand really looks like, where as [the 2D graphic] is just a basic picture.

Interviewer: Do you think most middle school students would rather see pictures that look more real 3D than 2D?
Lucy: Well I know I would. It's a lot more interesting to me to see the actual thing instead of seeing models of it because you get a good idea of what it looks like.

Sophia: They would be more interested in that picture (referring to the 3D graphic) rather than this one and [the 3D graphic] will show more to them than that one will.
Interviewer: Is there anything we can do to [the 2D graphic] to make it better?
Sophia: It's just kind of boring.
Interviewer: So in school you like more interesting pictures, even if they are more complicated?
Sophia: Yeah.

Rachel: [The 2D graphic] seems a little plain to me. I think kids might look at it and just keep going.

Mindy: Once I saw [the 3D graphic], I understood what this was (referring to the 2D graphic), but if I saw [the 2D graphic] first, I probably wouldn't get it.

Not all of the participants agreed that the 3D graphics were more easily interpreted. These students preferred to learn through simplistic pictures before additional detail was introduced. Several students acknowledged that their preference for the 2D graphics parallel how concepts are typically covered by middle school teachers. The following quotes offer insights as to why the participants may have preferred the 2D graphics.

Linda: [The 2D graphic] is very simple and it's easy to understand. I understood that one a lot better than the other one (referring to the 3D graphic).
Andrea: [The 3D graphic] is more detailed than the other one.
Interviewer: And you think it is easier to understand first simplistic and then detailed?
Andrea: Yeah, so you tell them and explain and once they get [the 2D picture], then you show them [the 3D picture] and you say this is what [the 2D] is, but more detailed . . . [The 2D graphic] is better because it is more simplistic and once [middle school students] get that then you show them [the 3D graphic] so they can get a more broader view of what it actually looks like.

Theresa: It seems that this one is more like a high school level because you're looking at the exact molecules and trying to figure out every single thing and [the 2D graphic] seems like . . . at middle school you'll only learn the pattern and things because that's what it is all about and not all the little small parts.

Lisa: In [the 2D graphic] you don't have a bunch of little details to take you off of what's really happening. In [the 3D graphic], they added some stuff over here and I wasn't really sure what was going on.
Interviewer: So it's distracting to have too much in a picture?
Lisa: Yeah.

Sharon (after explaining that she had understood the 2D graphic better): If you are able to understand something, it makes it more interesting. That's a big part of teaching, getting somebody's interest and directing it toward what you are teaching to them. Otherwise they are not going to pay any attention. And if they don't pay any attention, you can sit up there and talk all you want but they are not going to learn anything.

DISCUSSION

In this study, the corresponding 2D simple and 3D complex visual representations of each slide set were informationally equivalent, but not computationally equivalent. To be informationally equivalent, every item of information represented in one graphic should be represented in the other. To be computationally equivalent, learners must be able to retrieve the same information from the two representations (Larkin and Simon, 1987). The corresponding 2D and 3D graphics represented the same information, however, they differed in terms of their usefulness. Most participants were unable to extract the same information because they relied on cues such as complexity, color, and shape that were unique to either the 2D or 3D graphic.

Complexity, or the amount of detail, can attract attention provided the level of complexity does not exceed the learner's cognitive resources (Fleming and Levie, 1978). A number of studies, dating far back in the literature, have dealt with the amount of complexity and detail graphics should contain. Early on, a controversy ensued when some researchers recommended that realistic pictures with emphasis on detail have a greater probability to facilitate learning because students are able to make discriminations (Peeck, 1987). Other researchers have disputed this claim, suggesting that the complexity and detail associated with realism can confuse learners and distract them from relevant information (Dwyer, 1969; Travers and Alvarado, 1970). Dwyer's research (Dwyer, 1969; Joseph and Dwyer, 1984) indicated that students have more difficulties learning from realistic drawings and photographs of the heart than from simplified diagrams. He concluded that simplified diagrams were more effective in facilitating learning since they could be used to emphasize relevant parts, while other details could be deemphasized.

While student identification of relevant features is an important goal, some amount of detail and complexity are needed to hold student attention. Otherwise, students are likely to view the representation superficially and assume they understand it (Weidenmann, 1989). The optimum amount of complexity and detail warranted seems to depend on many factors including learner characteristics (age, gender, prior knowledge), subject matter, and task (Hegarty *et al*., 1991; Myatt and Carter, 1979). In this study, the 3D representations of DNA replication were, overall, more complex graphics than the 2D representations. However, because there was not a clear preference in the interviews for either type of representation, the results indicate that subjects were using more than a simple versus complex distinction to determine which graphic was more helpful in their understanding of DNA replication. In fact, the results of this study suggest that participants relied more heavily on color and shape to make sense of the graphics.

It is impossible to overestimate the role color plays in attracting attention and helping learners extract meaning from graphics (Reid and Wicks, 1988). On the one hand, color can be used to highlight features in graphics, assisting students in making discriminations and detecting relationships. Using color can reduce cognitive load by reducing the need for visual search, therefore directing more cognitive resources to the relevant material. On the other hand, color may unnecessarily complicate the instructional materials by giving the learner too much information to process. In this case, color may serve to direct student attention away from the relevant parts of the graphic (Peeck, 1987).

In this study, color served as a cue to attract the attention of participants. In the 2D graphics, the color contrast of the yellow used to distinguish the middle section (nitrogen bases) of the parent DNA strand from the purple sides (sugar-phosphate backbone), received a higher fixation count than in the 3D graphics. Likewise, in the daughter DNA strand, different colors used to represent the two halves of the strand also attracted considerable attention in the 2D graphics. In this manner, color helped the subjects make discriminations between the different parts. Helicase and polymerase, the brightly colored enzymes, also attracted attention. Even though they received more fixations in the 3D graphics, these enzymes still received a high number of fixations in the 2D graphics. It is possible that the coloration of helicase may have distracted participants in the 3D Leading Strand set graphic. The high number of fixations on helicase may have taken their attention away from the more relevant polymerase and leading strand in the graphic.

Shape or geometric form can be used to make sense of graphics, particularly the function of features in the graphic. The twisting seen in the parent and daughter DNA strands in the 2D graphics provided more information to the participants regarding the helical shape of DNA compared to the 3D graphics. The geometric forms used to represent enzymes in the 2D graphic were not well received by participants. Most preferred the more realistic shapes used in the 3D graphics. These shapes allowed the participants to understand the function of these enzymes. The more intricate enzymes enabled the subjects to determine the direction in which the enzymes were moving to unzip the parent DNA strand and create the daughter DNA strand.

Although characteristics like color and shape allowed participants to interpret graphics of DNA replication fairly well, most participants indicated the need for more tools to help facilitate their learning. For example, some participants suggested including labels and captions with the graphics. Captions not only describe what can be seen in a graphic, but also guide students in how to look at the more relevant aspects of the graphic (Pozzer-Ardenghi and Roth, 2005). Labels can also be used to focus student attention on important material (Beck, 1984). Captions and labels would have allowed the physical integration of text and graphics, instead of a text slide followed by a graphics slide. In the latter case, reading the text and holding it in working memory while searching the graphic was cognitively more demanding (Sweller *et al.*, 1998). When content is presented in two modes and synchronized, cognitive load on working memory is decreased (Chandler and Sweller, 1992).

Visual representations should purposefully use cueing strategies to attract attention and influence what information learners will extract. When students do not know what information to attend to, they are likely to draw incorrect conclusions from the graphic (Rieber, 1991). Making relevant information more salient through the use of complexity, color, or shape could free more cognitive resources for constructing an internal mental model of the content. The creation of a mental model is a schema driven process and an indication of learning, as opposed to merely perceiving a representation (Schnotz, 2002). For example, using the green and purple color contrast made the 2D daughter strand salient and allowed students to comprehend the underlying principle. The participants were able to understand that a new strand was being added to create a new double helix; they were able to see beyond the colors.

Drawing attention to the relevant features is helpful, but some learners are unable to perform this higher level cognitive processing. These learners can comprehend pictures at a perceptual level but they are never able to understand the underlying concepts. For example, a few students recognized that a new color was being introduced in the 2D Leading Strand slide, however, they were unable to interpret meaning from it. The salient feature captured their attention, however these students were left without the cognitive resources to explore the underlying concepts. In a similar instance, some participants noticed the brightly colored, triangular helicase, however were unable to interpret its function. Instead, these students were focused on the poor continuation between the zipped portion and the unzipped portion.

Visual representations play an important role in communicating knowledge of science concepts to students. To understand the influence of visual representations in the learning process, it is important to study the way they are read by the learner. Analyzing eye movement measures in coordination with interview responses can provide a more complete understanding of how different features of graphics can affect interpretation. Differences between learners who rely on perceptual processing of surface features and those who construct internal mental models can offer insight into the instructional design of multimedia materials, specifically how to use salient features to develop deep knowledge structures.

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