Using 3D Animation in Biology Education: Examining the Effects of Visual Complexity in the Representation of Dynamic Molecular Events

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This study examines the effectiveness of visual complexity in animation for learning about molecular events. Undergraduate biology students (n=8) were assessed using tests, verbal reports, and eye tracking data in order to characterize their understanding. Our findings suggest that students attend to the same narrative elements regardless of the complexity depicted in each animation, and that visual complexity was positively correlated with elaborated explanations of events depicted. However, our results also suggest that students have difficulty understanding the random nature of molecular events and anthropomorphize these processes.

Introduction

The study of biology takes place at multiple levels, from the nanoscale to the study of entire populations of organisms. Naturally the complexity of interactions operating along multiple spatial dimensions and temporal scales is a challenge for the novice undergraduate student to grasp. Students often approach biological phenomena as a series of discrete events, failing to appreciate the critical patterns and relationships of the whole (Tibell and Rundgren 2010). Subject areas of particular difficulty for students include protein conformational change and stability (Robic 2010), diffusion and random molecular motion (Garvin-Doxas and Klymkowsky 2008), and molecular crowding (Ellis 2001). These factors pose a teaching challenge to instructors, who increasingly seek out additional resources (commonly illustrations and animated representations) to explain molecular processes. While there has been enthusiastic adoption of these tools at various levels of education, surprisingly little is known about the efficacy of this visual medium.

In two related studies, we examined the relative effectiveness of 3D animation for learning about molecular biology, specifically protein conformation and molecular motion in association with a cell-binding event. Increasingly complex versions of the same receptor-ligand binding event were depicted in each of four animated treatments. The preliminary study (reported in Jenkinson and McGill 2012) examined learning along the complexity continuum, and asked whether or not complexity is an appropriate predictor of instructional effectiveness. The second study (reported here) examines understanding from the perspective of the learner, asking if prior knowledge in a content area influences a student's ability to benefit from visualized instruction; as well, this study explores the perceptual affordances of the medium, asking to what extent does perceptually salient information contribute to the development of an accurate mental model of depicted events?

Theoretical Background

In exploring the ways in which students struggle with some complex dynamic concepts, Chi (2005) offers an explanation that is illustrated by contrasting the differences between "direct" processes and those that are "emergent". Misconceptions surrounding direct processes (for example, the human circulatory system) are much more easily corrected than those surrounding emergent processes (for example, molecular diffusion). Direct processes may be broken down into subgroups or classes. Emergent processes, on the other hand, are not as easy to describe in terms of subgroup or hierarchy. They consist of a collection of components contributing equally to a reaction. Chi suggests that students fail to comprehend emergent or dynamic events because they seek causality and group entities according to shared perceptual properties. In the case of a students' trying to understand diffusion, they might associate water and dye on the basis of colour, rather than thinking about water and dye molecules collectively interacting (one collection). There is increasing evidence to suggest that visualization may play a key role in science education to support students understanding of emergent phenomena (Ainsworth and VanLabeke 2004; Ainsworth 2008).

The Role of Dynamic Visualization – Learning From Animation

Biology is an inherently visual domain. Perhaps more than in any other area of science, visualization helps us grasp the complexity of biological events that are too small to see with the naked eye (or microscope in the case of biomolecules), or too rapid to experience with our own senses. Animated media

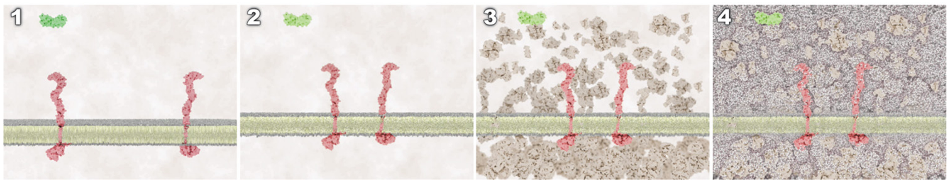

***Figure 1**. Frames from four animations representing the same receptor-ligand binding event.1) treatment 1 depicts the event using smooth, directed motion of the ligand towards the receptors; 2) treatment 2 introduces random, non-directed (Brownian) motion; 3) treatment 3 builds upon treatment 2 and introduces molecular crowding; 4) treatment 4 builds upon treatment 3 and introduces molecular water.*

is particularly well suited to demonstrating temporal processes, as it can convey dynamic change over time. While it seems as if the potential educational value of animations should be great, this is not borne out by the research assessing the impact of animation upon learning. Many studies have demonstrated that animation is equal to (Rieber 1989; Rieber and Hannafin 1988; Sanger and Greenbowe 2000) or, in some cases, less effective than static imagery (Lewalter 2003; Lowe 2003; Tversky et al. 2002). This is not surprising, since a single form of educational media is not likely to be equally effective across all learning contexts. Regardless of the negative or neutral effects reported in the literature, our enthusiasm for animated media persists.

Emergent Views on Learning from Animation

More recently, researchers such as Ainsworth (2008; 2004) and Lowe (2004; 2008; 2011) have begun to explore the ways in which we do learn from animation that might in turn inform how animation should be designed in order to support learning. In discussing the role of animation in supporting learning, Ainsworth (2008) remarks that much of the research examining the impact of animation is based solely upon the cognitive level of explanation. Both Mayer's Theory of Multimedia Learning (2005) and Sweller's Cognitive Load Theory (1998) are examples of this. It is surprising that so little attention is paid to the perceptual aspects of animation.

Examining the basic perceptual characteristics of animation has become an area of discussion in recent research by Schnotz and Lowe (2008). The authors argue for a unified approach to examining both animations and images. The basis for this argument is rooted in the observation that animations and pictures are psychologically more similar than they are different. Both are processed by the same perceptual and cognitive system. If we consider the visual attributes that are preattentively processed by the brain (for example, colour and contrast), with the exception of motion, these are evident in both static imagery and animation. We mustn't ignore the fact that motion is a powerful preattentive feature. However, we may apply these theories of pattern recognition and preattentive processing, usually reserved for static imagery, to the design and evaluation of animated representations.

Background to the Present Study

In a preliminary study, undergraduate students (n=131) were recruited from the Biology program at University of Toronto Mississauga (Jenkinson and McGill 2012). Participants were randomly assigned to one of four animated treatments (Figure 1). Students were tested at three time points (Pre-test, Post-test, and Delayed Post-test). Overall we found that the learning effects of the more complex visualizations were lasting, but only with regard to the more basic concepts.

Methods

Overview

The present study was conducted to characterize the learning that occurred with respect to each of the four animations viewed by collecting data on thought process (as captured by verbal reports), and perceptual processing (eye tracking measurements). In this scenario participants viewed each of the four animations.

Participants

The participants in this study were eight undergraduate biology students (aged 18-24; two males and six females), in either the first (n=1), second (n=3), third (n=2), or fourth (n=2) year of study at University of Toronto Mississauga (UTM). All students had a basic understanding of cell biology.

Materials and Measures

The animations used in this study were developed in the Center for Molecular and Cellular Dynamics at Harvard Medical School. We identified three visual variables (in addition to protein conformation) that pose particular difficulty for students: 1) Brownian (random) motion; 2) molecular crowding; and 3) depiction of molecular water. These three features were introduced additively to each of the four animated treatments (Figure 1). Stem cell factor (SCF) ligand and the receptor tyrosine kinase (KIT) were used as a classical example of a ligand-induced receptor dimerization and activation event. These animations may be viewed at the following address: http://www.molecularmovies.com/bindingstudy/.

Verbal reports were elicited concurrent with viewing the animations (Ericsson and Simon 1993). The goal of the think-aloud procedure was to document thought processes as they occurred and thus capture the learners' thoughts as they engaged with the animations. Verbal reports were recorded with an iPhone® 4 and an attached microphone. Participants' eye movements were recorded with a 60Hz video-based remote eye-tracking device from Mirametrix with an angular resolution of less than 0.5 degrees. The stimulus PC was a 27-inch Apple® iMac®, running Windows® XP SP2 in Boot Camp®.

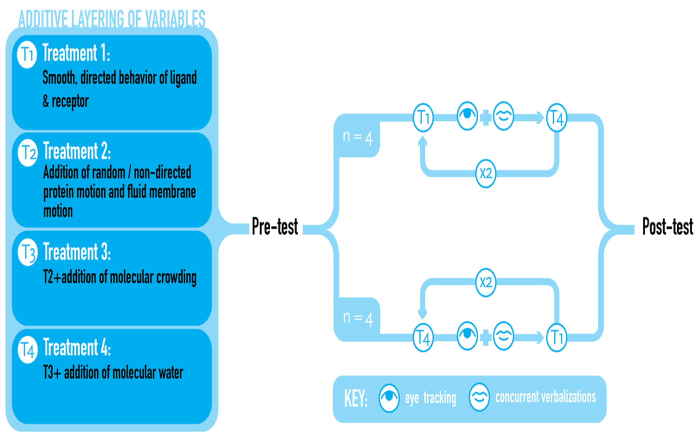

Figure 2. Experimental protocol for assessing how students attend to and interpret an animated depiction of a receptor ligand binding event rendered at varying levels of visual complexity.

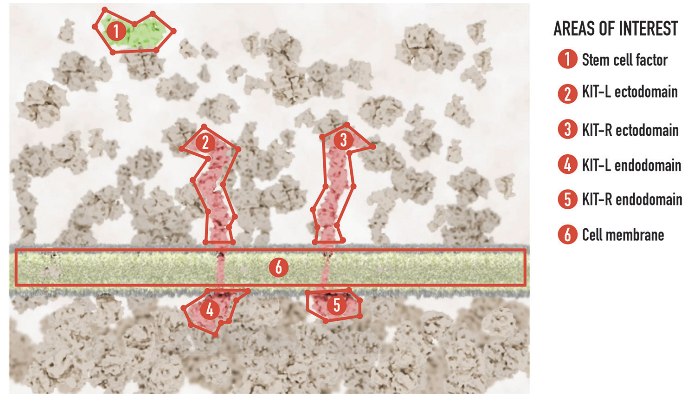

Figure 3. Areas of Interest identified for the assessment of visual attention.

Procedure

Participants were randomly assigned to one of two instructional conditions (Figure 2), and viewed the animations either in order of complexity or in reverse order (to ensure that the viewing order did not bias qualitative data collection measures). Each student completed a background form and pre-test that served as a baseline measure for ensuring equivalent prior knowledge across the two groups. Participants were then asked to view the animations once through and instructed to "…think-aloud your thought process without censoring anything." Recording of eye movements and verbalizations was initiated. After this initial viewing the animations, participants were asked to view the animations again, only this time to verbalize their thought process in relation to "the factors that influence the binding event". Following the second viewing, students completed the post-test.

Analysis

Test answers were scored as either correct (1 point) or incorrect (0 points) out of a possible total of ten points on each test. Descriptive statistics on test scores were generated to measure the difference in mean scores between the pre-test and post-test. Given the small sample size, nonparametric testing (Wilcoxon) was used to evaluate the difference between pre-test and post-test scores.

Verbal reports were transcribed verbatim, with records coded into individual units of analysis, in keeping with Lowe's (1999) distinction between descriptive statements and explanatory statements. Descriptive statements make reference to activity by observing visually salient features without attempting to account for effects observed. Explanatory statements attempt to identify causal agents or establish linkages between cause and effect. Since an important aspect of this study involved understanding the role of visual complexity in the development of understanding, eye tracking served as a measure of perceptual salience. In all, six Areas of Interest (AOI – see Figure 3) were identified, each of which corresponded to a functionally relevant aspect of the narrative (Boucheix and Lowe 2010; Kriz and Hegarty 2007; de Koning et al. 2010). For each participant, a count was made of the number of fixations (eye movements) that occurred within each AOI. Data collected throughout this experiment (post-test responses, verbal reports, and eye tracking videos) were analyzed in relation to each other; this served to triangulate the data and to help enhance the credibility of the findings and assertions made (Lincoln and Guba 1985).

Results

The results of statistical analysis showed a mean score of 4.0 (SD=2.39) on the pre-test and a mean score of 5.13 (SD=2.99) on the posttest. Although post-test performance was demonstrably superior to pre-test performance, a nonparametric assessment (Wilcoxon Signed Rank Test) comparing performance at both time points indicates that the differences between the pre-test and post-test scores were not significant (p=102). A quantitative assessment of the verbal protocol data showed that the majority of reports contained a greater number of descriptive statements than explanatory statements (Figure 4). The number of explanatory statements reported was positively correlated with both prior knowledge (r=81, p<.05) and the complexity of representation depicted (r=98, p<.05), as illustrated in Figure 5.

Interpretation of Descriptive Statements

Descriptive statements were evaluated for evidence of thematic relevance and perceptual salience. The majority of descriptive statements were identified as thematically related. Often students would describe the narrative in a linear stepwise fashion. The following is an example of a verbal report referencing the second animation (random motion, no molecular crowding):

> **Participant 4:** *The ligand joins to one of the receptors… and then goes away… and then comes towards the middle… and attaches to one of them… and the second one unites and then the yellow thing glows.*

Many of the descriptive statements relating to the perceptual

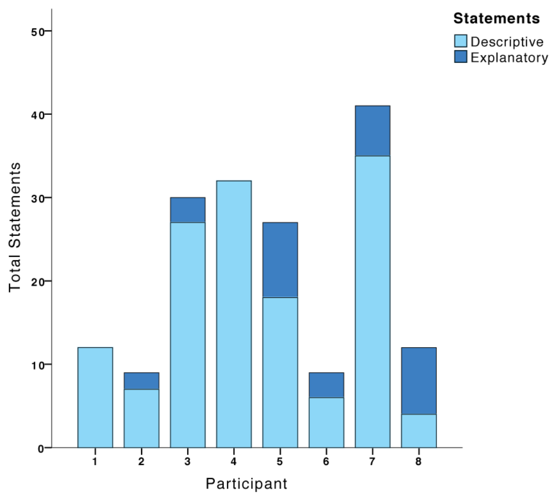

***Figure 4**. Proportion of descriptive and explanatory statements contained in participants' verbal reports.*

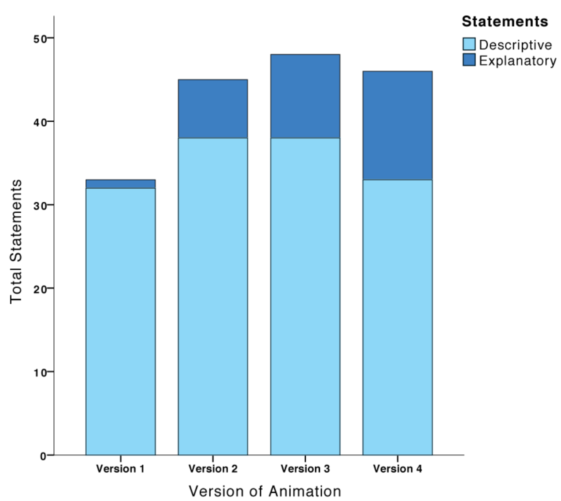

***Figure 5**. Frequency of descriptive and explanatory statements referencing each version of the animation*

salience of features were focused on the fluidity of the cell membrane, the motion of the ligand, the "background", or the colour of the activated KIT endodomain. A number of descriptive statements relating to the presence of other molecules (crowding) treated them as a "background" to the main narrative. These monochromatic molecules have salience due to their stochastic movements, unlike the KIT monomers and the ligand, which have salience due to their colour coding.

In select cases, statements evoked by perceptually salient features contributed to the development of explanatory statements. For example, while viewing the third animation, Participant 2 commented on the background as a detracting factor, then shifted her focus, while viewing Version 4, as her understanding about its role in the binding process evolved.

> **Participant 2:** *My focus is more on the background than on the interaction between protein and ligand… Mmm… although the background doesn't seem to have any influence… Mmm… wondering how the background is affecting the binding process.*

Even some of the more advanced students depended upon perceptual cues in the formulation of explanatory statements. For example Participant 5, who is advanced in terms of her prior knowledge, used perceptual cues to inform her understanding of activation.

> **Participant 5:** *The two proteins bind together and they turn one solid colour, and the inside of the protein membrane protein changes colour… So it might be activating something on the inside.*

Interpretation of Explanatory Statements

Explanatory statements were assessed for evidence of understanding in three areas: 1) conformational change; 2) random molecular motion; 3) molecular crowding. Results showed that the majority of participants demonstrated an existing or emergent understanding of the relevance of protein conformation to the binding process. This finding was supported by post-test results. For example, Participant 8 made several implicit references to the conformation of KIT as she attempted to conceptualize the binding process:

> **Participant 8**: *I think it has to attach the right way... and then it gets accepted by the receptor.*

This student next suggested that SCF won't properly bind with KIT unless it is held by the two monomers at once:

> **Participant 8:** *If it's only attached to one receptor then it gets detached… unless it's squeezed between the two of them… then it remains intact.*

Finally, Participant 8 arrived at an understanding of binding that is related to the conformation of the receptor.

> **Participant 8:** *It depends on how it binds to the ligand… if it binds properly to the ligand then it will stick on to it… the receptor has to be in a certain direction… certain position to -uh- hold on to the ligand.*

The concepts of random motion and molecular crowding were not as well understood by participants. There were very few instances of explanatory statements relating to random motion except among students with a more elaborated mental model of the binding process as a whole. Even among these students, while they understood the general concept of random motion, they attached agency to the actions of the molecules in relation to the ligand. For example, the ligand and other molecules are described using terms such as "trying to bind" (Participant 5), "in search of" (Participant 5), "it needs to dimerize" (Participant 7), "it needs to get back" (Participant 7 – in reference to the detachment of the ligand). Similarly, students had a basic understanding of crowding, as demonstrated in post-test responses, but not as it related specifically to the animation. Molecular crowding was treated more as a background feature, one that prevented binding rather than enabling it.

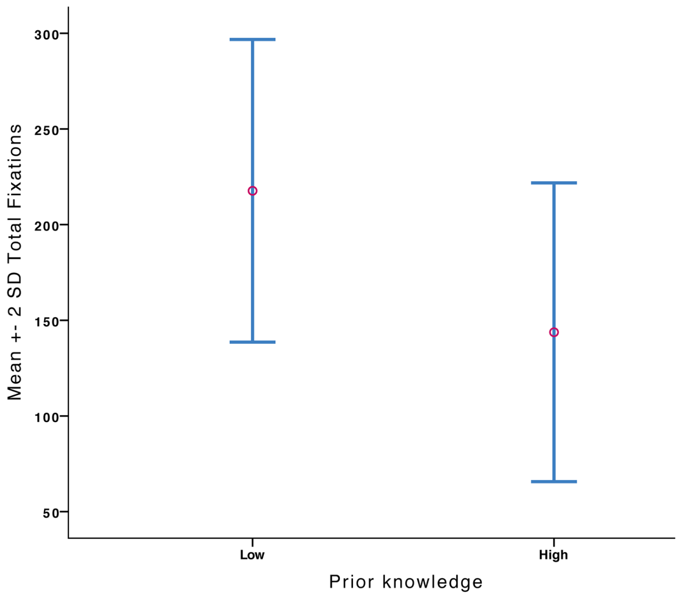

Figure 6*. Error bars (two standard deviations above and below the mean) for the mean number of fixations among participants with low and high prior knowledge*

Results of Eye Tracking Measures

Eye tracking measures served a primary purpose of informing the findings of the verbal reports. However they were also analyzed to gauge the comparative distribution of fixations across each version of the animation. Results showed that the greatest number of overall fixations occurred in Version 2 of the animation, and the fewest number of fixations occurred in Version 4. In every version of the animation the number of fixations within specified AOI was greater than the number of fixations outside of these defined areas, suggesting that the most thematically relevant material (material linked directly to the narrative) attracted the greatest amount of visual attention. Version 3 contained the greatest mean number of fixations distributed outside specific AOI, while Version 4 comprised the fewest number of fixations outside AOI. A comparison of viewing patterns among participants suggests that fixation patterns related more closely to the individual student's viewing characteristics than to the visual complexity of each animation. An independent-samples t test was conducted to determine whether or not fixation patterns were influenced by prior knowledge. Although there was a trend toward increased total fixations among participants with low prior knowledge (*M=217.67, SD=39.55*) when compared with high prior knowledge participants (*M=143.75, SD=39.04*), this proved not to be significant, $t(5)=2.46$, p= 057 (Figure 6).

Discussion and Implications

The Role of Prior Knowledge

There is increasing evidence that learning from visualizations is moderated by students' level of domain-specific prior knowledge (Lowe 2003; Scheiter et al. 2008). Although the findings of our preliminary research did not point to significant differences in learning amongst students in different years of study, there was a trend toward improved learning amongst senior students, and this was more deeply explored in the present study.

An examination of the verbalizations of participants showed that students with a high level of prior knowledge (in their fourth year of study) made a greater number of explanatory statements in their verbal protocols, demonstrating depth of understanding in key areas such as protein conformation and molecular diffusion. Students with lower levels of prior knowledge focused predominately on narrative explanations of the event, rather than wondering which physical mechanisms might explain the phenomenon.

Prior knowledge did not guide students' understanding of the random nature of molecular events. Consistently, students described random motion and molecular crowding as though they were impediments to the ligand reaching its target protein. Students interpreted molecular movement as either "pushing" the ligand or "getting in the way", and described the ligand as though it had a mission or goal to fulfill.

An assumption of this study was that, in part, these misconceptions about molecular motion are due to the way in which these events are traditionally portrayed. Typically molecular events are depicted as schematized static illustrations, or as highly simplified animations that may be interpreted literally by students. However, even in the context of this study, these misconceptions proved to be robust and resistant to change. In part this may have to do with our basic propensity toward narrative structure. It is a trait that proves to be very useful in navigating our surroundings, and rationalizing our experiences (Scholl and Tremoulet 2000). However, this makes it very difficult to appreciate the undirected nature of emergent phenomena. This sentiment is echoed by Chi (2005), who, as noted previously, proposes that students seek causality according to shared perceptual properties among entities within a visual display. Chi's explanation of students' concepts of emergent processes helps to inform our understanding of how the perceptual features of a visual display can be manipulated (for better or for worse) to impact upon students' understanding.

The Role of Visual Perception

The design of stimuli used in this study involved creating representations that would focus viewers' attention on thematically relevant aspects of the animations by increasing their perceptual salience. We made the decision to use colour selectively and applied it to only the most thematically relevant AOI, namely the ligand and receptor. The remaining features in the display were shaded with tone. Selective use of colour proved successful as a means of helping the viewer focus on the main narrative. However, it may also have inadvertently contributed to students' classification of other molecules in the environment as "background" elements rather than considering them as part of a collective whole.

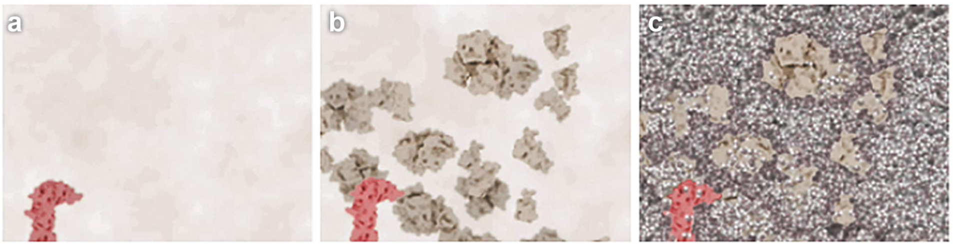

***Figure** 7. A comparison of contrast levels in the figure-ground relationship of KIT to the extracellular space. This is shown across three versions of the animation. Each represents a corresponding region outside the areas of interest. a) Versions 1 and 2; b) Version 3; and c) Version 4.*

In designing this study we expected that Version 4, given its high level of detail, would be the most distracting of the four treatments (containing the greatest number of fixations outside the AOI). However, this expectation was not borne out in the results. Rather, our findings revealed quite the opposite effect. The fewest number of fixations outside the AOI was recorded in Version 4, and the highest number of non-AOI fixations was recorded in Version 3, followed by Versions 1 and 2 respectively. A possible explanation that might account for this, involves viewers' preattentive processing of feature contrast in each of the representations. While Version 4 contains the greatest level of visual detail, the figure-ground contrast (the relationship of the figure, KIT, to its surrounding environment) is low when compared to the same elements in Version 3. Figure 7 illustrates the comparative figure ground relationships in each of the four animated treatments. The absence of molecular water in Version 3 serves to heighten the contrast between molecules in the extracellular space and the background of the animation, thus heightening the perceptual salience of the individual molecules. This finding is supported by Parkhurst and Niebur's (2003) study reporting higher levels of fixation upon areas with greater contrast. Another possible explanation for Version 4 containing the fewest fixations outside the AOI might have to do with the amount of effort required to view that animation. Version 4 would have demanded more effort on the part of the students in order to focus on the narrative. Perhaps the increased investment of mental effort helped to focus viewers' attention.

Motion was used in the design of the animated treatments primarily for the purpose of guiding the narrative. It also served the purpose of emphasizing the stochastic nature of molecular movements throughout the extracellular space. While it was not entirely successful in fostering students' understanding of randomness it was successful in conveying various aspects of the binding process. At one point during the animation the ligand makes contact with the receptor and then detaches before making contact for a second time and subsequently binding to the protein. This feature was incorporated into the animations to enforce two concepts: 1) that binding occurs quite randomly; and 2) that the protein receptor must be in the proper conformation in order to bind with the ligand. This proved to be a highly successful feature, as it elicited many statements from participants. Students first questioned the detachment of the ligand from the receptor and then attempted to rationalize this event. Perhaps the success of this feature owes more to the "surprise factor" of viewing the unexpected than it does to the perceptual salience of the motion cues. It may be that by incorporating these unexpected events into the narrative that we can encourage students to interrogate the narrative more thoughtfully.

Limitations

There are certain limitations to this research that need to be addressed in future studies. In designing this experiment, the focus of attention was solely on the impact of visual variables in supporting understanding. Given these parameters it was important not to introduce confounding factors such as narration in either audio or text format. While this was a necessary omission in the development of the animations, it detracted from participants' overall enjoyment and the educational benefit of the material.

A second potential limitation concerns the small sample size used in this study. While a sample of eight students limits the generalizability of our findings, it is worth noting that the goal of this study was to characterize the learning that may have taken place within a much larger sample of 131 students, drawn from the same population. The findings of the present study are supported by the results of our preliminary research.

Despite the limitations of the present study, it suggests some interesting implications for the use of animated visualizations in undergraduate molecular biology. The purpose of the study was to examine whether or not more complex representation would impact positively or negatively upon students' understanding of molecular environments. It would appear that with exposure to greater visual complexity, students were able to focus on the more thematically relevant aspects of the animation. Indeed, the more complex animations contributed the greatest level of insight into the events depicted. This contradicts what we have come to understand about cognitive load and its implications for instruction. Rather, these findings suggest that students are more capable of processing visual complexity than the literature on cognitive load would suggest. This raises questions about prevalent attitudes toward depicting complexity (that complex content must be simplified in order for students to understand it).

Conclusion

In summarizing the role of visual complexity in fostering understanding of animated visualizations, it is worth considering how preattentive cues might be manipulated to best serve the needs of viewers with different levels of prior knowledge. Our findings suggest that students benefit from visual complexity regardless of their level of prior knowledge. As well, these students benefit from the selective highlighting of preattentive features. This technique draws attention to thematically important features of the display (drawing them to the foreground) and suppresses remaining features of the display (in effect, sending them to the background). However, there is a point at which students cease to make necessary connections between foreground and background features, associating them by shared visual features rather than by shared behaviors. This is particularly problematic when learning about complex dynamic systems. One possible way to avoid the development of misconceptions might involve treating perceptual cueing as a form of visual scaffold that may be faded as the learner's understanding increases. In this way, students may be introduced to subject matter in a guided way; one that directs their focus first to specific details and ultimately to the whole of the display.

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