Computer Visualizations: Factors That Influence Spatial Anatomy Comprehension

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Computer visualizations are increasingly common in education across a range of subject disciplines, including anatomy. Despite optimism about their educational potential, students sometime have difficulty learning from these visualizations. The purpose of this study was to explore a range of factors that influence spatial anatomy comprehension before and after instruction with different computer visualizations. Three major factors were considered: (1) visualization ability (VZ) of learners, (2) dynamism of the visual display, and (3) interactivity of the system. Participants ($N = 60$) of differing VZs (high, low) studied a group of anatomical structures in one of three visual conditions (control, static, dynamic) and one of two interactive conditions (interactive, non-interactive). Before and after the study phase, participants' comprehension of spatial anatomical information was assessed using a multiple-choice spatial anatomy task (SAT) involving the mental rotation of the anatomical structures, identification of the structures in 2D cross-sections, and localization of planes corresponding to given cross-sections. Results indicate that VZ had a positive influence on SAT performance but instruction with different computer visualizations could modulate the effect of VZ on task performance. Anat Sci Educ 00: 000-000. © 2011 American Association of Anatomists.

Key words: spatial ability; gross anatomy education; computer-assisted learning; computer visualization; animation; dynamism; interactivity; learning; medical education

INTRODUCTION

The study of anatomical structure and function is a fundamental aspect of medical education, and cadaveric dissection has been the paradigm of anatomy instruction since the Renaissance (McLachlan and Patten, 2006). It is often perceived that the process of dissection provides unique views of human anatomy that facilitates mental construction and mapping of the body's visuospatial information (McLachlan et al., 2004).

Given sufficient time, adequate facilities, and an appropriate student-cadaver ratio, cadaveric dissection is regarded as an effective learning tool (Prentice et al., 1977). Unfortunately, however, many medical schools in the United States and Canada have experienced a decrease in curriculum hours compounded by a scarcity of donated bodies and reduced supply and demand of instructors who can teach gross cadaveric dissection (Collins et al., 1994; Cottam, 1999; Drake et al., 2009; Gregory et al., 2009). These conditions, in turn, have resulted in either an unacceptable student-cadaver ratio or the elimination of dissection altogether. In the former condition dissection becomes an inefficient learning tool, and in the latter situation the elimination of dissection precipitates total reliance on other forms of instruction in anatomy (Prentice et al., 1977; Rizzolo et al., 2006, 2010).

Technology-based instruction encompassing visually rich and often interactive computer visualizations is a growing trend in medical education. Compared to dissection, computer visualizations offer advantages in terms of accessibility,

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convenience, cost, safety, and versatility (Aziz et al., 2002; McLachlan et al., 2004; McLachlan and Patten, 2006). As a result, many medical schools have begun a dramatic shift toward introducing computer visualizations into its learning programs with the intention that these visualizations will enhance or amplify cognition (Keehner et al., 2008b). The explosion in the use of computer visualizations, however, is occurring well in advance of adequate research-based accounts of how learners cognitively process and learn from such instructional resources (Lowe, 2004). Accordingly, there is very little principled or empirically established guidance available as to what characteristics should be included in the visualization to maximize its educational effectiveness (Khalil et al., 2005). Although this is beginning to change as a result of recent empirical work in cognitive and educational psychology, a far greater understanding of the processes involved in learning from computer visualizations is needed as a foundation for principled design.

Zhang and Norman (1994) theory of distributed cognition provides a framework for understanding how external representations such as computer visualizations are related to internal representations such as propositions, schemas, or mental images. According to the theory, a wide variety of complex learning tasks require the processing of information distributed across the internal mind and the external object or artifact. Task performance involves a tradeoff between internal and external resources that are available to the learner. In any distributed task, external representations are not just peripheral aids to cognition; they are an obligatory component of the representational space and their inherent properties affect how people interact with them. They anchor and structure cognitive behavior within an "action space" that constrains the range of possible behaviors, and they can change the very nature of the task, as different external representations can mean that more or less of the task load is carried out internally.

In this study, we examined anatomy comprehension in the context of this distributed model. More specifically, we explored a range of internal and external factors that may influence anatomy comprehension. Three factors were considered: (1) visualization ability (VZ) of the learner, (2) dynamism of the visualization, and (3) interactivity of the visualization. Rather than assuming that there is a single type of computer visualization that is equally effective for all learners, we examined the premise that different learners will bring different abilities, skills, and knowledge to the comprehension process, so that different computer visualizations may be effective for different learners.

Characteristics of Computer Visualizations

Although not yet mainstream in medical education, many prototypes and first-generation computer visualizations are emerging in anatomy courses, with content directed at target audiences ranging from first-year medical students to residents in advanced training programs. Examples of these include the human head (Nguyen and Wilson, 2009), pelvis (Venuti et al., 2004; Sergovich et al., 2010), mediastinum (Conley et al., 1992), semicircular canal (Nicholson et al., 2006), vasculature (Petersson et al., 2009), and ankle (Sora et al., 2007). These visualizations are patient-specific; in that, they are rendered from human data including CT, MRI, and cryosections obtained from the Visible Human Project (Spitzer et al., 1996). As a result, they offer highly detailed views of the inner body that are not generic representations (McGhee, 2010; Tam, 2010).

With growth in computer technology, the ability to communicate anatomical information visually has extended from static (or nondynamic) representations to animated (or dynamic) visualizations, and more recently, to manipulated (or interactive) simulations (Khalil et al., 2005). These visualizations differ in how much information they represent about the human body, in how explicitly that information is represented, and in the type of mapping between the external representation and its referent (Hegarty and Kriz, 2008). For example, static representations can explicitly represent part(s) of the human body. These images are commonly used to show anatomical structures (e.g., muscles of the lower limb) in one of six canonical orientations, similar to the ones printed in anatomy textbooks and atlases. The image itself is isomorphic to its referent (i.e., the muscles), in the sense that the shapes of the objects represented in the image correspond to the shapes of the muscles, and the spatial relations between the objects correspond to spatial relations between the muscles. An animation or video, on the other hand, is the prototypical example of a dynamic visualization (Hegarty, 2004). A traditional animation consists of a sequence of frames that play at a constant rate; each frame image exists only transiently to be replaced by subsequent frames (Ainsworth and Van Labeke, 2004). In contrast to a static image, an animation can explicitly represent both the parts of the human body and how those parts change with respect to time (e.g., how muscles contract and relax). Hence, in an animation, the movements of objects are isomorphic to the movements of parts in the human body. In addition to portraying a visible sequence of events in real time, or proportional to real time, animations can also be used to increase depth information in the display (e.g., by having the muscles rotate in virtual space). The multiple views provided by rotating an object more accurately depicts the visuospatial properties of anatomical structures.

If the visualization does not allow any mode of interaction other than watching, then it is passive interaction. Many of the highly useful static and dynamic computer visualizations used in anatomy courses support passive interaction only. If the visualization allows viewer control over the presentation of information, then it is active interaction. Betrancourt (2005) distinguished broadly between two categories of active interaction: control and interactivity. "Control" refers to the capability of the viewer to act on the pace and direction of the presentation sequence (e.g., play, pause, rewind, etc.). "Interactivity" refers to the capability of the viewer to alter parameters (e.g., viewpoints) of the object in the visualization, allowing for exploration from different perspectives.

Effects of Visualization Ability (VZ)

In the context of anatomy education, a distinction must be made between two types of knowledge structures. The first, called nonspatial anatomical knowledge, refers to knowledge of terminology such as the names and functions of anatomical structures. The second, called spatial anatomical knowledge, refers to knowledge of visuospatial information, such as the size, 3D shape, orientation, and spatial location of structures in the body. A thorough understanding of anatomy requires knowledge of not only the names and functions of anatomical structures but also their visuospatial properties.

Generally, learning visuospatial information is considered a visual process, involving visuospatial working memory (VSWM) (Miyake et al., 2001). Processing information in VSWM is strongly influenced by spatial ability, which Carroll (1993) defines as individuals' abilities in searching the visual field, apprehending the forms, shapes, and positions of objects as visually perceived, forming mental representations of those forms, shapes, and positions, and manipulating such representations "mentally." Although there are several subcomponents of spatial ability, the one that has been of special interest to medical educators is VZ—the ability to apprehend, encode, and mentally manipulate spatial forms in two- and three-dimensions (Carroll, 1993).

Given the importance of visuospatial information in medicine, questions arise about the role of VZ in learning spatial anatomical information. Several studies have found VZ to be highly correlated with performance on spatial anatomy tasks as well as success in anatomically demanding fields such as surgery and radiology. In fact, early evidence provided by Rochford (1985) found a significant correlation between visualization disabilities and underachievement among university anatomy students. Students with low VZ achieved consistently lower marks than their high VZ counterparts on both practical anatomy examinations and multiple-choice anatomy questions classified as being spatially three-dimensional. More recently, similar relationships were demonstrated between VZ and functional anatomy task performance (Guillot et al., 2007), cross-sectional anatomy task performance (Cohen and Hegarty, 2007; Hegarty et al., 2009), and surgical performance (Anastakis et al., 2000; Wanzel et al., 2002). Findings such as these suggest that there is a strong spatial component in the way anatomical knowledge is mentally represented. It also implies that individuals with lower VZ will have a harder time acquiring, representing, and manipulating spatial mental representations of anatomy.

In many of these studies, however, performance on the anatomy tasks may reflect other abilities or competencies other than VZ. For example, in Cohen and Hegarty's (2007) cross-sectional study, participants were given an egg-shaped object with a transparent exterior that revealed an internal network of duct-like structures. In the experimental trials, a superimposed vertical or horizontal line on the printed images indicated where participants should imagine the object had been sliced. An arrow indicated the orientation from which the participants were to imagine the cross-section. Participants were asked to draw the cross-section that would result if the object were sliced at the line and viewed from the perspective of the arrow. In this study, performance on the task might reflect drawing ability rather than VZ. Similarly, in Guillot et al. (2007) study, participants were asked to relate written anatomical questions to visual images, and performance on the task might reflect verbal comprehension rather than spatial anatomy comprehension. Based on these findings, we suggest that more research is needed to determine the true role of VZ in learning spatial anatomical information.

Effects of Dynamism and Interactivity

With increased computer visualizations, a more important concern for educators is whether the effects of VZ on spatial anatomy comprehension could be modulated by instruction with computer visualizations. Although computer visualizations are often seen as having the potential to augment cognition, it is not known whether these hypothesized benefits are equal for all learners, or whether they differ for individuals with varying levels of VZ. Hegarty and Kriz (2008) proposed that there are at least four possible ways in which computer visualizations such as animations may influence individuals of different VZs. One possibility is that some minimal level of VZ is a necessary prerequisite for learning from animations. In which case, animations will have a greater facilitating effect on the performance of high VZ learners than low VZ learners, magnifying performance difference between them (ability-as-enhancer hypothesis). A second possibility is that animations compensate for lack of VZ, so that animations act as a cognitive prosthetic for those with low VZ. In this case, animations will have a greater facilitating effect on the performance of low VZ learners than high VZ learners, attenuating performance differences between them (ability-as-compensator hypothesis). A third possibility is that animations augment performance equally for both high and low VZ individuals, so that individuals of all VZs are helped equally. Finally, it is possible that animations impede learning equally for both high and low VZ individuals.

Previous research on the role of animations does not uniformly support any one of these possibilities. In a study where multiple views of wrist bone anatomy were presented to medical students via an automatically rotating animation, a subsequent test of spatial anatomical knowledge showed a significant disadvantage to students with low spatial ability (Garg et al., 1999). For these students, learning was effective only if the visualization was restricted to simple depictions entailing just two cardinal views. A similar interaction effect between spatial ability and dynamism of the display (i.e., static vs. dynamic anatomical model) has been shown in the domain of cell biology (Huk, 2006) and respiratory anatomy (Mayer and Sims, 1994). In both cases, only students with high spatial ability benefited from the presence of the dynamic display, while low spatial ability students were disadvantaged. By contrast, other studies found animations to compensate for low spatial ability. In two experiments, Hoffler and Leutner (2011) compared animation with a series of static representations for learning the role of surfactants during the washing process. In both experiments, students with low spatial ability showed poor learning outcome when learning from static representations, while those with high spatial ability did not. When learning from animations, however, learning outcome was independent of spatial ability, suggesting that individuals of high and low spatial ability benefited equally from the animation. Finally, some studies found no interaction between spatial ability and dynamism of the display. In an experiment comparing interactive animations with still images for learning hepatobiliary anatomy, Keedy et al. (2011) showed higher satisfaction ratings for the animation; however, the animation neither enhanced nor inhibited learning compared to static images, and spatial ability was not associated with test performance.

Taken together, the role of spatial ability (particularly VZ) on learning with computer visualizations is still unclear. Many questions concerning the moderating effects of VZ and format of instruction are still open: What role does VZ play in spatial anatomy comprehension? If learner's VZ is low, how should the format of instruction be designed to support the learning process? This study had two aims. The first was to determine the specific role of VZ on spatial anatomy comprehension. The second was to determine whether the effects of VZ could be modulated by instruction with different computer visualizations. Spatial anatomy comprehension was assessed with a multiple-choice task involving the mental rotation of anatomical structures, identification of these structures in 2D cross-sections, and localization of planes corresponding to given cross-sections. We hypothesized that VZ will positively influence spatial anatomy comprehension—individuals with high VZ should perform better on the anatomy task than those with low VZ. Next, we hypothesized that there will be an interaction between VZ and dynamism of the computer visualization—individuals with high VZ should benefit more from dynamic visualizations, while individuals with low VZ should benefit more from static representations. Finally, we hypothesized that there will be an interaction between VZ and interactivity of the visualizations—individuals with high VZ should benefit more from non-interactive visualizations, while individuals with low VZ should benefit more from interactive visualizations.

MATERIALS AND METHODS

Participants

Sixty students, staff, and faculty (31 females; mean age = 25.6 years) from The University of Western Ontario participated in the study. The study was approved by the Ethics Review Board at The University of Western Ontario. Informed consent was obtained from all participants.

Instructional Materials

A computer-generated visual representation of a group of anatomical structures (i.e., the aorta, trachea, and esophagus) was developed for the study (Fig. 1, left side). The anatomical model was developed using cross-sectional images of a human male subject from the Visible Human Project (Spitzer et al., 1996), and segmentation procedures reported previously (Nguyen and Wilson, 2009). In addition to the anatomical model, a geometrical cube model was also developed and would later serve as the control condition in the study phase of the experiment (Fig. 1, right side). For ease of distribution and display, both the anatomical and geometrical models were exported onto Unity (Unity Technologies, San Francisco, CA), an integrated game development tool for creating and viewing interactive contents and real-time 3D animations. Within Unity, three separate files were created to display the visual contents. The first was a dynamic video (animation) depicting multiple views of the anatomical model rotating continuously in the *x*-, *y*-, and *z*-axes. The second depicted static representations of the anatomical model in the six canonical orientations, similar to the ones printed in anatomy textbooks and atlases. The third depicted static representations of the geometrical model in the six canonical orientations.

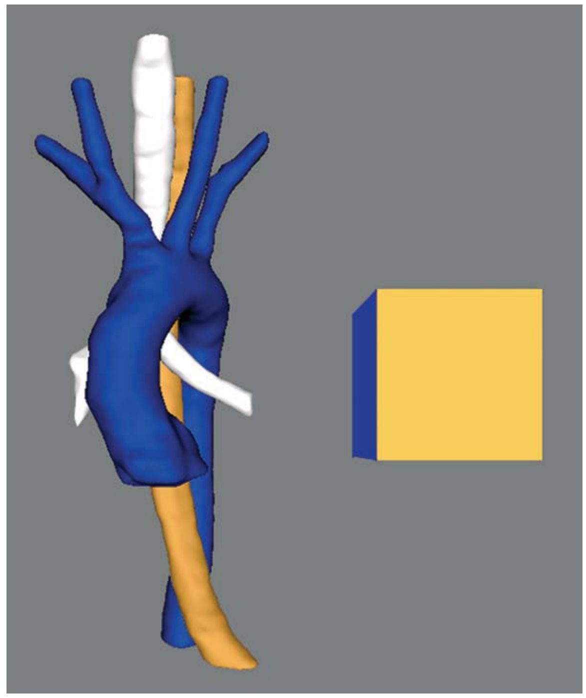

Figure 1.

Screenshot of the anatomical and geometrical models. The anatomical model was reconstructed from cross-sectional images of a human male from the National Library of Medicine Visible Human Project (Spitzer et al., 1996).

Performance Measures

Mental rotations task (MRT). An electronic version of the MRT (Vandenberg and Kuse, 1978; Peters et al., 1995) was used to assess participants' VZ. The task consists of 24 items. Each item is made up of one target figure, two correct alternatives (i.e., rotated images of the criterion figure), and two distractors (i.e., rotated mirror images of the criterion or of one or two of the other criteria). Participants had to determine as quickly and accurately as possible which two of the four test figures are rotations of the target figure. Participants were given 360 secconds to complete as many questions and possible. A single credit was given if both correct stimuli were identified; zero credits otherwise. The maximum score was 24.

Spatial anatomy task (SAT). An electronic version of a novel task pertaining to the spatial properties of the anatomical model was developed to assess spatial anatomical knowledge. The task consists of 30 multiple-choice questions—10 involving the mental rotations of the anatomical model (Fig. 2a), 10 involving the identification of the model in 2D cross-sections (Fig. 2b), and 10 involving the localization of planes or levels corresponding to selected cross-sections (Fig. 2c). Participants were given 180 secconds to complete each part of the SAT. A countdown timer appearing on the top right-hand corner of the computer screen was used to record the amount of time participants spent on each part of the task. Hence, the maximum time a participant can spend on the SAT was 540 seconds and the maximum score was 30.

Study design. The research design is illustrated in Figure 3 and described below. The entire study took ~45 min to complete. Participants were tested individually. All participants completed two pretasks, a study phase, and a post-task.

Pretasks. At the start of the study, all participants completed the MRT and SAT. Based on the scores obtained in the MRT, participants were allocated to one of two visualization groups—low VZ (N = 30, lower median group) or high VZ (N = 30, higher median group).

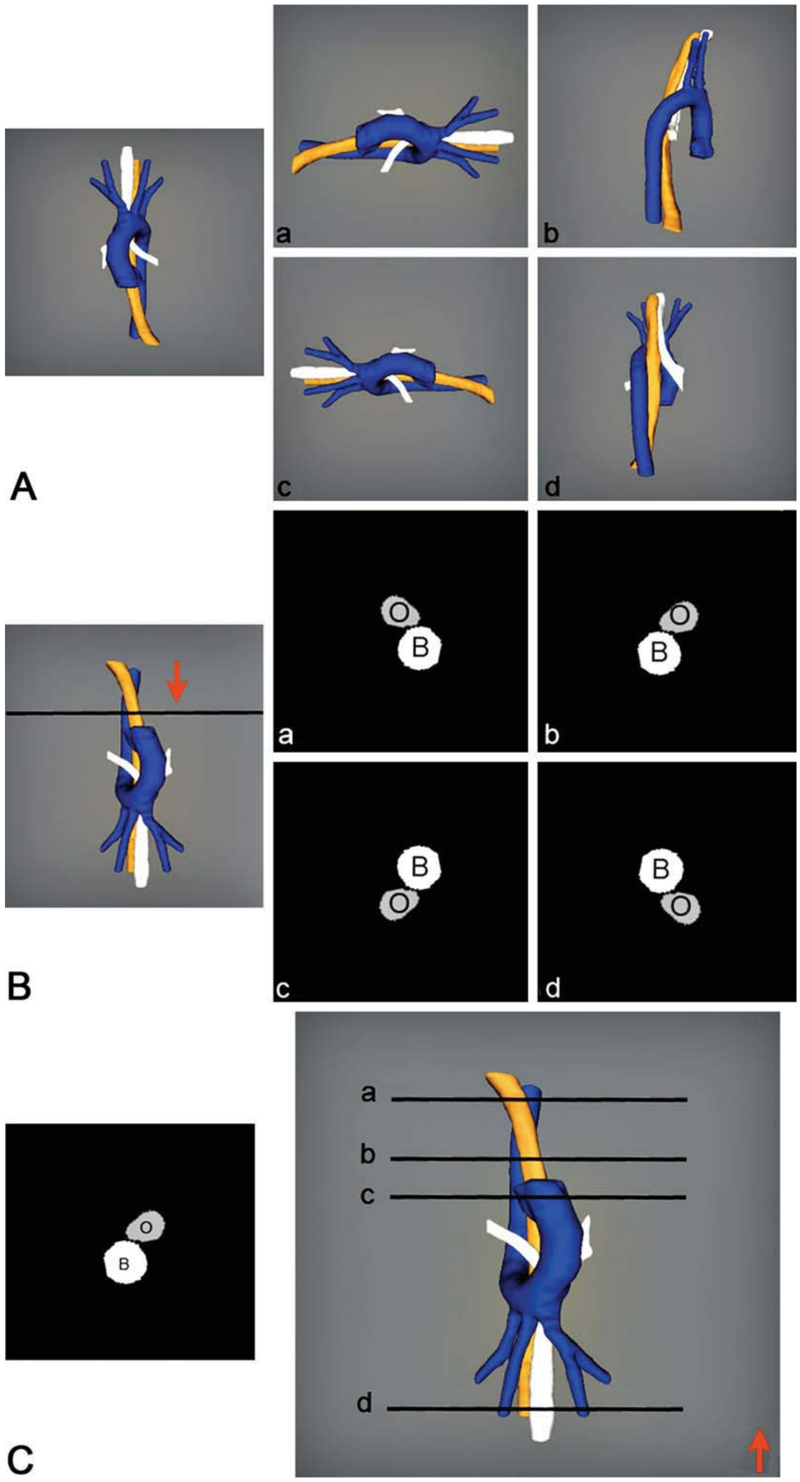

Figure 2.

Screenshots of three different question types developed for the spatial anatomy task (SAT) questionnaire. Participants had 180 seconds to complete as many questions as possible. A, Mental rotations task question. Each question consists of five figures—a target (the left-most image), two correct alternatives (i.e., rotated images of the target), and two distractors (i.e., rotated mirror images of the target or of one or two of the other targets). Participants had to determine as quickly and accurately as possible which two of the four test figures are rotations of the target figure. A single credit was given if both correct alternatives were identified; zero credits otherwise; B, Identification task question. Participants were given an image of the anatomical structures with a superimposed horizontal or vertical line and an arrow pointing towards the line. Participants had to determine as quickly and accurately as possible the correct cross-section that would result if the anatomical structures were cut at the line and they were looking at the resulting structures from the direction of the arrow. A single credit was given for each correct answer; C, Localization task question. Participants were given a selected cross-section of the anatomical structures. Participants had to decide which superimposed horizontal or vertical line represents the level at which the cross-section was taken. A single credit was given for each correct answer.

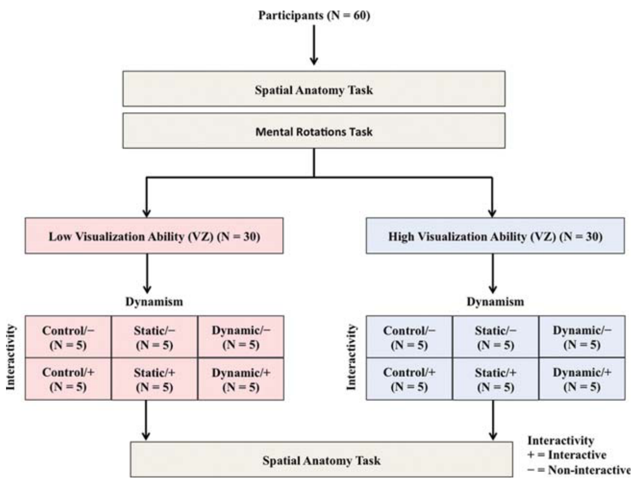

Figure 3.

Flowchart illustrating the procedure for the study. All participants had to complete two pretasks (i.e., the mental rotations task and spatial anatomy task), a study phase, and a post-task (i.e., the spatial anatomy task).

Study phase. Participants in each visualization group were randomly assigned to one of three dynamic visual groups—dynamic, static, or control, and then to one of two interactive groups—interactive (+) or non-interactive (–). Participants in the dynamic group watched a video of the anatomical model continuously rotating around the x-, y-, and z-axes, while those in the static group viewed static representations of the anatomical model switching between the six canonical views. Participants in the control group were not exposed to the anatomical model. Instead, they viewed static images of the geometric model switching between the six canonical views. Within each visual group, non-interactive (–) participants either viewed a video of anatomical model self-rotating in the x-, y-, and z-axes or static images of the anatomical or geometric model switching between the six canonical views. Interactive participants, on the other hand, had active control over the rotation or viewpoints of the visualization using the four arrow keys on the keyboard. The duration of exposure to the anatomical and geometric models was the same for all participants (150 seconds).

Post-task. Subsequently, the same SAT administered to participants before the study phase was used again to assess spatial anatomical knowledge. However, the order of the questions was changed to prevent memorization of answers.

DATA ANALYSES

Descriptive statistics of overall range, mean, and standard deviation for the MRT and SAT were computed. Separate paired t-tests were used to determine whether the score and time spent on the SAT (in seconds) before instruction with the computer visualizations (i.e., pre-SAT scores) were significantly different than those after instruction (i.e., post-SAT scores).

To address the first aim of the study, separate Pearson's (r) correlations were used to examine the relationship between MRT scores and pre-SAT scores, and between MRT scores and amount of time spent on the pre-SAT (seconds). Subsequently, separate t-tests were used to determine whether pre-SAT scores and amount of time spent on the pre-SAT were significantly different for participants of high and low VZ. To address the second aim of the study, separate $2 \times 3 \times 2$ completely randomized factorial (CRF) analyses were used to determine whether there were any significant interactions between VZ (high, low), dynamism (control, static, animated), and interactivity (interactive, non-interactive) on post-SAT scores and total time spent on the post-SAT. Covariates appearing in the CRF analyses were scores and amount of time spent on the pre-SAT, respectively.

RESULTS

Descriptive Statistics

Table 1 lists the overall range, mean, and standard deviation for the MRT and SAT before and after instruction with the computer visualizations. Mean score on the post-SAT was significantly higher than pre-SAT, $t\ (59) = -6.73$, $P < 0.05$. Amount of time spent on the post-SAT was significantly lower

Table 1.

The Range, Mean, and Standard Deviation for the Mental Rotations Task and Spatial Anatomy Task Before and After Instruction with Computer Visualizations (N = 60)

	Range	Mean	Standard deviation
Before instruction			
MRT scores (maximum possible score = 24)	2–24	10.27	4.80
Pre-SAT scores (maximum possible score = 30)	2–27	15.22	5.55
Time spent on the pre-SAT (maximum possible time = 540 sec)	330–540	494.52	53.90
After instruction			
Post-SAT scores (maximum possible score = 30)	9–30	18.47	5.02
Time spent on the post-SAT (maximum possible time = 540 sec)	256–540	451.50	67.72

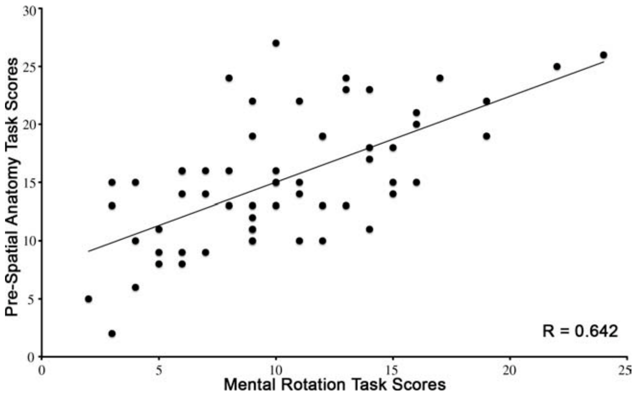

Figure 4.

Scatter plot representing the relationship between prespatial anatomy task scores and mental rotations task scores. The correlation is positive ($r = 0.64$) and significant ($r^2 = 0.41$, $P < 0.05$).

than pre-SAT, t (59) = 6.48, $P < 0.05$. Mean MRT scores for participants with high VZ ($N = 30$) and low VZ ($N = 30$) were 14.03 ± 3.51 and 6.50 ± 2.30, respectively.

Figure 4 shows a scatter plot of pre-SAT scores as a function of MRT scores. The correlation between the two variables was positive ($r = 0.64$) and significant, $r^2 = 0.41$, $P < 0.05$. Figure 5 shows a scatter plot of time spent on the pre-SAT as a function of MRT scores. The correlation between the two variables was negative ($r = -0.67$) and significant, $r^2 = 0.45$, $P < 0.05$. T-test analyses revealed significant differences on both pre-SAT scores, t (58) = 4.54, $P < 0.05$, and amount of time spent on the pre-SAT, t (58) = −4.50, $P < 0.05$, for participants of high and low VZs. Those with high VZ scored higher on the pre-SAT ($M = 18.03 \pm 4.87$) than those with low VZ ($M = 12.04 \pm 4.73$). Those with high VZ also spent less time on the pre-SAT ($M = 467 \pm 60.70$ sec) than those with low VZ ($M = 521 \pm 26.42$ sec).

The CRF analysis of post-SAT scores (with pre-SAT scores as a covariate) revealed no main effects of VZ, F (1, 48) = 0.273, $P > 0.05$, dynamism, F (2, 48) = 0.279, $P > 0.05$, or interactivity, F (1, 48) =1.01, $P > 0.05$, and no interaction effects between VZ × interactivity, F (1, 48) = 0.905, $P > 0.05$, dynamism × interactivity, F (2, 48) = 0.217, $P > 0.05$, or VZ × dynamism × interactivity, F (2, 48) = 0.06, $P > 0.05$. However, a significant interaction effect between VZ and dynamism of the display was found, F (2, 48) = 3.38, $P < 0.05$. Table 2 and Figure 6 show the mean post-SAT scores for all dynamism by VZ level combination. Fol-

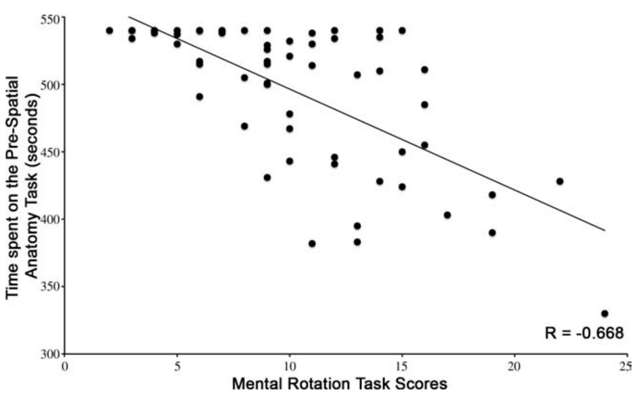

Figure 5.

Scatter plot representing the relationship between time spent on the prespatial anatomy task (in seconds) and mental rotations task scores. The correlation is negative ($r = -0.67$) and significant ($r^2 = 0.45$, $P < 0.05$).

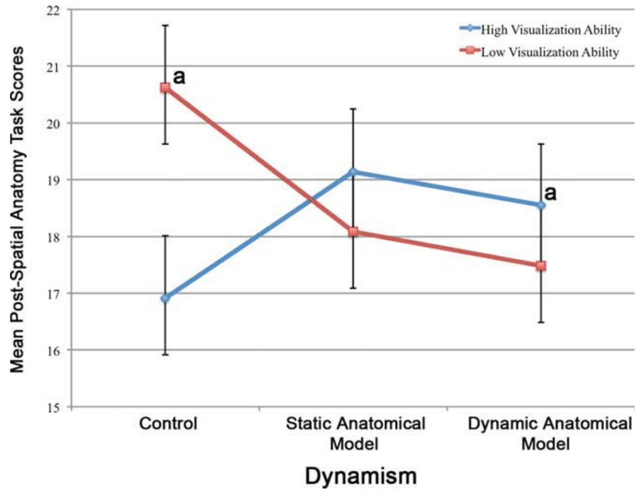

Figure 6.

Profile plot of mean post-spatial anatomy task scores as a function of dynamism of the visual display. The plot shows an interaction between visualization ability and dynamism of the visual display. The two lines represent the high and low visualization ability groups. The crossing of the lines indicates an interaction effect; [a] $P < 0.05$.

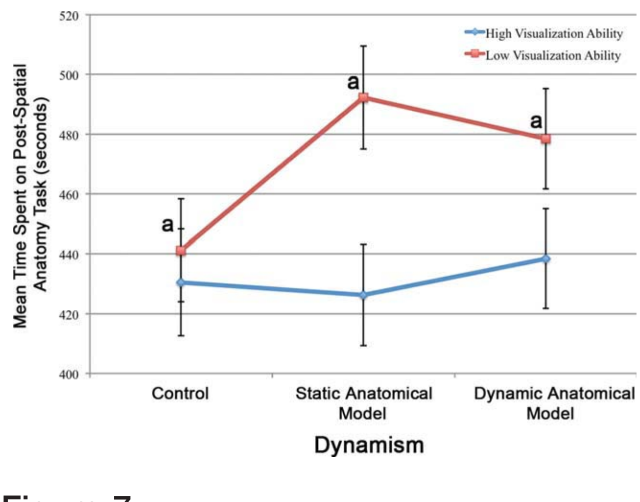

Figure 7.

Profile plot of mean time spent on the post-spatial anatomy task as a function of dynamism of the visual display. The plot shows a main effect of visualization ability on the amount of time spent on the postspatial anatomy task. The two lines depict the high and low visualization ability groups. The parallel lines indicate no interaction effect. Participants with high visualization ability spent less time on the spatial anatomy task than those with low visualization ability. [a] $P < 0.05$.

Table 2.

Mean Post-spatial Anatomy Task Scores for All Dynamism by Visualization Ability (VZ) Level Combination

Visualization ability (VZ)	Dynamism	Mean score	Standard error
High VZ	Control	16.91[a]	1.10
	Static anatomical model	19.14[a]	1.10
	Dynamic anatomical model	18.55[a]	1.08
Low VZ	Control	20.63[a]	1.09
	Static anatomical model	18.09[a]	1.09
	Dynamic anatomical model	17.48[a]	1.10

[a]Covariates appearing in the model are evaluated at a mean pre-SAT score of 15.22.

lowing the significant interaction, simple effect tests revealed significant differences in post-SAT scores for high and low VZ participants viewing the static geometric model ($P < 0.05$) and the dynamic anatomical model ($P < 0.05$), but not for those viewing the static anatomical model ($P > 0.05$). For the static geometric model, those with low VZ scored significantly higher on the post-SAT ($M = 20.63$, SE = 1.09) than those with high VZ ($M = 16.91$, SE = 1.10). For the dynamic anatomical model, those with high VZ scored significantly higher on the post-SAT ($M = 18.55$, SE = 1.08) than those with low VZ ($M = 17.48$, SE = 1.10). For the static anatomical model, post-SAT scores were not significantly different for high VZ ($M = 19.14$, SE = 1.10) and low VZ ($M = 18.09$, SE = 1.09) individuals.

The CRF analysis of time spent on the post-SAT (with time spent on the pre-SAT as a covariate) revealed a significant main effect of VZ, $F\ (1, 48) = 6.59$, $P < 0.05$, no main effects of dynamism, $F\ (2, 48) = 1.15$, $P > 0.05$, or interactivity, $F\ (1, 48) = 2.66$, $P > 0.05$, and no interaction effects between VZ × dynamism, $F\ (2, 48) = 1.26$, $P > 0.05$, VZ × interactivity, $F\ (1, 48) = 1.78$, $P > 0.05$, dynamism × interactivity, $F\ (2, 48) = 0.78$, $P > 0.05$, or VZ × dynamism × interactivity, $F\ (2, 48) = 1.23$, $P > 0.05$. Table 3 and Figure 7 show the mean times spent on the post-SAT (seconds) as a function of dynamism of visual display. Across all levels of dynamism, individuals with high VZ spent less time on the post-SAT than those with low VZ.

DISCUSSION

Recall, the first aim of this study was to determine the specific role of VZ on spatial anatomy comprehension and the second aim was to determine whether the effects of VZ could be modulated by instruction with different computer visualizations.

Effects of Visualization Ability (VZ)

Since a thorough knowledge of human anatomy must include visuospatial information, and learning visuospatial information is influenced by one's VZ, we predicted that VZ would have positive effects on spatial anatomy comprehension. The results of this study supported this hypothesis by indicating a positive correlation between VZ and SAT score and a negative correlation between VZ and amount of time spent on the task. Furthermore, significant differences were observed for both score and time spent on the task for individuals of high and low VZ. Even without instruction, participants with high VZ scored higher and spent less time on the anatomy task than those with low VZ.

Effects of Dynamism

Since learners bring different abilities, skills, and knowledge to the learning process, we predicted that different types of computer visualizations might be effective for different learners. The results of this study supported this hypothesis by indicating an interaction effect between VZ and dynamism of the visual display. Static anatomical representations augmented learning equally for individuals of high and low VZ. By contrast, the dynamic anatomical visualization particularly benefited individuals with high VZ, as their mean score on the performance task was significantly higher than those with low VZ. This finding is consistent with the ability-as-enhancer hypothesis, which advocates that some minimal level of VZ is required for accurate perception and comprehension from dynamic visualizations such as animations (Mayer and Sims, 1994; Hegarty and Kriz, 2008; Hoffler and Leutner, 2011).

Table 3.

Mean Time Spent on the Post-spatial Anatomy Task for All Dynamism by Visualization Ability (VZ) Level Combination

Visualization ability (VZ)	Dynamism	Mean time (sec)	Standard error
High VZ	Control	430.49[a]	17.86
	Static anatomical model	426.24[a]	16.99
	Dynamic anatomical model	438.36[a]	16.66
Low VZ	Control	430.49[a]	17.86
	Static anatomical model	426.24[a]	16.99
	Dynamic anatomical model	438.36[a]	16.66

[a]Covariates appearing in the model are evaluated at a mean pre-SAT time of 494.52 seconds.

When viewing the anatomical structures self-rotating in virtual space, participants observed a single frame at a time, and once the sequence advanced to the next frame, it was no longer available for viewing. Since VZ is related to speed of processing spatial information (Salthouse, 1996), this might have affected speed of encoding information in the display, such that only participants with high VZ were able to keep up with the pace of the animation. Since VZ is related to greater working memory capacity (Just and Carpenter, 1985; Shah and Miyake, 1996; Miyake et al., 2001), perhaps only participants with high VZ had the cognitive resources to store and process the transient information in working memory. Thus, due to the transient nature of the spatial information presented in the animation, on the one hand, and the limited capacity and duration of working memory, on the other, only those with high VZ benefited from the dynamic anatomical visualization.

Although the dynamic anatomical visualization had a greater facilitating effect on the performance of high VZ individuals, the static geometric visualization had a greater facilitating effect on the performance of low VZ learners. This finding is in line with the ability-as-compensator hypothesis, which advocates that instruction with computer visualizations acts as a cognitive prosthetic for individuals with low VZ, thus improving the performance of low VZ individuals more than their high VZ counterparts. This result was not expected, as the geometric model was irrelevant and unrelated to the items on the SAT (which were based on the anatomical model), and therefore should not have affected task performance. One possible explanation for this result is that perhaps the canonical views of the geometric model compensated for inefficient mental rotation. Since individuals with low VZ are likely to be less efficient and less accurate in mental animation, the canonical views of the geometric model might have acted as cognitive reference orientations that were later used to guide the mental rotation of the anatomical structures (presented in the performance task) in a more direct and more efficient manner. Hence, those with low VZ benefited more from the cognitive reference orientations than those with high VZ, who presumably do not need the reference orientations because they can manipulate mental objects with ease. This assumption is in line with results from a previous study comparing the learning of bone (vertebra) anatomy with and without orientation references (Stull et al., 2009). Stull et al. found that orientation references (in the form of visible lines overlapping the vertebra's major axes) not only helped learners manipulate computer representations of the vertebra during the learning process but also helped learners develop mental representations of the bone. Furthermore, the orientation references elevated learning by low spatial ability individuals to a level near that of high spatial ability individuals. Thus, spatial orientation references acted as a cognitive prosthetic for those with low spatial ability and assisted them with manual and mental manipulations of the vertebra.

Effects of Interactivity

In addition to predicting an interaction effect between VZ and dynamism of the visual display, we hypothesized to find an interaction between VZ and interactivity of the visualization, such that interactive visualizations will compensate for low VZ. The results of this study showed no significant advantage of interactivity on SAT performance. There are several potential reasons for why we found no advantage of interactivity. One possible factor is the nature of the user control interface. The key-press control system used to manipulate the visualization was not intuitive, and as such it is possible that merely operating it produced additional cognitive demands on interactive participants, counteracting any potential benefits from active control. Keehner et al. (2008b) suggest that a more naturalistic control interface that allows the manipulations made by the users to be exactly mirrored in the movements of the visualization should be especially beneficial in helping learners create an integrated spatial mental representation of any object they are viewing. Hutchins et al. (1985) used the term direct manipulation to refer to this type of natural interface. The term directness refers to the feeling that results from interacting with an interface and it can be broken down into two distinct features: distance and engagement. Distance involves the notion that there is a gulf between the learner's goal (i.e., the task the learner has in mind) and the way the task can be accomplished with the interface. A short distance means that the translation is simple and straightforward; in that, the learner's thoughts and goals are readily translated into physical actions by the system, and that the system's output matches the thoughts and goals of the learner. Engagement, on the other hand, involves a feeling of "first-personness," of direct engagement with the object of interest (Qvarfordt and Santamarta, 2000). Hutchins et al. (1985) suggest that an interface introduces a gulf between the learner's goals and the system's output, and cognitive resource is needed to deal with this gulf. Direct manipulation interface can bridge this gulf by providing immediate feedback and control, as well as a sense of direct engagement with the object. As a result, when the learner performs operations on the object, the impact of those operations on the object is immediately visible. Another possible factor is how participants interact with the visualization. Some authors suggest that spatial anatomical information is not remembered in 3D, but rather in specific 2D cardinal views, and that unfamiliar orientations are recognized by mental rotation of these 2D views (Garg et al., 1999, 2001, 2002). Therefore, the quality of the information that learners acquire from computer visualizations depends not just on whether learners are allowed active control over the visualization but also on how they interact with the visualization and whether the manipulated views are in line with how spatial information is stored in working memory (Keehner et al., 2008a). Thus, we suggest that future research in this field move beyond simply comparing interactive with non-interactive visualizations to examining how learners interact with visualizations and what factors affect the usefulness of these visualizations.

Limitations

The authors recognize that this study has some limitations. Most notably, the geometric control model had an effect on spatial anatomy comprehension. This result was not expected, as the geometrical model was unrelated to the SAT. Further experiments assessing the educational value of static and dynamic visualizations should adopt a control model that is not just unrelated to items on the performance task but also rely on separate cognitive mechanisms for processing the information in working memory. For example, verbal reading tasks and arithmetic problem-solving tasks are unrelated to the SAT and require a separate verbal channel for processing the linguistic and numerical information. We predict that these tasks can be used as the control models to keep participants occupied during the same time frame in which the static and dynamic anatomical models are being examined, while eliminating any possible interaction with the visual information presented. A second limitation is that the key-press control interface used to manipulate the visualization was not intuitive; in that, the actions produced by pressing the four arrow keys did not mirror the movements of the anatomical and geometric models. Further experiments assessing the educational value of interactive visualizations should adopt a more naturalistic user control interface such as motion trackers or data gloves that allow for translation along three perpendicular axes (forward/backward, left/right, up/down) as well as rotation along these axes (pitch, yaw, roll). These six degrees of freedom input devices have the power to accommodate for more interaction techniques and has the potential to shorten the cognitive distance between the user's action and the system's feedback. Finally, further experiments are also warranted to increase the number of participants. For this the study 60 participants were assigned to 12 groups, resulting in only five participants in each experimental group. Such an increase in sample size would enhance our ability to generalize our results.

Educational Implications

In the past, instructors have frequently made the mistake of allowing new technology to generate the learning experience rather than using our growing knowledge of the cognitive processes involved in learning to guide us in how best to design and use technology for instructional purposes. It is clear from our own research and others that the processes involved in learning spatial anatomical information occur both internally in the mind of the learner and externally in the world, and that there is neither a simple advantage of dynamic over static visualizations, nor interactive over non-interactive visualizations. Yet, most educators and researchers in this field continue to believe that interactive and dynamic visualizations are always superior to static representations. We need to be critical of this assumption and focus our attention to understanding what conditions must be in place for these visualizations to be effective. In the present study, we showed that dynamic visualizations particularly benefited individuals with high VZ. For low VZ individuals, learning was effective only if the visualization was restricted to simple depictions in the cardinal views. However, because of the small number of participants in our study, more research is warranted to validate our findings.

CONCLUSION

In conclusion, we showed that, even without instruction, VZ is a strong predictor of success in spatial anatomy comprehension. Furthermore, we showed that the effect of VZ on spatial anatomy comprehension could be modulated through instruction with different computer visualizations. As we continue to design and use computer visualizations in anatomical education, it is important to recognize that individual differences among learners affect both the use of computer visualizations and what is learned from these external visual resources. Hence, further research on the educational efficacy of computer visualizations should involve the analysis of factors inherent to both the "machine" and the "human" in order to establish instructional visualizations that are most likely to benefit individual learners.

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