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Anatomy: The Relationship Between Internal and External Visualizations

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ANATOMY: THE RELATIONSHIP BETWEEN INTERNAL AND EXTERNAL VISUALIZATIONS

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Anatomy: The Relationship Between Internal and External Visualizations

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Abstract

This dissertation explored the relationship between internal and external visualizations and the implications of this relationship for comprehending visuospatial anatomical information. External visualizations comprised different computer representations of anatomical structures, including: static, animated, non-interactive, interactive, non-stereoscopic, and stereoscopic visualizations. Internal visualizations involved examining participants' ability to apprehend, encode, and manipulate mental representations (i.e., spatial visualization ability or Vz). Comprehension was measured with a novel spatial anatomy task that involved mental manipulation of anatomical structures in three-dimensions and two-dimensional cross-sections. It was hypothesized that performance on the spatial anatomy task would involve a trade-off between internal and external visualizations available to the learner.

Results from experiments 1, 2, and 3 demonstrated that in the absence of computer visualizations, spatial visualization ability (Vz) was the main contributor to variation in spatial anatomy task performance. Subjects with high Vz scored higher, spent less time, and were more accurate than those with low Vz. In the presence of external computer visualizations, variation in task performance was attributed to both Vz and visuospatial characteristics of the computer visualization. While static representations improved performance of high- and low-Vz subjects equally, animations particularly benefited high Vz subjects, as their mean score on the SAT was significantly higher than the mean score of low Vz subjects. The addition of interactivity and stereopsis to the displays offered no additional advantages over non-interactive and non-stereoscopic visualizations. Interactive, non-interactive, stereoscopic and non-stereoscopic visualizations improved the performance of high- and low-Vz subjects equally.

It was concluded that comprehension of visuospatial anatomical information involved a trade-off between the perception of external visualizations and the ability to maintain and manipulate internal visualizations. There is an inherent belief that increasing the educational effectiveness of computer visualizations is a mere question of making them dynamic, interactive, and/or realistic. However, experiments 1, 2, and 3 clearly demonstrate that this is not the case, and that the benefits of computer visualizations vary according to learner characteristics, particularly spatial visualization ability.

Keywords

Internal visualizations, external visualizations, computer visualizations, spatial visualization ability, visuospatial anatomy comprehension, education, static images, animation, interactivity, stereopsis

Co-Authorship Statement

The written material in this thesis is the original work of the author. Ngan Nguyen participated in all aspects of the work contained herein: conception of the hypotheses, conduct of the experiments, and authorship of the manuscripts. The roles of the co-authors are detailed below by chapter.

Chapter 2: Experiment 1

The manuscript is published in the journal *Anatomical Sciences Education* (5:2, 98-108, 2012). All authors on the manuscript shared in the conception of this research study. The instructional materials and Spatial Anatomy Task was developed by N.Nguyen. The data for this study was collected, analyzed and interpreted by N. Nguyen. N.Nguyen carried out the composition of the manuscript with inputs from Drs. Wilson and Nelson.

Chapter 3: Experiment 2

Conception of this research study was shared by N.Nguyen, T. Wilson, and A. Nelson. The design of the Matlab testing interface was carried out by N.Nguyen and A.Mulla. The data for this study was collected, analyzed and interpreted by N.Nguyen. Preparation of the manuscript was carried out by N.Nguyen with inputs from Drs. Wilson and Nelson. The manuscript will be submitted to the journal Anatomical Sciences Education.

Chapter 4: Experiment 3

Conception of this research study was shared by N.Nguyen, T. Wilson, and A. Nelson. The design of the Matlab testing interface was carried out by N.Nguyen and A.Mulla. The data for this study was collected, analyzed and interpreted by N.Nguyen. Preparation of the manuscript was carried out by N.Nguyen with inputs from Drs. Wilson and Nelson. The manuscript will be submitted to the journal Anatomical Sciences Education.

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List of Abbreviations

CF ______________________________ Closure Flexibility

CS ______________________________ Closure Speed

DOF ______________________________ Degree of Freedom

MRT ______________________________ Mental Rotations Task

P ______________________________ Perceptual Speed

SR ______________________________ Spatial Relations

Vz ______________________________ Visualization ability or spatial visualization ability

SAT ______________________________ Spatial Anatomy Task

CRF ______________________________ Completely Randomized Factorial

Preface

" Wisdom is not a product of school but of the lifelong attempt to acquire it."

- Albert Einstein, 1954

Chapter 1

1 General Introduction

1.1 Medical Education

The primary goal of medical education is to teach students how to perform clinical procedures with minimum risks and maximum benefits to patients. Since patients are three-dimensional (3-D) entities, healthcare and medical education often involve learning and applying 3-D information (Marks, 2000). A cornerstone in the foundation begins in anatomy courses, where, in addition to terminology, students learn visuospatial information, including the shape of anatomical structures, their position in 3-D space, and their location relative to other structures. When carrying out medical procedures, often the internal structures of the patient's body are not directly visible, so that medical professionals have to rely on internal or mental representations of visuospatial anatomical information.

1.2 Anatomy Education

Given the importance of visuospatial information in medicine, educators have endeavoured to find ways of helping students acquire visuospatial anatomical knowledge. Traditionally, anatomical learning took place in the dissection room, supplemented by anatomy textbooks and atlases (McLachlan and Patten, 2006). It is a widely held perception that the process of dissection or inspection of prosected specimens provides unique views of anatomical structures 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 both the United States and Canada have experienced a decrease in curriculum hours compounded by a scarcity of donated bodies and reduced supply of, and demand for, 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 scenario, dissection becomes an inefficient learning tool, and in the latter condition the elimination of dissection precipitates total reliance on other forms of instruction in anatomy (Prentice et al., 1977; Rizzolo et al., 2006)

With the development in graphical technologies and widespread availability of computers, computerized representations of anatomy have become prevalent in all levels of medicine and allied health sciences – from undergraduate anatomy education to surgical training. Compared to real world objects, computer visualizations offer advantages in terms of accessibility, convenience, cost, safety, and versatility (Aziz et al., 2002; McLachlan et al., 2004; McLachlan and Patten, 2006). As a result, medical education has begun a dramatic shift towards introducing computer visualizations into its learning program with the intention that they will "enhance" or "amplify" cognition (Keehner et al., 2008; AFMC, 2010). The ability to communicate anatomical information visually has extended from static (or non-dynamic) to animated (or dynamic) representations, non-interactive to interactive displays, and non-stereoscopic to stereoscopic visualizations (Khalil et al., 2005; Luursema et al., 2006). Many benefits have been claimed for interactive and dynamic visualizations. These include the belief that (a) 3-D visualizations are better than 2-D images, (b) animations are better than static representations, (c) interactive visualizations are better than non-interactive ones, and (d) virtual reality simulations based on stereoscopic images are better than animations (Scaife and Rogers, 1996).

Such generalizations about the benefits of technologically-advanced visualizations over simple static representations beg the question however, what is actually gained cognitively from having more explicit, dynamic and interactive representation of information (Scaife and Rogers, 1996)? Why, for example, should an animation of an anatomical structure that rotates in response to user interaction be more effective at facilitating the acquisition of visuospatial anatomical knowledge than static diagrams available in traditional anatomy textbooks or atlases? Why not the other way around, where static diagrams are more effective than animations or non-interactive visualizations are better interactive ones?

Despite much optimism about their educational potential, our understanding of the instructional value of different computer visualizations is relatively limited. Within cognitive science, there is mounting evidence that the effectiveness of instructional visualizations depends on how well their design reflect human cognitive architecture (Mayer, 2005). Specifically, the educational value of these visualizations depends on whether learners have enough cognitive resources (i.e., working memory and long-term memory) to construct, maintain, and integrate information in the external display (Sweller et al., 1998; Mayer, 2005). Therefore, within cognitive science there has been a move towards examining the relationships between external visualizations and internal thought process and to explore a full range of factors that affect learning from computer visualizations (Zhang and Norman, 1994; Zhang et al., 2002; Hegarty et al., 2007; Keehner et al., 2008). A striking finding from cognitive research studies is that computer visualizations are not equally effective for all learners, and that task performance often involves a tradeoff between internal and external resources available to the learner. On the one hand, different characteristics of the learner (e.g., prior knowledge, spatial ability, and motivation) can mean that more or less cognitive resources are devoted to the main instructional task. On the other hand, different characteristics of the external computer visualization can mean that more or less task load is carried out internally.

1.3 Overview of Dissertation

The purpose of this dissertation is to explore the relationship between internal and external visualizations and the implications of this relationship for comprehending visuospatial anatomical information. The move towards understanding how anatomical knowledge is constructed through the interaction of internal and external visualizations is a substantial move away from the traditional approach to cognition, which assumes that cognition is exclusively in the mind, and external objects, if they had anything to do with cognition at all, are at most peripheral aids (Zhang and Norman, 1994). Giving external computer visualizations a more central functional role in relation to internal visualizations allows us to account more adequately for how the representational system works (Scaife and Rogers, 1996). The value of this approach is that it allows us to focus our attention more on the properties of the internal and external visualizations and cognitive processing involved when interacting with visual representations. In addition to enabling us to better understand the cognitive value of different graphical representations, this approach also allows us to begin to assess more effectively how instructional innovation in anatomy education should be approached.

The remainder of this dissertation is divided into five chapters:

Chapter 2 is the literature review. It begins with an operational definition of 'visualization' and outlines the differences between internal and external visualizations. Next, the properties of external computer visualizations used in anatomy courses (static, dynamic, stereoscopic, monocular, interactive, and non-interactive) are described followed by a review of previous research studies evaluating their educational effectiveness. Finally, the role of internal spatial visualization ability, a sub-factor of spatial ability, is examined along with a review of previous literature describing its role in anatomy education.

Chapters 3 – 5 are three experiments in this dissertation. Experiment 1 examines whether spatial visualization ability influences performance on a novel spatial anatomy task and whether the effects of spatial visualization ability could be modulated through instruction with different computer visualizations. Experiment 2 examines the problem solving strategies of individuals with high and low spatial visualization ability in order to determine whether differences in strategies contribute to differences in anatomy task performance. Experiment 3 examines whether increasing the realism of the display will inherently improve the educational effectiveness of the computer visualization.

Chapter 6 is the general discussion and conclusion. Here, explanations for the patterns of performance observed in experiments 1, 2, and 3 are proposed and their implications for

anatomy education are offered. Finally, recommendations for future experimentation are provided.

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Chapter 2

2 Literature Review

2.1 Visualization

The New Oxford American Dictionary defines "visualization" as the process of "forming a mental image" or "making (something) visible to the eye" (McKean, 2005). In cognitive science, these are two entirely difference constructs. The former, called an internal visualization, is a representation in the mind of an individual derived from imagery or imagination (Hegarty, 2004b); the latter, called an external visualization, is a representation in the environment that can be perceived by an individual (Hegarty, 2004b). For example, an image of the human heart printed in an anatomy textbook or atlas is an external representation of the heart; it is not the heart reduced in size and transposed onto a 2-D surface, but only a physical copy of what the heart looks like from a particular vantage point. Similarly, if one has ever dissected the heart and can envision what the heart looks like, from whichever perspective one wishes, then one is relying on an internal or mental representation of the heart. The heart is not physically in one's head, but rather a mental image of the heart accessed from memory.

One key feature of external visualizations is that they can provide valuable assistance for learning. This assistance, called "cognitive support," can occur through a number of mechanisms that reduce demands on the learner's working memory and allow an effortful internal cognitive process to be offloaded onto a less effortful external perceptual-motor process (Tory and Moller, 2004; Keehner et al., 2008b). There are many tools that can support or augment the learning process, the most common of these being visual and aural representations. This dissertation focuses particularly on visual representations, specifically computer - generated visual representations, or simply computer visualizations.

2.2 External visualizations

Throughout history, advancement in technology has significantly improved our ability to create external representations of anatomy. While cadaveric dissection has been acknowledged as the paradigm of anatomy teaching since the 16th century, access to dissections was limited due to the lack of fresh bodies and the lack of effective preservation techniques (Olry, 2000; McLachlan and Patten, 2006). As a result, external representations in the form of physical models with fine anatomical details were created as alternative teaching aids. These had the advantages of being more widely available and were not at risk of decay. In the 17th and 18th centuries, anatomical models were made from available materials such as wax, ivory and cardboard (Olry, 2000). Starting in the early 20th century, plastic or polychromatic rubber became the material of choice for creating anatomical models (Olry, 2000). In recent years, computers have changed the way we create and use anatomy representations. Because of computers, anatomical representations can be created automatically at time of use, can be made dynamic and interactive, can be used anywhere, with or without an internet connection, and can be stored on almost any network - capable devices ranging from desktop computers to tables and smartphones.

2.2.1 Computer visualizations

While 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 undergraduate anatomy students to residents in advanced medical 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). Many of these visualizations are rendered directly 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).

Computer visualizations can be classified in many ways. Commonly, they are described in terms of features such as their modality (text or picture), abstraction (iconic or symbolic), sensory channel (auditory or visual), dimensionality (2-D or 3-D), dynamism (static/non-dynamic or dynamic), or interactivity (active or passive) (Ainsworth and VanLabeke, 2004). Different types of external computer representations of anatomy vary in terms of 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 (i.e., the represented structure) (Hegarty and Kriz, 2008).

2.2.1.1 Modality: text versus pictures

Comparisons of information processing requirements of text and pictures have been used to explain why pictorial representations can have advantages over text for presenting certain types of information to learners. Texts are descriptive representations consisting of symbols describing an object, such as spoken or written words and mathematical expressions (Schnotz and Kürschner, 2008). Symbols are signs that have no similarity with the content they represent. For example, the word 'heart' has no similarity with a real heart. It is a symbol, and it's meaning is based on a convention. In a sentence like, "the resting heart beats 70 times per minute", nouns (such as 'heart') are symbols for objects and events; verbs (such as 'beats') are symbols for actions, and adjectives (such as 'resting') are symbols for attributes. Pictures, on the other hand, are depictive representations consisting of icons (Schnotz and Kürschner, 2008). Icons are signs that are associated with the content they represent through common structural features. A map of Canada or a picture of the human body are examples of depictive representations that have some similarity with the corresponding referent (Schnotz, 2005).

One advantage of pictures over texts is that they can make complex information easier to comprehend. Specifically, they are useful for communicating cause-and-effect information (e.g., turning a key can unlock a door), organizing information to reduce search efforts (e.g., a map or flowchart), and representing relationships amongst elements that are difficult to explain verbally (e.g., a Venn diagram) (Zhang and Norman, 1994). Another advantage of pictures is they can promote parallel processing by the visual system, which can increase the bandwidth of information extraction. According to the modality principle (Lowe, 2004), under certain, well-defined conditions, presenting some information in visual form and other information in auditory form can effectively expand working memory capacity and so reduce the effects of excessive cognitive load. Finally, pictures can be used to drive cognitive behaviour without conscious awareness (Zhang and Norman, 1994; Zhang, 1997). For example, physically salient cues, such as bright colors, labels, and motion, can be added to the display to draw learners' attention towards important concepts or features, increasing the likelihood that these features will be brought into the information processing system (Desimone and Duncan, 1995).

The comparisons of text and pictures referred to above concern the way their different visuospatial characteristics impact on information processing requirements such as search and the detection of relationships (Lowe, 2004). It is possible to take this theme one step further and make similar comparisons between static and dynamic, and 2-D and 3-D visualizations.

2.2.1.2 Dynamism: static versus dynamic

A static (or non-dynamic) image printed in an anatomy textbook or atlas can explicitly represent the parts of the human body. This type of image is commonly used to show anatomical structures (e.g., muscles of the lower limb) from one of six canonical orientations: anterior (or front), posterior (or back), superior (or top), inferior (or bottom), left–lateral (or left-side), or right–lateral (or right-side). 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 (Hegarty and Kriz, 2008).

An animation is the prototypical example of a dynamic visualization (Hegarty, 2004b). 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 VanLabeke, 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 (Hegarty and Kriz, 2008). 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 may more accurately depict the visuospatial properties of anatomical structures (Garg et al., 1999).

2.2.1.3 Dimensionality: 2-D versus 3-D

The human body is a 3-D entity (actually, 4-D if time is included), in that it has a length, width, and height. When looking at an image (static or dynamic, 2-D or 3-D) there are visual cues incorporated in the image that the brain attends to. The visual system relies on these cues to infer the visuospatial properties of objects within the field of view, in this case, anatomical structures. These depth cues are typically divided into two broad categories - monocular cues that require the visual input of one eye and binocular cues that require the visual input of two eyes (Schwartz, 2010).

Monocular cues can be broken down into two categories depending on whether they can be reproduced in a 2-D static picture (called pictorial cues) or a 3-D dynamic picture (called motion cues). Pictorial cues are listed in Table 2.1 and include relative size, familiar size, linear perspective, texture, interposition (or occlusion), light, shading, and shadow (Schwartz, 2010). Most of these cue properties are based on the concept that the size of the retinal image of an object is proportional to the object’s size and inversely proportional to the distance of the object. Hence, an object that casts a smaller retinal image is perceived as being farther away than an object that casts a larger retinal image.

The incorporation of pictorial depth cues to a 2-D flat surface can create a sense of depth where none previously exists.

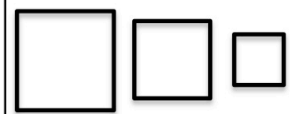
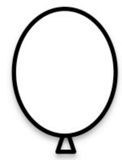
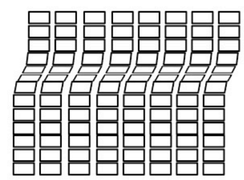
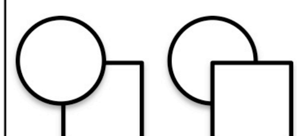
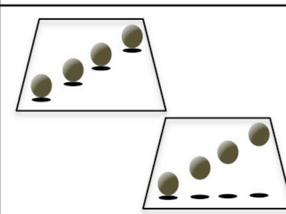
Depth Cue	Description	Example
Relative Size	This cue is used when two objects are known to be the same size but their absolute size is unknown. Relative size cues can provide information about the relative depth of the two objects. The object that cast a smaller retinal image is perceived as being farther way than the object that casts a larger retinal image.	
Familiar Size	This cue is used when viewing objects of known size. Through experience, the standard size of certain objects becomes familiar. Since the visual angle of an object projected onto the retina decreases with distance, this information can be combined with previous knowledge of the object's size to determine the absolute depth of the object.	
Linear Perspective	This cue is based on the fact that parallel lines, such as railroad tracks, appear to converge with distance, eventually reaching a vanishing point at the horizon. The property of parallel lines converging at infinity allows the relative distance of two parts of an object to be perceived. Closer lines cast a smaller retinal image and are perceived as more distant.	
Texture	This cue is based on the fact that a texture gradient arises whenever viewing a surface from a slant, rather than directly from above. The texture elements become smaller, denser and less detailed with distance. Densely packed objects cast a smaller retinal image and are perceived as more distant.	
Interposition/occlusion	This cue is used when one object overlaps or partly blocks the view of another object. The covered object is perceived as more distant.	
Light, Shading, Shadow	This cue is based on the way light falls on an object and reflects off its surfaces. The shadows that are cast by objects provide effective cues for the brain to determine the shape of objects and their position in space.	

Table 2.1: Monocular pictorial depth cues (Schwartz, 2010)

Motion cues include multiple forms of parallax. The perception of motion can be thought of simply as a change in the visual direction of an object as a function of time when one, then another, retinal locus is stimulated by its image (Steinman and Garzia, 2000). If the observer is moving relative to a stationary object, the resulting movement is called moving-viewer motion parallax (Bowman et al., 2005). If the observer is stationary but the object is in motion (e.g., it is rotating or translating), the resulting movement is called stationary-viewer motion parallax (Bowman et al., 2005). In both cases, objects will move at different speeds on the retina depending on their distance from the observer. Objects closer to the observer will appear to move faster than objects farther away. The sequence of images in Figure 2.1 illustrates motion parallax as a visual cue. The incorporation of motion depth cues to a display (e.g., having an object rotating in virtual space) can provide a 3-D impression of an object that better communicates its visuospatial properties (Keehner et al., 2008b). Because these motion-based depth cues depend on the object's ability to move and not on whether the movements are actively controlled by the learner, this type of spatial information is made available regardless of whether a visualization's level of interactivity is passive or active (Keehner et al., 2008a; 2008b).

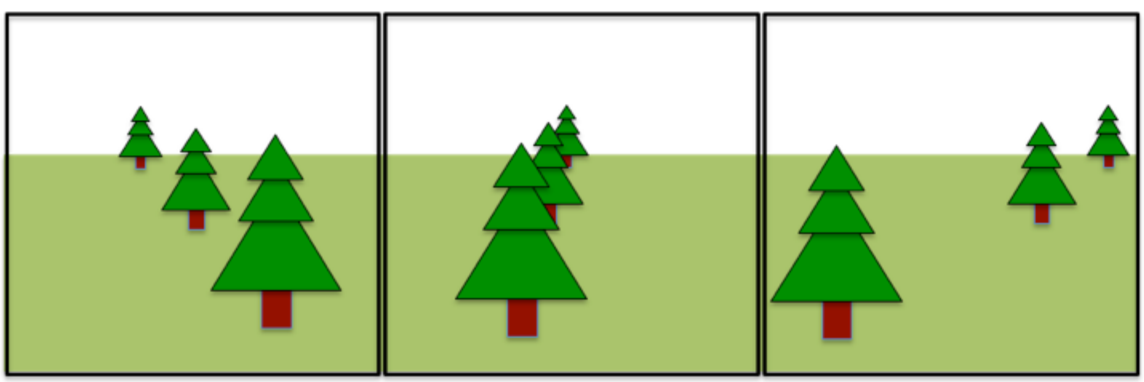


Figure 2.1: Motion-parallax as a visual cue. As the observer moves from left to right, the tree closest to the observer appears to move the most, while the tree farthest away appears to be moving the least.

Binocular cues exist because of the differential location of the two eyes. On average, the human eyes are separated by approximately 6.4 cm in the horizontal direction (Ware, 2004). Due to this separation, the two eyes receive slightly different images of the external environment and the brain uses the disparity between these images to recover information about the relative distance or depth of objects in the visual world (Steinman and Garzia, 2000). This process is called stereopsis and its sole basis is the horizontal (or binocular) disparity between the two retinal images (Poggio and Poggio, 1984). There are, of course, several cues to depth, like texture gradients, shading, and motion parallax, which are based on the visual input of only one eye. However, stereopsis is the most important and accurate of them, especially when it comes to depth perception in close visual field (Ware, 2004).

While stereopsis occurs naturally in animals with overlapping visual fields (Ware, 2004), the effect can be achieved using a standard computer monitor coupled with stereo glasses. The monitor is used to generate and display the disparate images (one for each eye) while the stereo glasses are used to filter the screen images so that each eye receives only one screen image. Bowman et al. (2005) recommends a monitor with a high refresh rate (100 Hz or better) because the display of the two images reduces the refresh rate by 50%. The stereo glasses can either be active or passive. Active (or shutter) stereo glasses are synchronized to open and close their shutters at the same reduced refresh rate as the monitor (Bowman et al., 2005). Passive stereo glasses are based on polarization or spectral multiplexing. Polarization multiplexing filters the overlaid images with polarized filters that run in opposite directions (e.g., one filter could be horizontally polarized while the other is vertically polarized). Spectral multiplexing (or anaglyph stereo) displays the two overlaid images in two different colours (e.g., blue and red). The coloured filters are used so that light from any colour other than the filter’s colour is washed out. Although active stereo produces the highest stereo quality, it is expensive and requires synchronization between the glasses and the images generated on the monitor. Passive stereo is relatively inexpensive but the colour filters reduce the overall quality of the images (Bowman et al., 2005).

2.2.1.4 Interactivity: interactive versus non-interactive

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 (Garg et al., 1999; Luursema et al., 2008). 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.

The ability to interact with computer visualizations can be achieved through various input hardware, ranging from the traditional desktop devices such as keyboards, 2-D mice and trackballs to more sophisticated devices that track users' hand motion. Many different characteristics can be used to describe input devices. One of the most important characteristics is the number of degrees of freedom (DOF) that the input device allows. A degree of freedom may be defined as the number of independent dimensions of the motion of a body (Bowman et al., 2005). A traditional 2-D mouse, for example, allows for translation along two perpendicular axes (up/down along the y-axis and left/right along the x-axis). Since the movement along the axes is independent of each other, a traditional mouse has two DOF. A tracker, on the other hand, allows for translation along three perpendicular axes (up/down along the y-axis, right/left along the x-axis, and forward/backward along the z-axis) as well as rotation about these axes (pitch, yaw, roll). Since the movement along each of the three axes is independent of each other, a tracker has six DOF. Typically a device's DOF gives an indication of how complex the device is and the power it has in accommodating various interaction techniques.

Another way of characterizing input devices is by the input type and frequency of data (i.e. reports) they generate. Data reports are composed of discrete components, continuous components, or a combination of both components. Discrete input device components typically generate a single data value (e.g., Boolean value or an element from a set) based on the user's action (e.g., key presses) and produce a discrete (or stepped) system response (e.g. making a menu selection or following a hyperlink). Continuous input device components generate multiple data values (e.g., real-value numbers, pixels, coordinates) in response to a user's action and produce a flow of system responses (Bowman 2005). This mode of interaction is important for direction manipulation interfaces, where there is a short "cognitive distance" between a user's action and the system's feedback, resulting in a feeling of first-personness or direct engagement with the object displayed (Hutchins et al. 1985). In many cases, input devices combine discrete and continuous components, providing a larger range of device-to-interaction technique mapping (Bowman et al., 2005).

In summary, computer visualizations used in anatomy courses vary widely in the type of depth cues incorporated in the display and the degree to which they permit interactive control by the user. A static image provides a 2-D representation of a 3-D object. Pictorial depth cues such as shading, shadow, and texture gradient are applied to a 2-D surface, creating a sense of depth where none previously existed. An animation of an object rotating in virtual space provides a 3-D impression of the object. The incorporation of motion parallax enables multiple views of the object, which better communicates the visuospatial information of anatomy (Keehner et al., 2008b). The incorporation of computer-implemented stereopsis enhances depth information, especially at near distances, by providing the left and right eye of the viewer with two images, representing two perspectives of the same object, with a minor deviation equal to the perspectives that both eyes naturally receive in binocular vision (Bowman et al., 2005). Computer visualization can be made interactive through a number of input devices ranging from keyboard presses to trackers with six DOF (Bowman et al., 2005).

2.2.2 Comparative research studies

2.2.2.1 Static representations versus animations

Intuitively, one might expect that animations will offer advantages over static representations, especially since the additional depth cues incorporated in these displays better communicate the visuospatial properties of anatomical structures (Keehner et al., 2008b). At best, static depictions, such as illustrations or photographs printed in anatomy textbooks, can present implicit representations only of dynamic or visuospatial information. They therefore require learners to infer the situational dynamics or spatial properties, respectively (Lowe, 2004). This can be seen as imposing a processing burden on the information processing system. In contrast, animations have the advantage of being able to present the dynamic or spatial content explicitly such that there is an isomorphism between the content being represented in the dynamic display and its referent (Lowe, 1999; 2004). Thus, when learning with animation the majority of learners' working memory resources could be devoted to comprehending the content directly. However, initial research comparing the educational effectiveness of animations and static depictions failed to show clear advantages for animated displays. For example, Tversky et al. (2002) reviewed over 20 studies comparing learning from static representations and animations. In the majority of the studies, including those in the domain of physics, biology, and mechanics, there was no advantage of animations over static representations. In cases where there was an advantage, further examination revealed lack of equivalence between the animated and static displays in both content and procedures, such that the animation conveyed more information or interactivity was involved. In contrast, Hoffler and Leutner (2007) published a meta-analysis of 26 studies comparing animations and static representations in an attempt to identify factors responsible for successful learning with animations. Their analysis revealed an overall advantage of animated over static representations. The analysis further revealed that animations are more effective than static representations only when they are representational (i.e., where the topic to be learned is explicitly depicted in the animation) rather than decorative (i.e., where the animation is used to motivate the learner) in nature.

The analysis also showed a larger benefit of animations over static representations when the target knowledge was procedural-motor knowledge rather than problem-solving knowledge or declarative knowledge.

In the specific domain of anatomy, Hariri et al. (2004) compared the utility of interactive animations and static representations for learning shoulder joint anatomy. Students received ten-minute learning sessions with either a simulator that provided dynamic graphic display and haptic feedback or static textbook images. Subsequently, students had to identify anatomical structures videotaped during a shoulder arthroscopy. They found that the animation had no instructional advantage over the textbook images. Keedy et al. (2011) compared the value of interactive animations and static representations for learning hepatobiliary anatomy. Students studied hepatobiliarly anatomy with either a learning module comprised of text, still images, and interactive animations or a learning module comprised of only text and still images. Following the learning module, students completed a satisfaction survey and a nine-item anatomy knowledge test. They found higher satisfaction ratings for the interactive animations; however, the animations had no instructional advantage over the textbook style approach.

Despite their seemingly endless pedagogical potential, it is clear from initial research that there is not a simple advantage of animations over static representations. A common response to this result is to assume that the animations used in these research studies were poorly designed, so that the solution is to improve the design of the animations (Kriz and Hegarty, 2007). Several researchers have suggested principles for the designing of effective animations, including adding binocular depth cues to increase the depth and accuracy of the display (Luursema et al., 2006; Luursema et al., 2008) and adding interactive control to engage learners in the learning process (Hegarty, 2004b; Schwan and Riempp, 2004).

2.2.2.2 Stereoscopic versus non-stereoscopic visualizations

In education, it is often assumed that increasing the realism of a display will inherently improve its educational effectiveness (Scaife and Rogers, 1996). If this is the case, then computer visualizations that better communicate the visuospatial properties of anatomy should assist learners in constructing a more accurate mental representation of anatomical structures. Since stereopsis offers the advantage of improved depth perception and accuracy (especially in close proximity to the viewer), one might expect that it will have instructional advantages over monocular displays. To date, only two studies have examined the contribution of stereopsis on virtual anatomy learning. In the first study, participants learned abdominal anatomy through interaction with a stereoscopic animation or non-stereoscopic static representations (Luursema et al., 2006). Anatomy competency was measured with a task that involved identification of abdominal structures in 2-D cross-section and localization of corresponding plane/level of selected cross-sections. The authors found that the stereoscopic animation had an overall instructional advantage over non-stereoscopic static representations for both identification and localization problems. In the second study, interactivity was omitted and participant's learned abdominal anatomy via stereoscopic animation or non-stereoscopic animation (Luursema et al., 2008). The authors found that computer-implemented stereopsis improved performance on the localization task but not the identification task.

Although few studies have examined the instructional value of stereoscopic displays for learning anatomical information, plenty of studies have examined the usefulness of these displays on surgical skill training. However, these studies have yielded inconsistent results as to the benefits of computer-implemented stereopsis. Some studies found clear advantages for stereoscopic displays. Peitgen et al. (1996), for example, examined the effects of computer-implemented stereopsis on laparoscopic task performance. Performance time and accuracy were recorded. Compared to the non-stereoscopic display, the stereopscopic display improved performance (both speed and accuracy) on the surgical task. Falk et al. (2001) and Byrn et al. (2007) examined the impact of stereopsis on the performance of surgeons using the da Vinci Robot System. Performance time and accuracy were measured. In both studies, stereoscopic displays improved task performance (speed and accuracy) compared to non-stereoscopic displays.

By contrast, other studies found that the addition of stereopsis offered no additional advantages over monocular displays. Hanna et al. (1998) examined the impact of computer-implemented stereopsis on laparoscopic cholecystectomy for symptomatic gallstone disease. The addition of stereopsis to the display did not offer advantages over the non-stereoscopic display. Furthermore, surgeons reported adverse symptoms immediately after the operations with both systems; however, the score for visual strain, headache, and facial discomfort were higher with the stereoscopic display. Roach et al. (2012) evaluated the impacts of stereopsis on the acquisition of new surgical skills - the rhombic flap and double z-plasty procedures. Students' technical skills (i.e., dexterity, respect for tissue, instrument control, time and progressive thought) were assessed with a five-point Global Rotating Scale. The stereoscopic display did offer additional training advantages over the non-stereoscopic display.

Finally, in some cases, computer-implemented stereopsis hinders task performance. Wentink et al. (2002) compared a standard laparoscopic viewing system comprised of a monocular endoscope with a high-resolution monitor with three advanced laparoscopic viewing systems (including a stereoscopic 3D endoscope system) in a laparoscopic training experiment. Performance time was obtained. The time on the task was significantly greater with the stereoscopic viewing system than with the standard viewing system. Therefore, compared to the standard system, task performance (as measured by time on task) actually decreased.

2.2.2.3 Interactive versus non-interactive visualizations

Like films, animations and static representations (monocular or stereoscopic) are mass media presentations that do not address the needs of a single viewer, rather a general audience. Typically, the cognitive characteristics of audience members will vary (Schwan and Riempp, 2004). Examples of such differences include prior knowledge, motivation, and abilities. Hence, it is impossible for traditional animations or static images to take these individual differences into account. Here, interactivity comes into play. The advantage of interactivity is that it enables the viewer to adapt the presentation to his/her individual cognitive needs by actively deciding “what” is presented on the screen and “when” it is presented (Schwan and Riempp, 2004). It is tempting to assume, then, that making visualizations more effective in anatomy education is merely a question of making them more interactive. However, studies examining the educational value of interactive visualizations have demonstrated mixed results.

Some studies found significant advantages for interactivity. Mayer and Chandler (2001) showed that learners who had simple control over the pace of an animation (i.e., pause, play) not only found the material more enjoyable but also performed better on transfer tests (i.e. test of deep learning) than learners who had no control over the presentation. Schwan and Riempp (2004) demonstrated that having complete control over the pace and direction of an animation (i.e., stop, replay, reverse or change speed) accelerates the process of skill acquisition (i.e., tying a nautical knot). Subjects with complete control over animations had a better understanding of the depicted processes than subjects with no control. By contrast, subjects with no control needed substantially more time than subjects with control to acquire procedural skills. In the context of anatomy education, Luursema and Verwey (2011) examined the contribution of interactivity to learning abdominal anatomy. Students received three-minute learning sessions with a stereoscopic abdominal model. Half the students had active control over the rotation of the model (by using a mouse) while the other half witnessed the active participants’ explorations. After the study phase, an anatomical knowledge test consisting of identification questions (identify structure in 2D cross-section) and localization questions (localize the plane/level of selected cross-sections) assessed participants’ learning. Active exploration provided a small but significant benefit over passive exploration.

By contrast, other studies found no additional advantages of interactive over non-interactive visualizations. Keehner et al. (2008a) conducted a series of experiments examining the effects of interactive visualizations on a task requiring participants to infer and draw cross-sections of an unfamiliar three-dimensional (3-D) object. In experiment 1, they contrasted the performance with an interactive visualization to that with a non-interactive visualization. In experiment 2, they used a yoked design to observe the effects of interactivity while controlling for visual input in interactive and non-interactive conditions. In experiment 3, they contrasted an interactive visualization with a non-interactive visualization that was designed to model the visual information accessed by the most successful interactive participants in earlier experiments. In experiment 1, interactivity produced better performance than passive viewing, but the advantage of interactivity disappeared in experiment 2 when the visual input for the two conditions was equalized through the yoked design. In experiment 3, non-interactive participants who watch optimal movements of the visualization performed as well as interactive participants who manipulated the visualization effectively and better than interactive participants who manipulated the visualization ineffectively. The results suggest that interactivity per se is not the critical factor in the performance of the cross-section task. Instead, the quality of the visual information available predicts success on the task, regardless of whether participants have control over it.

2.2.3 Summary

Despite their seemingly endless pedagogical potential, it is clear from initial research that there is not a simple advantage of animations over static representations, stereoscopic over non-stereoscopic displays, and interactive over non-interactive visualizations. Yet, most educators continue to believe making computer visualizations more dynamic and interactive will enhance their educational effectiveness (Hegarty, 2004b). By focusing on improving the methods by which visual information is communicated, these educators automatically assume a bottom-up model of learning (Kriz and Hegarty, 2007). According to this model, learning is primarily a function of encoding information from the external display, so that improving characteristics of the display will, by necessity, improve learning. In contrast, less attention has been given to how the learning process is affected by learners' abilities, skills, goals, and prior knowledge, that is, top-down influences on comprehension (Kriz and Hegarty, 2007; Hegarty and Kriz, 2008). Therefore, the next section of this literature review focuses on an important learner characteristic that has been found to influence anatomy learning through traditional methods and more recently from computer visualizations.

2.3 Internal visualizations

While technology has significantly improved our ability to create external visualizations, our ability to internally visualize has probably not changed significantly over the last few decades. Internal visualization has been an important topic of research in cognitive science since the 1800s (Hegarty, 2004a; Zacks and Michelon, 2005). Studies of internal visualization often involve examining people's ability to construct, inspect, and transform mental representations (Hegarty, 2004a). In the working memory literature, the internal visualization system is collectively known as the visuospatial sketchpad (Baddeley, 1992). In the human intelligence literature, internal visualization ability is also called spatial ability (Carroll, 1993; Hegarty, 2004a).

2.3.1 Spatial visualization ability (Vz)

Generally, the process of constructing and maintaining internal visualization is considered a visual process, involving the visuospatial sketchpad of working memory (Clark and Paivio, 1991; Baddeley, 1992; Mayer and Sims, 1994; Miyake et al., 2001). Processing information in the visuospatial sketchpad is strongly influenced by spatial ability (Miyake et al., 2001), 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' (Carroll 1993, p. 304). My simply stated, an internal representation of a perceived object or scene must be created and maintained in such a way that mental manipulations are possible.

As the acts of creating, maintaining, and transforming internal visualizations all require different but important abilities, several sub-factors of spatial ability have been identified and together they form the broad concept of spatial ability. These sub-factors are: (a) *Visualization (Vz),* the ability to apprehend, encode and manipulate visuospatial representations, often involving rotation in two or three-dimensions; (b) *Spatial relations (SR)*, speed of manipulating simple visuospatial representations by transformation; (c) *Closure speed (CS),* speed in retrieving visuospatial representations from long-term memory when presented with incomplete, disguised or obscured forms of those representations; (d) *Closure flexibility (CF),* speed of identifying given visuospatial patterns in a complex visual environment; and (e) *Perceptual speed (P),* speed of making correct comparisons when given a number of alternative patterns (Carroll, 1993).

Although there are several sub-factors of spatial ability, the one that has been shown to be most relevant to anatomy education is visualization ability (Vz), or more commonly known as spatial visualization ability. The main difference between spatial visualization ability (Vz) and spatial relations ability (SR) (which also requires mental transformation) is that SR problems are solved more rapidly than Vz problems, and the tests themselves are administered in a format that emphasizes speed in the former case and both speed and accuracy in the latter case (Mumaw and Pellegrino, 1984). The second difference involves the stimulus and its complexity. A gross index of complexity is the number of individual stimulus elements or parts that must be stored and processed in working memory (Mumaw and Pellegrino, 1984; Pellegrino et al., 1984). SR problems, although varying among themselves in complexity, involve less complex stimuli than Vz problems. Therefore, SR problems usually require a single mental transformation, while Vz problems require a sequence of transformations (Pellegrino et al., 1984)

The remaining three factors (CS, CF, and P) do not play significant roles in visualization research and are rarely assessed. Perceptual speed (P) involves speed or efficiency in comparing figures or symbols or finding a figure or symbol. The difference between P and Vz is that P problems require no mental transformations and typically rely more on visual than spatial processing (Hegarty and Waller, 2006). Closure speed (CS) and closure flexibility (CF) involve speed or efficiency in identifying a stimulus (or part of a stimulus) that is either embedded in or obscured by visual noise (Hegarty and Waller, 2006). In the case of CF, the examinee is given information about the target stimulus in advance. He or she needs to hold the given information in working memory while attempting to identify it from a complex pattern. In the case of CS, the examinee is not given information about the stimulus pattern (usually a familiar object) in advance. He or she needs to access the representation quickly from long-term memory. The difference between CS, CF, and Vz is that the former two factors require no mental transformation and rely on storage and retrieval of information from memory.

2.3.1.1 Measures of Vz

The ability to apprehend, encode, and manipulate visuospatial representation is often measured using tasks such as the Paper Folding Test (French et al., 1963) and the Mental Rotations Task (Vandenberg and Kuse, 1978). In the Paper Folding Test (French et al., 1963), the subject must imagine that a sheet of paper has been folded in a certain way, a hole is punched through all thicknesses of the paper at a certain point, and the sheet is unfolded. The folding and punching are indicated on the left side of the vertical line, and the subject must select which of the five unfolded sheets on the right of the vertical line is the result. In the Mental Rotations Task (Vandenberg and Kuse, 1978), the subject must imagine rotating three-dimensional block figures. The target/criterion figure is represented on the far left, and the subject must determine as quickly and accurately as possible which two of the four option figures on the right are rotations of the target figure.

Detailed analysis of the different tests of Vz suggest that they have a least two aspects in common – each seems to require the execution of a series of mental transformations in two- or three-dimensions, and in each, intermediate products must be stored temporarily in visuospatial working memory during the processing of other information (Salthouse et al., 1990; Carroll, 1993; Hegarty et al., 2007). For example, in the mental rotations task, two or more of the block figures must be rotated in order to determine whether the blocks are rotations of the target. Furthermore, the orientations of various parts of a block have to be remembered while other parts are rotated.

2.3.1.2 Individual differences in Vz

Like any ability, Vz varies significantly within the general population. Some people can store and process visuospatial information with ease, while others have difficulties performing these cognitive processes. Cognitive analysis of performance on tests of Vz suggests that differences in Vz reflect variations in speed of processing visuospatial information (Mumaw and Pellegrino, 1984; Salthouse, 1996), visuospatial working memory capacity (Shah and Miyake, 1996; Miyake et al., 2001), and strategies for processing visuospatial information (Just and Carpenter, 1985; Cohen, 2005). Compared to low Vz individuals, high Vz individuals are faster at carrying out mental operations, have more working memory resources for storing and processing visuospatial information, and adopt more efficient strategies for solving Vz problems.

2.3.1.3 Vz and anatomy education

Spatial visualization ability (Vz) is a subfactor of spatial ability that is relevant to many disciplines of science, including biology (Russell-Gebbett, 1984; Rochford, 1985; Russell-Gebbett, 1985; Macnab and Johnstone, 1990; Eun-mi et al., 2003), chemistry (Carter et al., 1987; Pribyl and Bodner, 1987; Coleman and Gotch, 1998; Eun-mi et al., 2003), and physics (Kozhevnikov et al., 2007). As applied to anatomy education, Vz tasks often involve imagining the shape and relation of anatomical structures in both three-dimensions and two-dimensional cross-sections. Russell-Gebbett (1984) identified two skills often used by secondary school pupils to understand three-dimensional structures in biology. These discrete skills include the ability to infer the shapes of cross-sections of anatomical structures and the ability to understand the spatial relationships among the internal parts in the anatomical cross-sections. Further analysis revealed that these skills were positively correlated with success on 3-D biology problems (Russell-Gebbett, 1985). Rochford (1985) found a positive correlation between Vz and achievement among medical students at the University of Cape Town. High Vz students achieved consistently higher marks than low Vz students on both practical anatomy examinations and multiple-choice anatomy questions classified as being spatially three-dimensional. Recently, Lufler et al. (2012) found similar results when assessing medical students at Boston University School of Medicine. High Vz students achieved consistently higher marks than their low Vz counterparts on both practical and written examinations.

In addition to practical anatomy task performance, Vz has also been correlated with functional anatomy task performance (Guillot et al., 2007), cross-sectional anatomy task performance (Cohen and Hegarty, 2007; Hegarty and Kriz, 2008), and surgical task performance (Wanzel et al., 2002). Findings such as these suggest that there is a strong visuospatial component to the way anatomical information is mentally represented. It also implies that low Vz individuals will have a harder time constructing, maintaining, and manipulating internal visualizations of anatomy.

In many of these studies, however, performance on the anatomy tasks may reflect other abilities or competencies in addition to 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 spatial visualization. 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, more research is needed to establish the relationship between Vz and visuospatial anatomy task performance.

While Vz is shown to predict anatomy learning through traditional methods, more recently it has also been shown to influence anatomy learning from computer visualizations (Garg et al., 1999; 2001; 2002; Huk, 2006; Hoffler and Leutner, 2011). However, there are disagreements as to possible aptitude-treatment interactions. For example, some studies have demonstrated that instruction with animations (compared to static representations) augments the performance of high Vz individuals more than low Vz individuals. Garg et al. (1999; 2001; 2002) conducted a series of experiments comparing the usefulness of animation and static representations for learning wrist bone anatomy. In the first experiment, students received three-minute learning sessions with either an auto-rotating animation (anatomy self rotating at 10° intervals in the horizontal plane) or static key-view representations (anatomy self rotating by 180° in the horizontal plane) (Garg et al., 1999). In the second experiment, students were allowed active control over the presentation. Those using the animation were allowed to actively rotate the anatomical structures through the multiple views, while those viewing the static images were restricted to rotating the structures in the anterior and posterior views (Garg et al., 2001). In the third experiment, both groups were again allowed active control over the presentation. The rotation was unconstrained for participants viewing the animation but restricted to a "wiggle" (+/- 10° rotation around the anterior and posterior orientations) for those viewing key-view representations (Garg et al., 2002). After each study phase, an anatomical knowledge test assessed participants' learning. Overall, the authors found that animation had no instructional advantage over the key-view images. Further analysis revealed that animations hinder anatomy learning for individuals with poor Vz. For these students, learning was only effective if the display was restricted to a simple depiction entailing just two cardinal views. Findings such as these suggest that animations might actually impair spatial understanding for low Vz individuals. More recently, Huk (2006) examined the impact of interactive 3-D models on learning about the structure of plant and animal cells. Test scores in a subsequent knowledge acquisition test demonstrated a significant interaction between Vz (high, low) and learning with interactive animations. While high Vz learners did better with the animation than without them, the opposite was true for low Vz learners, whose performance was poorer in the presence of the animation. By contrast, other studies have shown that instruction with animations (compared to static representations) augments the performance of low Vz individuals more than high Vz individuals. Hoffler and Leutner (2011) conducted two experiments to evaluate the role of Vz in learning from an instructional animation versus a series of static images. In both studies, test scores in a subsequent knowledge test revealed significant interaction between Vz and type of visualization. When learning with static images, Vz correlated with learning outcomes; students with high Vz performed better than those with low Vz. When learning with animations, however, learning outcome was independent of Vz; students with low Vz performed just as well as their high Vz counterparts.

2.3.2 Summary

Spatial visualization ability (Vz), which can be seen as a measure of internal visualization (Hegarty, 2004a), is correlated with performance on a number of anatomy tasks; however, its role in visuospatial anatomy task performance is still unclear. Furthermore, instruction with different computer visualizations modulates the effects of Vz on task performance; however, there are disagreements as to the aptitude-treatment interaction between Vz and format of the computer visualization.

2.4 Overview of empirical chapters

How does Vz influence performance on visuospatial anatomy tasks? What is the relationship between internal Vz and external computer visualizations (animation versus static representations, interactive versus non-interactive displays, and stereoscopic versus non-stereoscopic visualizations)? The purpose of chapters 3 (experiment 1), 4 (experiment 2), and 5 (experiment 3) is to provide answers to these research questions.

Across all the experiments, Vz was assessed with the standardized Mental Rotations Task (Vandenberg and Kuse, 1978; Peters et al., 1995). The Mental Rotations Task was chosen because it displays high internal consistency (Kuder-Richardson 20 = 0.88) and test-retest reliability (0.83) (Vandenberg and Kuse, 1978). Furthermore, administration of the Mental Rotation Task to university students, high school students, and elementary students revealed that it can be completed by most students in 10 minutes (Vandenberg and Kuse, 1978).

Across all the experiments, comprehension of visuospatial anatomical information was measured with a novel spatial anatomy task. The spatial anatomy task was designed to assess participants' ability to construct, maintain, and transform mental representations of a group of tubular anatomical structures in both three-dimensions and two-dimensional cross-sections. The spatial anatomy task consists of 30 multiple-choice questions – 10 involving the mental rotations of the anatomical structures in three-dimensions (Figure 2.2), 10 involving the identification of the anatomical structures in two-dimensional cross-sections (Figure 2.3), and 10 involving the localization of planes or levels corresponding to selected cross-sections (Figure 2.4).

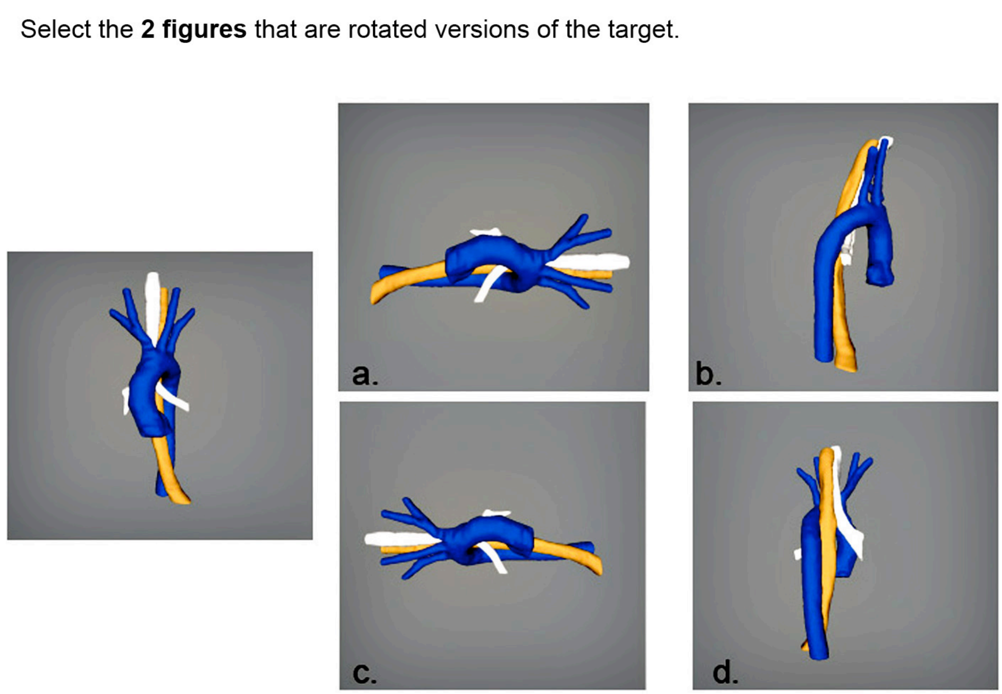


Figure 2.2: Example of a mental rotations task question

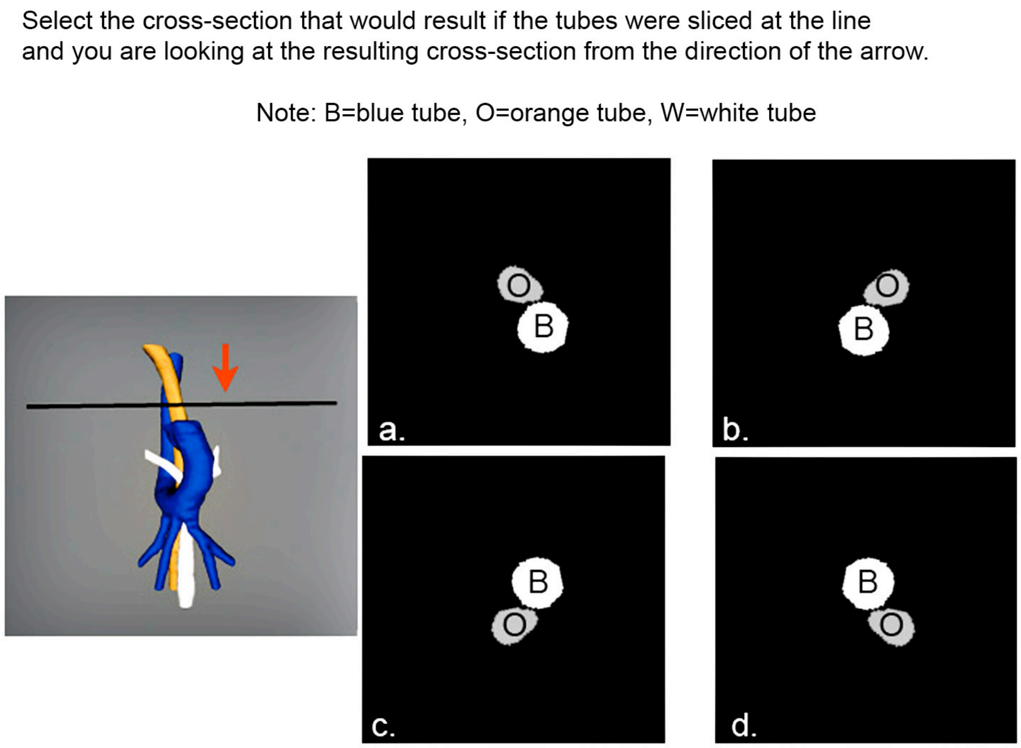


Figure 2.3: Example of an identification task question

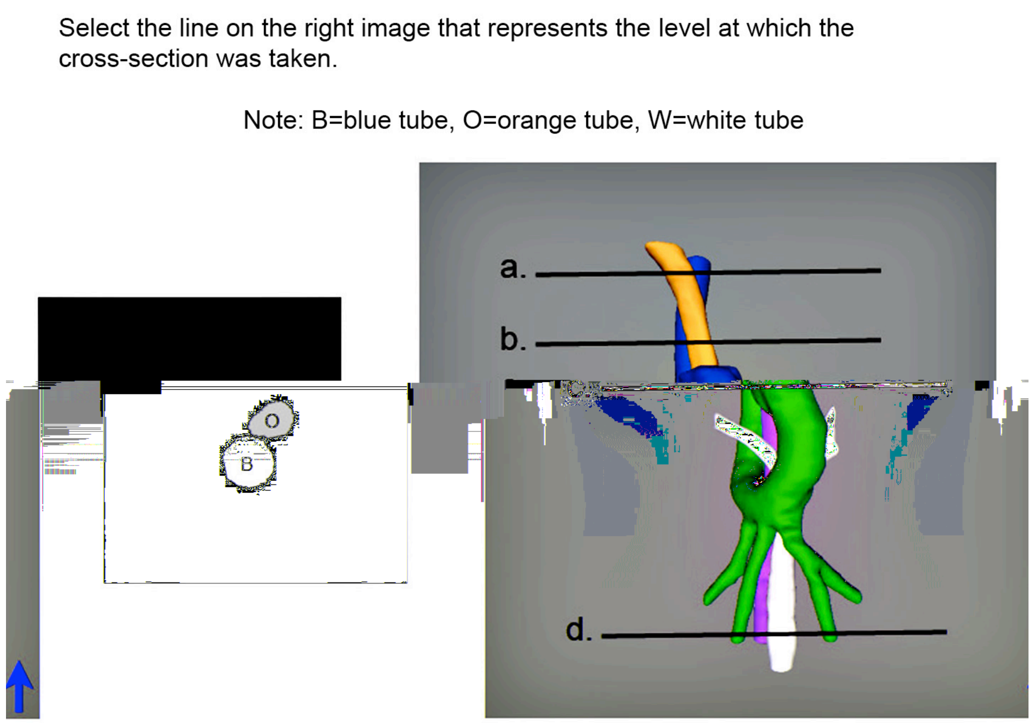


Figure 2.4: Example of a localization task question

Experiment 1 examines whether Vz influences performance on the spatial anatomy task. Performance measures include scores as well as time spent on the anatomy task (in seconds). Experiment 1 also examines whether the effects of Vz could be modulated through instruction with different computer visualizations, specifically static representations versus animation and interactive versus non-interactive displays. Because the spatial anatomy task used to measure visuospatial anatomy comprehension involves complex manipulations in two- and three-dimensions, it is amenable to a range of strategies. Therefore, experiment 2 examines the problem solving strategies of individuals of high- and low- Vz in order to determine whether differences in strategies contribute to differences in anatomy task performance. Experiment 3 examines whether increasing the realism of the display (i.e., through computer implemented stereopsis) will inherently improve the educational efficacy of the computer visualization.

2.5 Overall aims and hypotheses

The first challenge of this dissertation was to examine the contribution of Vz to performance on the spatial anatomy task. Given that the spatial anatomy task involves encoding, storing and mentally manipulating visuospatial information in three-dimensions and two-dimensional cross-sections, it was hypothesized that individuals with high Vz would perform significantly better on the anatomy task than those with low Vz.

The second challenge of this dissertation was to examine the relationship between different external computer visualizations and internal Vz. Hegarty (2004a) proposed that there are at least three possible ways in which external visualization can relate to internal visualizations. One possibility is that the use of external visualizations *depends* on the ability to internally visualize. In this case, some minimal level of spatial visualization ability is required to benefit from the external visualization. A second possibility is that external visualizations can *substitute* for lack of internal visualization ability. In this situation, the external visualization acts as a cognitive prosthetic for individuals who have difficulties constructing an adequate internal representation to perform a task. A third possibility is that external visualizations *augment* internal cognition. In this circumstance, the external visualization provides information or insights that are additional to those that can be inferred from internal visualizations.

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Chapter 3

3 Experiment 1 [†]

3.1 Introduction

Anatomy has always been regarded as an essential requirement in medical education (Drake et al., 2009). In anatomy courses, students not only learn anatomical terminology but also visuospatial information such as the size, three-dimensional (3-D) shape, orientation, and spatial location of structures in the body. When carrying out medical procedures, often the internal structures of the patient's body are not directly visible, so that medical professionals have to rely on internal or mental representations of visuospatial anatomical information.

Internal spatial visualization ability

Generally, learning visuospatial information is considered a visual process, involving visuospatial working memory (Miyake et al., 2001). Processing information in visuospatial working memory 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 spatial visualization ability (Vz), which refers to the ability to apprehend, encode, and mentally manipulate spatial forms in two- and three-dimensions (Carroll, 1993).

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Previous research studies have found Vz to be highly correlated with performance on a number of anatomy tasks, including practical anatomy tasks (Rochford, 1985; Lufler et al., 2012), functional anatomy tasks (Guillot et al., 2007), cross-sectional anatomy tasks (Cohen and Hegarty, 2007; Hegarty et al., 2009), and surgical tasks (Anastakis et al., 2000; Wanzel et al., 2002). Across all of these studies, individuals with high Vz performed significantly better than those with low Vz. While Vz has been shown to influence performance on a wide variety of anatomy tasks, its impact on visuospatial anatomy task performance has not been investigated.

External computer visualizations

Computer visualizations are increasingly common in education across a range of subject disciplines, including anatomy. The ability to communicate anatomical information visually has extended from static (or non-dynamic) to animated (or dynamic) representations, and from non-interactive to interactive displays (Khalil et al., 2005). Many benefits have been claimed for animations and interactive visualizations. These include the idea that animations are superior to static representations and that interactive visualizations are better than non-interactive displays (Scaife and Rogers, 1996). However, previous research comparing the instructional value of animations (versus static representations) and interactive visualizations (versus non-interactive displays) have failed to demonstrate an overall advantage for animations and interactive visualizations (Garg et al., 1999; Garg et al., 2001; Garg et al., 2002; Tversky et al., 2002; Keehner et al., 2008a; Luursema and Verwey, 2011). A striking finding from these studies is that benefits of animations and interactive visualizations vary according to learner's Vz. However, there are disagreements as to the aptitude-treatment interaction. For example, some studies found that animations augmented task performance of high Vz individuals more than low Vz individuals (Garg et al., 1999; Huk, 2006), while others showed that animations improved task performance of low Vz individuals more than high Vz individuals (Hoffler and Leutner, 2011). Finally, some studies established that animations did not improved task performance of high- or low-Vz individuals (Keedy et al., 2011).

Experiment 1 had two aims. The first was to determine whether spatial visualization ability (Vz) influences performance on a visuospatial anatomical task. The second was to determine whether the implementation of animation (compared to static representation) and interactive visualization (compared to non-interactive displays) are useful for low Vz individuals as opposed to high Vz individuals or whether the contrary is the case. We hypothesized that Vz will positively influence comprehension of visuospatial anatomical information – individuals with high Vz will perform better on a spatial anatomy task than those with low Vz. Next, we hypothesized that instruction with animations will augment the performance of high Vz individuals more than low Vz individuals. Finally, we hypothesized that instruction with interactive visualizations will augment the performance of low Vz individuals more than high Vz individuals.

3.2 Materials and methods

3.2.1 Participants

Sixty students, staff, and faculty (31 females; 29 males, 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. Participation in the study was completely voluntary and participants could opt out at any time during the course of the study.

3.2.2 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 (Figure 3.1, 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 (Figure 3.1, 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 3-D animations. Within Unity, six 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. The fourth, fifth, and sixth were similar to the first three, except participants were allowed active control over the presentation of information using the four arrow keys on the keyboard.

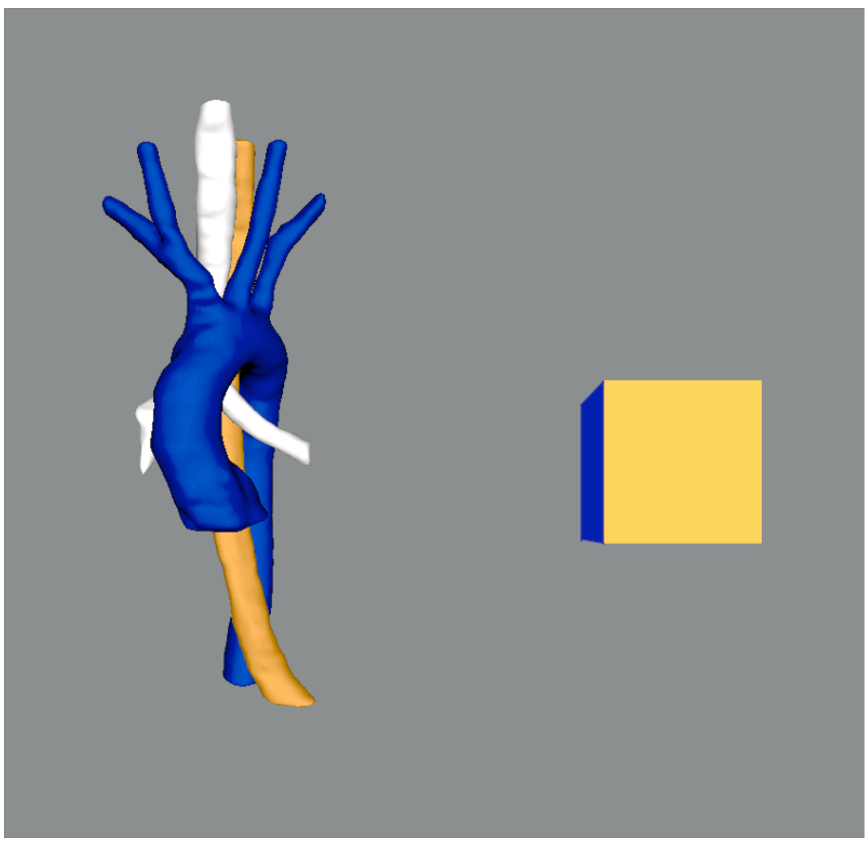

Figure 3.1: Screenshot of the anatomical and geometrical models. The anatomical model was reconstructed from cross-sectional images of a human male from the National Library of Medicine Visible Human Project (Spitzer et al., 1996).

3.2.3 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 consisted of 24 items. Each item was 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 seconds to complete as many questions and possible. A single credit was given if both correct stimuli were identified; zero credits otherwise. The maximum score a participant could get on the MRT was 24.

Spatial Anatomy Task (SAT). An electronic version of a novel task pertaining to the visuospatial properties of the anatomical model was developed to assess comprehension of visuospatial anatomical information. The task consisted of 30 multiple-choice questions - 10 involving the mental rotations of the anatomical model, 10 involving the identification of the model in 2D cross-sections, and 10 involving the localization of planes or levels corresponding to selected cross-sections. For each group of questions, participants were given 180 seconds to complete as many questions as possible. A countdown timer appearing on the top right-hand corner of the computer screen recorded the amount of time participants spent on the task. For the mental rotations questions, a single credit was given if both correct stimuli were identified. For the identification and localization task questions, a credit was given for each correct answer. The maximum score a participant could receive on the SAT is 30. The maximum time a participant could spend on the SAT is 540 seconds.

3.2.4 Study design

The research design is illustrated in Figure 3.2 and described below. The entire study took approximately 45 minutes to complete. Participants were tested individually. All participants completed two pre-tasks, a study phase, and a post-task.

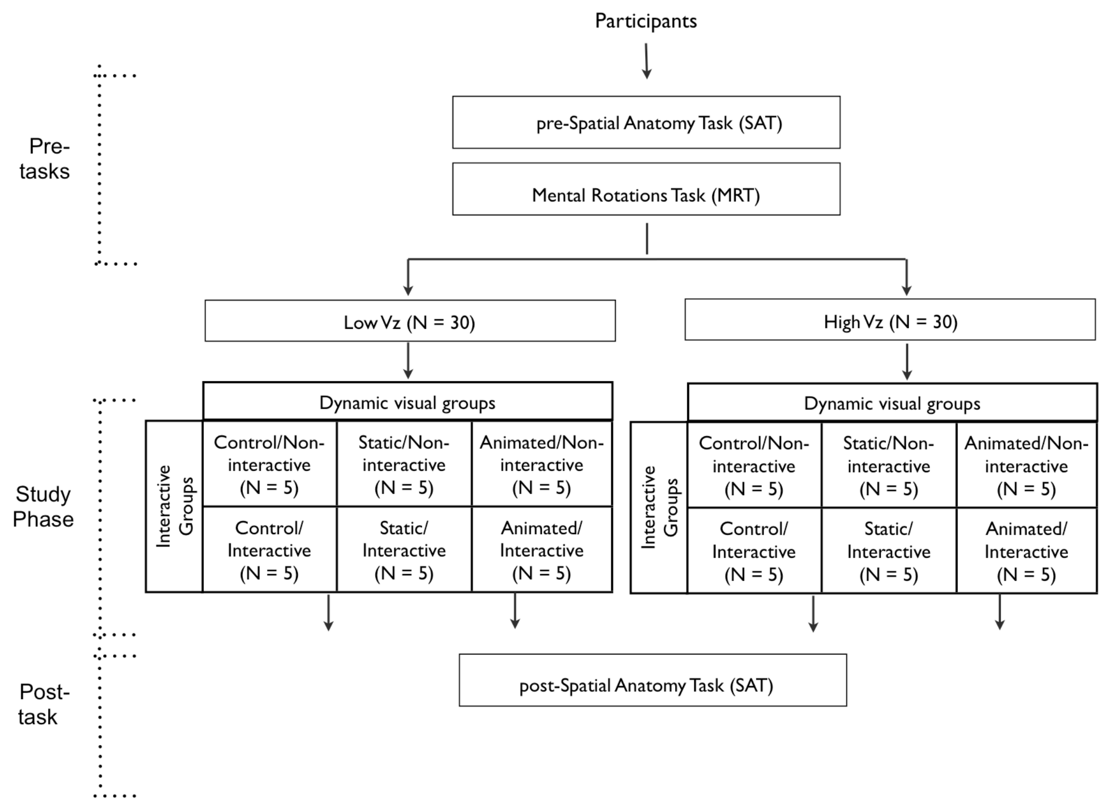

Figure 3.2: Flowchart illustrating the procedure for the study. All participants had to complete two pre-tasks (i.e., the mental rotations task and pre-spatial anatomy task), a study phase, and a post-task (i.e., the post- spatial anatomy task).

Pre-tasks. 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 spatial visualization ability groups – low Vz (N = 30, lower median group) or high Vz (N = 30, higher median group).

Study Phase. Participants in each spatial visualization ability group were randomly assigned to one of three dynamic visual groups – animated, static, or control, and then to one of two interactive groups – interactive or non-interactive. Participants in the animated group watched an animation 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 an animation of the 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 spatial anatomy task 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.

3.2.5 Data analyses

Descriptive statistics for the MRT, pre-SAT, and post-SAT were computed.

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.

Separate 2x3x2 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 time spent on the pre-SAT, respectively.

3.3 Results

Descriptive statistics for the MRT, pre-SAT, and post- SAT are presented in Table 3.1.

	MRT score	Pre-SAT score	Time spent on the pre-SAT (in seconds)	Post-SAT score	Time spent on the post-SAT (in seconds)
High Vz	14.03 ± 3.51	18.03 ± 4.87	467 ± 60.70	20.20 ± 4.91	412.60 ± 62.25
Low Vz	6.50 ± 2.30	12.04 ± 4.73	521 ± 26.42	16.73 ± 4.56	490.40 ± 48.22

Table 3.1: Descriptive statistics for the MRT, pre-SAT, and post-SAT for high Vz (N = 30) and low Vz (N = 30) subjects.

Figure 3.3 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 3.4 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, $r^2 = 0.45$, $p < 0.05$.

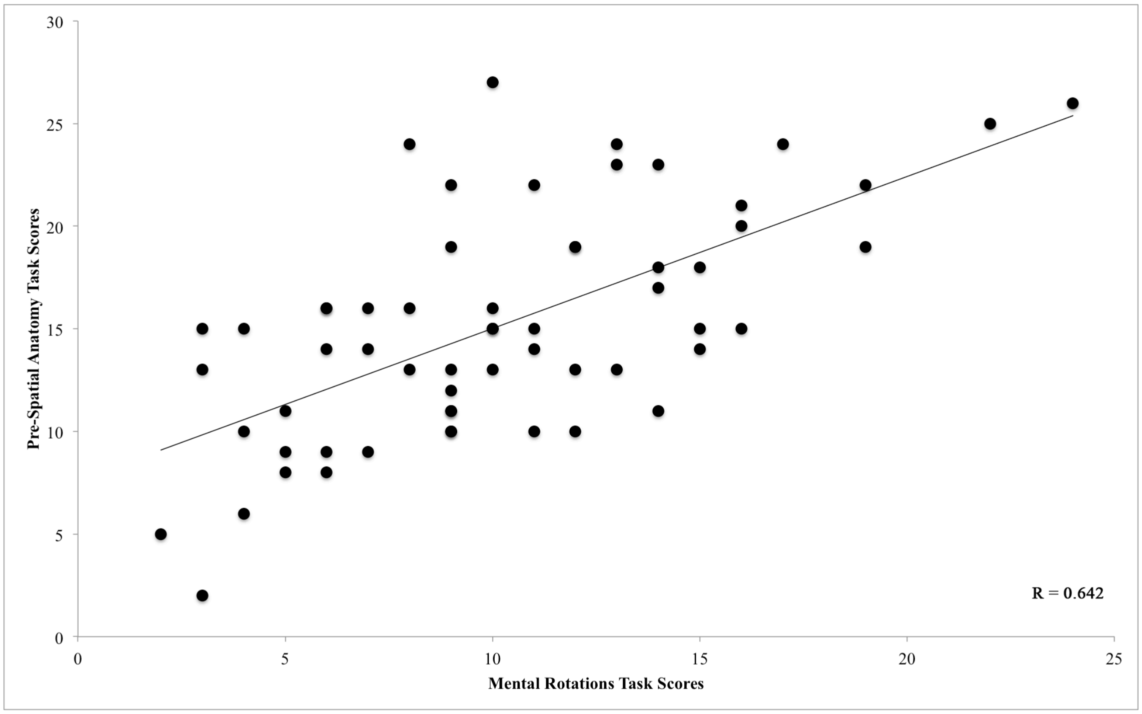

Figure 3.3: Scatter plot representing the relationship between pre-spatial anatomy task scores and mental rotations task scores. The correlation is positive (r = 0.64) and significant ($r^2 = 0.41$, $p < 0.05$).

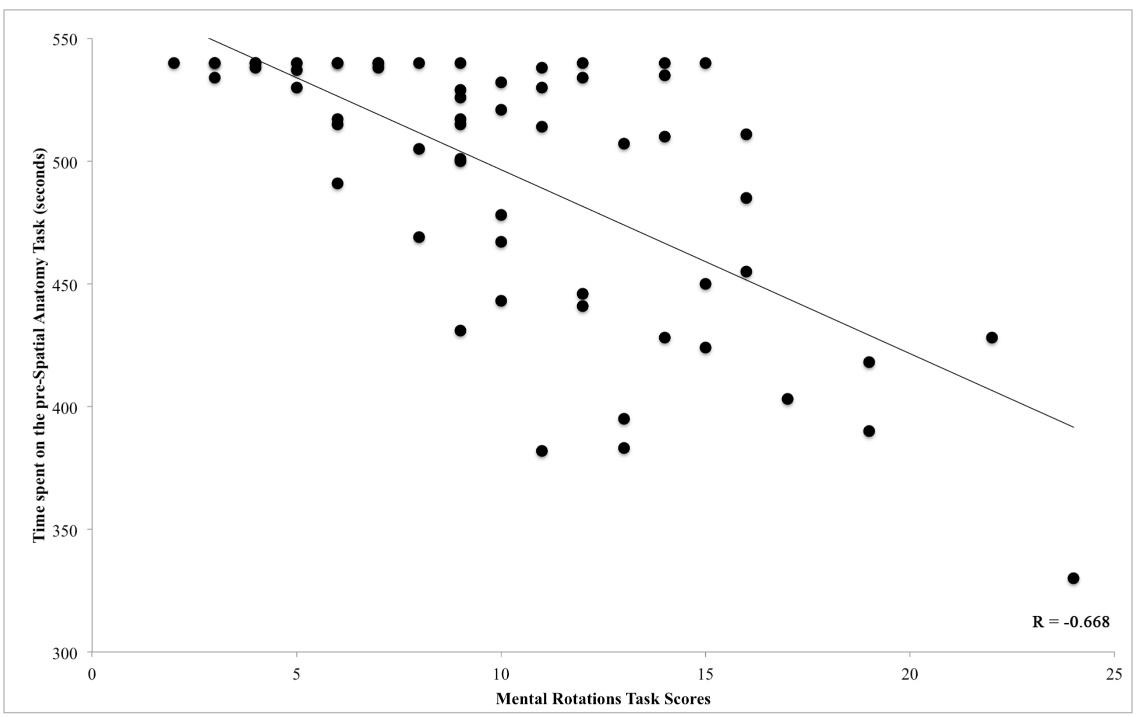

Figure 3.4: Scatter plot representing the relationship between time spent on the pre-spatial anatomy task (in seconds) and mental rotations task scores. The correlation is negative (r = - 0.67) and significant ($r^2 = 0.45$, $p < 0.05$).

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-Vz. 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 ($M = 467 \pm 60.70$) than those with low Vz ($M= 521 \pm 26.42$).

The F-statistics for the CRF analysis of post-SAT scores (with pre-SAT scores as a covariate) are listed in Table 3.2. The CRF analysis revealed a significant interaction effect between Vz and dynamism of the display.

Effect	F-statistics
Vz	$F(1, 48) = 0.273$, $p > 0.05$
Dynamism	$F(2, 48) = 0.279$, $p > 0.05$
Interactivity	$F(1, 48) =1.01$, $p > 0.05$
Vz x dynamism*	$F(2, 48) = 3.38$, $p < 0.05$
Vz x interactivity	$F(1, 48) = 0.905$, $p > 0.05$
Dynamism x interactivity	$F(2, 48) = 0.217$, $p > 0.05$
Vz x dynamism x interactivity	$F(2, 48) = 0.06$, $p > 0.05$

Table 3.2: F-statistics for CRF analysis of post-SAT scores (with mean pre-SAT score as a covariate).
*p < 0.05

Table 3.3 and Figure 3.5 show the mean post-SAT scores for all dynamism by Vz level combination. Following 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 ($M = 20.63 \pm 1.09$) than those with high Vz ($M = 16.91 \pm 1.10$). For the dynamic anatomical model, those with high Vz scored significantly higher on the post-SAT ($M = 18.55 \pm 1.08$) than those with low Vz ($M = 17.48 \pm 1.10$). For the static anatomical model, post-SAT scores were not significantly different for high Vz ($M = 19.14 \pm 1.10$) and low Vz ($M = 18.09 \pm 1.09$) individuals.

Spatial visualization ability (Vz)	Dynamism	Mean score ± standard error
High Vz	Control*	[a] 16.91 ± 1.10
	Static Anatomical Model	[a] 19.14 ± 1.10
	Dynamic Anatomical Model**	[a] 18.55 ± 1.08
Low Vz	Control*	[a] 20.63 ± 1.09
	Static Anatomical Model	[a] 18.09 ± 1.09
	Dynamic Anatomical Model**	[a] 17.48 ± 1.10

Table 3.3: Mean post-SAT scores for all dynamism by Vz level combination. Simple effect tests revealed significant differences in post-SAT score between high- and low-Vz participants viewing the static geometrical control model (*) and the dynamic anatomical model (**). [a] Covariates appearing in the model are evaluated at a mean pre-SAT score of 15.22

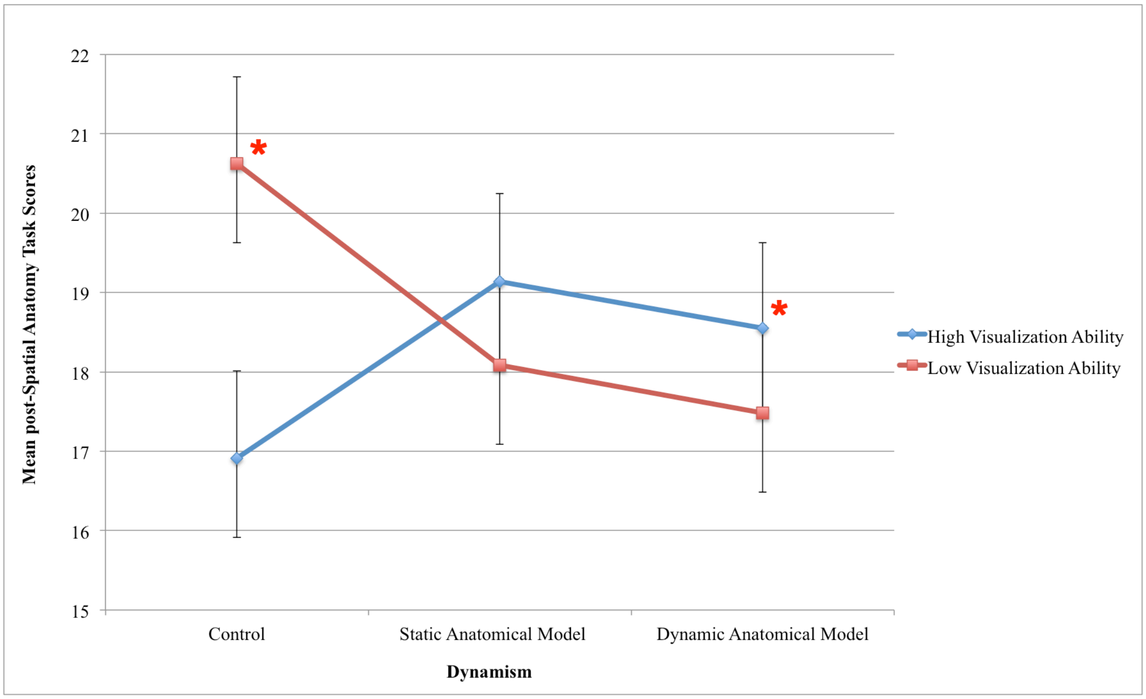

Figure 3.5: Profile plot of mean post-SAT scores as a function of dynamism of the visual display. The plot shows an interaction between Vz and dynamism of the visual display. The two lines represent the high and low-Vz groups. The crossing of the lines indicates an interaction effect. Simple effect tests revealed significant differences in post-SAT score between high- and low-Vz participants viewing the static geometrical control model (*) and the dynamic anatomical model (**).

The F-statistics for the CRF analysis of time spent on the post-SAT (with time spent on the pre-SAT scores as a covariate) are listed in Table 3.4. The CRF analysis revealed a significant interaction effect between Vz and dynamism of the display.

Effect	F-statistics
Vz*	$F(1, 48) = 6.59, p < 0.05$
Dynamism	$F(2, 48) = 1.15, p > 0.05$
Interactivity	$F(1, 48) = 2.66, p > 0.05$
Vz x dynamism	$F(2, 48) = 1.26, p > 0.05$
Vz x interactivity	$F(1, 48) = 1.78, p > 0.05$
Dynamism x interactivity	$F(2, 48) = 0.78, p > 0.05$
Vz x dynamism x interactivity	$F(2, 48) = 1.23, p > 0.05$

Table 3.4: F-statistics for the CRF analysis of time spent on the post-SAT (with time spent on the pre-SAT scores as a covariate).
*$p<0.05$

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. Table 3.5 and Figure 3.6 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.

Spatial visualization ability (Vz)	Dynamism	Mean time (seconds) ± standard error
High Vz	Control	[a] 430.49 ± 17.86
	Static Anatomical Model	[a] 426.24 ± 16.99
	Dynamic Anatomical Model	[a] 438.36 ± 16.66
Low Vz	Control	[a] 441.12 ± 17.18
	Static Anatomical Model	[a] 492.24 ± 17.28
	Dynamic Anatomical Model	[a] 478.46 ± 16.84

Table 3.5: Mean time spent on the post-SAT for all dynamism by Vz level combination.
[a] Covariates appearing in the model are evaluated at a mean pre-SAT time of 494.52 seconds.

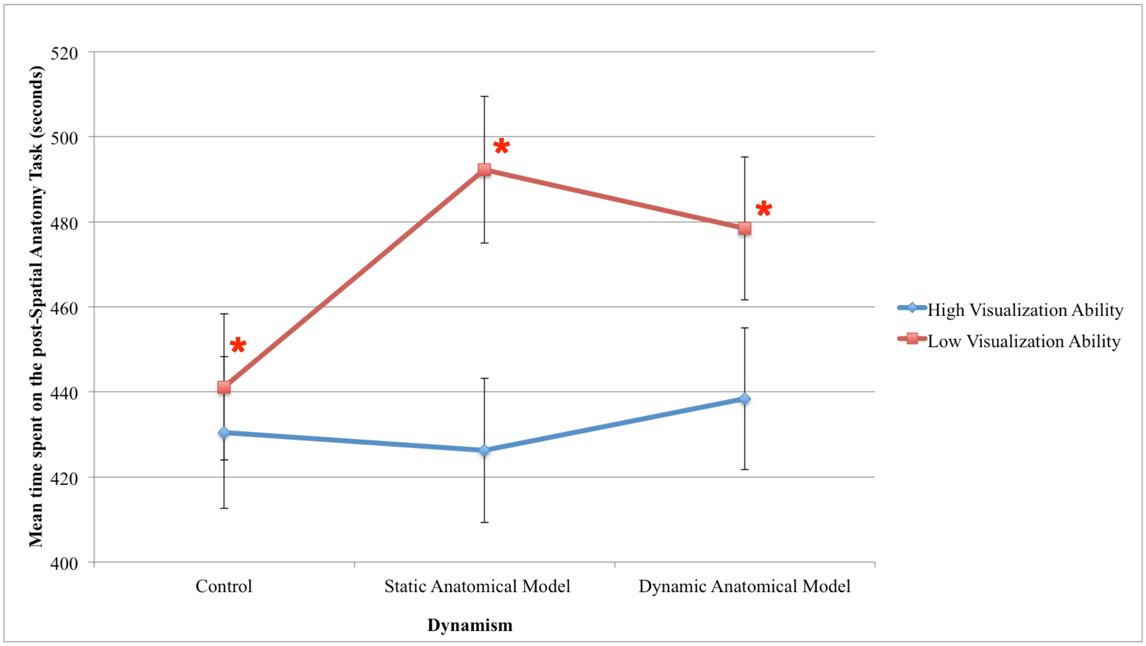

Figure 3.6: Profile plot of mean times spent on the post-SAT as a function of dynamism of the visual display. The plot shows a main effect of Vz on the amount of time spent on the post-spatial anatomy task. The two lines depict the high and low Vz groups. The parallel lines indicate no interaction effect. Participants with high Vz spent less time on the post- SAT than those with low Vz.

3.4 Discussion

Recall, experiment 1 had two aims. The first was to determine the role that spatial visualization ability (Vz) plays in comprehending visuospatial anatomical information. The second was to determine whether the implementation of animation (compared to static representation) and interactive visualization (compared to non-interactive displays) are useful for low Vz individuals as opposed to high Vz individuals or whether the contrary is the case.

Effects of spatial 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 experiment 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 SAT. 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 SAT 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, animation of the anatomical model particularly benefited individuals with high Vz, as their mean score on the performance task was significantly higher than those with low Vz. 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 animation.

While the animation of the anatomical model had a greater facilitating effect on the performance of high Vz individuals, static representations of the geometrical model had a greater facilitating effect on the performance of low Vz learners. This result was not expected, as the geometric cube model was irrelevant and unrelated to the items on the spatial anatomy task (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 and colleagues 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. Another possible factor is how participants interact with the visualization. Some authors suggest that spatial anatomical information is not remembered in 3-D, but rather in specific 2-D cardinal views, and that unfamiliar orientations are recognized by mental rotation of these 2-D 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 and future directions

We 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 spatial anatomy task. 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 spatial anatomy task 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 animated 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 (x, y, and z) 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 study 60 participants were assigned to 12 groups, resulting in only 5 participants in each experimental group. Such an increase in sample size would enhance the ability to generalize our results.

3.5 Summary

Experiment 1 demonstrated that spatial visualization ability (Vz) positively influences performance on the spatial anatomy task (SAT). Individuals with high Vz scored higher and spent less time on the SAT than those with low Vz. Experiment 1 also demonstrated that the effects of Vz on SAT performance could be modulated through instruction with different computer visualizations. Static representations of the anatomical model switching between the six canonical views improved SAT scores of high- and low-Vz subjects equally. Animation of the anatomical model rotating in virtual space augmented SAT scores of high Vz subjects more than low Vz subjects. Interactive and non-interactive visualizations enhanced SAT scores of high- and low-Vz subjects equally.

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Chapter 4

4 Experiment 2

4.1 Introduction

All medical professions depend on a comprehensive knowledge of human anatomy, which includes visuospatial concepts such as the shape of anatomical structures, their position in 3-D space, and their location relative to other structures (Marks, 2000; Hegarty et al., 2007). Learning visuospatial information is considered a visual process, involving the visuospatial working memory (Clark and Paivio, 1991; Baddeley, 1992; Mayer and Sims, 1994; Miyake et al., 2001). Processing information in visuospatial working memory is strongly influenced by spatial ability (Miyake et al., 2001). Spatial ability refers to an individual's ability 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' (Carroll, 1993). In other words, an internal representation of a perceived object or scene must be created and maintained in such a way that mental manipulations are possible.

As the acts of creating, maintaining, and manipulating internal representations all require different but important abilities, several sub-factors of spatial ability have been identified and together they form the broad concept of spatial ability. These sub-factors include: spatial visualization (Vz), spatial relations (SR), closure speed (CS), closure flexibility (CF), and perceptual speed (P) (Carroll, 1993). Although there are several sub-factors of spatial ability, the one that has been shown to be most relevant to anatomy education is spatial visualization ability (Vz). Spatial visualization ability (Vz) has been shown to influence success in anatomy and proficiency in anatomically demanding fields such as surgery and radiology. Rochford (1985) found positive correlations between Vz and achievement among medical students at the University of Cape Town. High Vz students achieved consistently higher marks than low Vz students on both practical anatomy examinations and multiple-choice anatomy questions classified as being spatially three-dimensional. Lufler et al. (2012) found similar results when assessing medical students at Boston University School of Medicine. More recently, Nguyen et al. (2012) demonstrated that Vz made significant contributions to performance on a novel spatial anatomy task that required mental manipulations in two- and three-dimensions. High Vz subjects not only scored higher on the anatomy task but they also spent less time on the task than low Vz subjects. Findings such as these suggest that there is a strong spatial component to the way anatomical information is mentally represented. It also implies that low Vz individuals may have greater difficulty acquiring, representing, and manipulating mental representations of anatomy.

While the positive influence of Vz on anatomy task performance is known, the causes are less well understood. Anecdotal evidence suggests that differences in task performance may be due to strategic differences in the way high- and low-Vz learners approach perceptual and transformation processes such as: (a) *sectioning*, visualizing a given section through an object, (b) *translating*, perceiving the apparent changes in the shape of an object when it is rotated in three-dimensions, (c) *rotating*, retaining in imagination the relative positions of the structures of a given body undergoing rotations in space, and (d) *visualizing,* synthesizing mentally the orthogonal sections of a given object to form an image of the whole (Rochford, 1985). However, to the best of our knowledge, no investigators have empirically tested the idea that individuals with differing Vz approach visual problems differently.

The purpose of experiment 2 was to examine the problem solving strategies of learners in order to determine whether differences in perceptual and transformation strategies between high- and low-Vz subjects contribute to spatial anatomy comprehension. Owing to the complex visual nature of the spatial anatomy tasks, we hypothesized that high Vz subjects will adopt more flexible and more efficient problem solving strategies that will lead to better performance (i.e., higher scores, less amount of time spent the task, and lower susceptibility to errors) than low Vz subjects. The results of this study provide further insights into the processing commonalities and differences among learners beyond the classification of Vz, and help elucidate what, if anything, high- and low-Vz learners do differently while approaching spatial anatomy task problems.

4.2 Material and methods

4.2.1 Participants

Forty-two students from The University of Western Ontario participated in the study (Female = 24; Male = 18; Mean age = 25.38 ± 5.86 years). This study was granted ethics approval by The Research Ethics Board at The University of Western Ontario. There were no exclusion criteria for this study. Participation in the study was completely voluntary and students could opt out at any time during the course of the study.

4.2.2 Performance measures

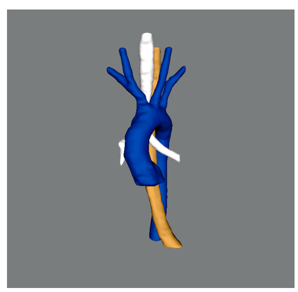
Mental Rotations Task (MRT). The MRT (Vandenberg and Kuse, 1978; Peters et al., 1995) was used to assess participants' Vz. The task involved mentally rotating three-dimensional block figures. The test consisted of 24 items. Each item was made up of one target figure and four option figures (two were rotated images of the target and two were distractors). Participants had to determine as quickly and accurately as possible which two of the four option figures were rotations of the target figure. Participants were given 360 seconds to complete as many questions as possible. A credit was given if both correct stimuli were identified. The maximum score a participant could receive on the MRT was 24.

Spatial Anatomy Task (SAT). The same spatial anatomy task used in experiment 1 was used again in experiment 2 to assess comprehension of visuospatial anatomical information. The task consisted of 30 multiple-choice questions - 10 involving the mental rotations of the anatomical structures, 10 involving the identification of the structures in two-dimensional cross-sections, and 10 involving the localization of planes corresponding to selected cross-sections. For each group of questions, participants were given 120 seconds to complete as many questions as possible. A countdown timer appearing on the top right-hand corner of the computer screen recorded the amount of time participants spent on the task. For the mental rotations questions, a single credit was given if both correct stimuli were identified. For the identification and localization task questions, a credit was given for each correct answer. The maximum score a participant could receive on the SAT was 30. The maximum time a participant could spend on the SAT was 360 seconds.

Self-reflective questionnaire. A 22-item questionnaire was used to collect general information about how participants approach answering the SAT questions, including strategies used during mental transformation as well as strategies used while answering the questions. The questionnaire consisted of 21 multiple-choice questions and one opened-ended question (i.e., question 2). The questions were based on previous pilot testing of students to determine common language and approaches used while answering the SAT. Example items from the self-reflective questionnaire are provided below.

Q1. When answering the **mental rotations task** questions:
a. I imagined rotating all 3 tubes in my mind when making the comparison
b. I imagined rotating 2 of the 3 tubes in my mind when making the comparison
c. I imagined rotating 1 of the 3 tubes in my mind when making the comparison
d. I imagined rotating part(s) of 1 or more tube(s) when making the comparison (e.g., the curvature of the blue tube, or the 'Y' shape branch coming off the blue tube)
e. Other (explain)____

Q2. Please explain or mark on the image below which tube(s) or tube feature(s) you used when making the comparison.



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Q16. When answering the **identification task** questions:
a. I was more concerned with getting the right answers than I was about the time limit
b. I was more concerned with getting all the answers completed than I was about getting the correct answers
c. I did not care how I did it
d. Other (explain)____

Q20. When answering the **localization task** questions:
a. I used movements of my body (e.g., finger, head, hand) and/or pencil to help me with the task
b. I did not use movements of my body (e.g., finger, head, hand) and/or pencil to help me with the task
c. Other (explain)____

4.2.3 Study design

Participants were tested on an individual basis at a computer in a quiet laboratory setting. All participants completed the MRT as a baseline measure of Vz, and then the SAT and self-reflective questionnaire. Matlab (The MathWorks, Natick, MA, USA) was used for implementation of the MRT and SAT. Participants' responses to individual items on MRT and SAT were automatically recorded. The amount of time (in seconds) spent on the SAT was also recorded. Upon completion of the MRT and SAT, all participants completed a pencil and paper version of the self-reflective questionnaire.

4.2.4 Data analyses

Separate Pearson's correlation analyses were used to assess the relationship between MRT scores and the three measures of SAT performance – scores, time spent on the task, and accuracy of responses. "Accuracy" is operationalized here as the number of SAT questions solved correctly divided by the number of questions attempted. For example, if a participant attempted 6 questions and received 3 correct then the accuracy for this participant was 0.5 or 50%.

Based on the obtained MRT scores, participants were allocated to one of two spatial visualization ability (Vz) groups – low Vz (N = 21, lower median group) or high Vz (N = 21, higher median group). Subsequently, separate t-test analyses were used to determine whether SAT scores, time spent on the SAT, and accuracy of SAT responses were significantly different for high and low Vz subjects. Bonferroni corrections were performed to counter the effects of multiple t-tests.

Responses to the self-reflective questionnaire (i.e., all questions except question 2) were examined and multiple-choice questions with more than two option choices were pooled to produce two response categories. For example, question 1 had the following five option choices before pooling (i.e., options a, b, c, d, and e). After pooling options b', 'c', 'd', and 'e' into a single category, question 1 had the following two option choices:

Q1. When answering the **mental rotations task** questions:
a. I imagined rotating the entire tube figure in my mind when making the comparison
b. I imagined rotating part of the tube figure in my mind when making the comparison

Subsequently, separate chi-square (χ^2) tests were used to determine whether responses to any of the pooled items on the self-reflective questionnaire were significantly different for high- and low Vz-subjects. The χ^2 tests were carried out twice –with and without Bonferroni corrections. Without Bonferroni corrections, a p-value of less than 0.05 was considered significant. With Bonferroni corrections, a p-value of less than 0.0024 (= 0.05 divided by 21 comparisons) was considered significant. Yate's (continuity) corrections were used when the expected frequency of a cell was too small (i.e., less than 5) in order to reduce the chances of a type 1 error (i.e., rejecting the null hypothesis when it is true).

Finally, responses to question 2 on the self-reflective questionnaire were examined qualitatively in order to determine which feature(s) of the anatomical model was used to assist with the mental rotations.

4.3 Results

Descriptive statistics for the MRT and SAT are presented in Table 4.1.

	MRT score	SAT score	Time spent on the SAT (in seconds)	Accuracy of SAT responses
High Vz	16.69 ± 4.33	18.48 ± 5.22	312.71 ± 41.66	0.74 ± 0.15
Low Vz	7.48 ± 2.87	12.67 ± 4.75	342.07 ± 26.29	0.61 ± 0.15

Table 4.1: Descriptive statistics for the MRT and SAT for high Vz (N = 21) and low Vz (N = 21) subjects.

Correlations between MRT scores and the three measures of SAT performance are presented in Table 4.2. The analyses revealed a significant positive correlation between MRT scores and SAT scores, a significant negative correlation between MRT scores and time spent on the SAT, and a significant positive correlation between MRT scores and accuracy of SAT responses.

	SAT scores	Time spent on the SAT (seconds)	Accuracy of SAT responses
Mental rotations task (MRT) scores	0.72*	- 0.70*	0.52*

Table 4.2: Correlations between mental rotations task (MRT) scores and SAT scores, amount of time spent on the SAT, and accuracy of SAT responses.
* $p < 0.05$

T-test analyses revealed significant differences on SAT scores, $t\ (40) = -3.77$, $p < 0.05$, length of time spent on the SAT, $t\ (40) = 2.73$, $p < 0.05$, and accuracy of SAT responses, $t\ (40) = -2.86$, $p < 0.05$, for high- and low-Vz subjects. High Vz subjects scored significantly higher, spent significantly less time, and were more accurate than low Vz subjects.

The numbers of responses for each answer option as selected by high- and low-Vz subjects for each multiple-choice question posed on the self-reflective questionnaire are presented in Table 4.3. Before correcting for multiple comparisons, χ^2 tests revealed an overall ability difference for question 5, $\chi^2(1)= 6.46$, $p < 0.05$, and question 16, $\chi^2\ (1)= 4.86$, $p < 0.05$. For question 5, significantly more of the low Vz than high Vz subjects reported using movements of body parts and/or surrounding objects while solving the SAT problems. For question 16, significantly more of the low Vz subjects than high Vz subjects stated they were more concerned about time; that is finishing all task questions, than they were about answering the questions correctly. After correcting for multiple comparisons, χ^2 tests revealed no ability differences for any of the questions posed.

When answering the mental rotations task questions:		High Vz subjects (N=21)	Low Vz subjects (N=21)
Q1	a. I imagined rotating the entire tube figure in my head when making the comparison	12	13
	b. I imagined rotating part of the tube figure in my head when making the comparison	9	8
Q3	a. I imagined rotating the tubes	20	16
	b. I imagined rotating myself	1	5
Q4	a. I thought through the steps verbally in my mind (e.g., "rotate tube to the right then up")	2	7
	b. I relied mainly on visualizing the figures and did not talk to myself through the steps	19	14
Q5 *	a. I used movements of my body (e.g., finger, head, hand) and/or objects around me to help me with the task	4	12
	b. I did not use movements of my body (e.g., finger, head, hand) and/or objects around me to help me with the task	17	9
Q6	a. I scanned the option figures systematically (e.g., trying the first, then the second, etc.)	17	16
	b. I scanned the option figures in a haphazard non-systematic way	4	5
Q7	a. I always compared the option figures to the target figure	9	9
	b. I did not always compare the option figures to the target figure (e.g., Once I found a match I compared the rest of the option figure to the match instead of the target)	12	12
Q8	a. I developed a specific approach to solving the questions	12	10
	b. I had no specific approach and tried a number of different approaches	9	11
Q9	a. I was more concerned with getting the right answer than I was about the time limit	19	16
	b. I was more concerned about the time limit than I was about getting the correct answers	2	5
When answering the identification questions:		**High Vz subjects (N=21)**	**Low Vz subjects (N=21)**
Q10	a. I performed the initial mental manipulation (e.g. slice, rotate, etc.) on the intact tube figure	20	19
	b. I performed the initial mental manipulation (e.g. slice, rotate, etc.) on a cross-section	1	2
Q11	a. I imagined rotating the tubes	19	15
	b. I imagined rotating myself	2	6
Q12	a. I scanned the cross-sections systematically (e.g., trying the first, then the second, etc.)	20	20

	b. I scanned the cross-sections in a haphazard non-systematic way	1	1
Q13	a. I thought through the steps verbally in my mind (e.g., “slice then rotate”)	5	6
	b. I relied mainly on visualizing the images and did not talk myself through the steps	16	15
Q14	a. I used movements of my body (e.g., finger, head, hand) and/or objects around me to help me with the task	5	9
	b. I did not use movements of my body (e.g., finger, head, hand) and/or objects around me to help me with the task	16	12
Q15	a. I developed a specific approach to solving the questions	18	13
	b. I had no specific approach and tried a number of different approaches	3	8
Q16 *	a. I was more concerned with getting the right answer than I was about the time limit	21	15
	b. I was more concerned about the time limit than I was about getting the correct answers	0	6
When answering the localization questions:		High Vz subjects (N = 21)	Low Vz subjects (N = 21)
Q17	a. I performed the initial mental manipulation (e.g. slice, rotate, etc) on the intact tube figure	4	5
	b. I performed the initial mental manipulation (e.g. slice, rotate, etc.) on a cross-section	17	16
Q18	a. I thought through the steps verbally in my mind (e.g., “slice then rotate”)	4	6
	b. I relied mainly on visualizing the images and did not talk myself through the steps	17	15
Q19	a. I scanned the horizontal/vertical lines systematically (e.g., trying the first, then the second, etc.)	20	16
	b. I scanned the horizontal/vertical lines in a haphazard non-systematic way	1	5
Q20	a. I used movements of my body (e.g., finger, head, hand) and/or objects around me to help me with the task	2	7
	b. I did not use movements of my body (e.g., finger, head, hand) and/or objects around me to help me with the task	19	14
Q21	a. I developed a specific approach to solving the questions	19	14
	b. I had no specific approach and tried a number of different approaches	2	7
Q22	a. I was more concerned with getting the right answer than I was about the time limit	21	17
	b. I was more concerned about the time limit than I was about getting the correct answers	0	4

Table 4.3: Responses for each answer option as selected by high- and low-Vz subject for each multiple-choice question posed in the self-reflective questionnaire.
* $p<0.05$ without correcting for multiple comparisons

Question 2 revealed that participants relied on distinguishing features of the anatomical figure to assist with the mental rotation task problems. Specifically, they were attentive to the curvature of the blue tube (i.e., the arch of the aorta), the three branches arising from the curvature (i.e., the brachiocephalic, common carotid, and subclavian arteries), the branching of the white tube (i.e., bifurcation of the trachea), the thickness of the terminal ends of the white tube (the primary bronchi), and/or the relative position of the orange and blue tubes (i.e., relation between the esophagus and descending aorta).

4.4 Discussion

The purpose of experiment 2 was to examine the problem solving strategies of learners in order to determine whether differences in strategies between high- and low-Vz subjects contribute to differences in spatial anatomy comprehension. Because the anatomy task used to measure visuospatial anatomy comprehension involved complex manipulations in two- and three-dimensions, it is amenable to a range of strategies. Therefore, we predicted that differences in strategic approach to particular questions on the SAT would be another important source of individual differences in SAT performance. Strategy reports established that there were in fact a number of different ways subjects approached answering the SAT questions. However, χ^2 analyses (with Bonferroni corrections) of the multiple-choice questions revealed that differences in problem solving strategies did not contribute to individual differences in SAT performance. Therefore, in the absence of instructional aids, Vz is the main source of variation in SAT performance.

Consistent with experiment 1, experiment 2 demonstrated that Vz positively influenced SAT performance. High Vz subjects scored significantly higher and spent significantly less time on the anatomy task than their low Vz counterparts. In addition to scores and amount of time spent on the SAT, we included accuracy of response (or proportion correct) as a third measure of performance. Accuracy data revealed that high Vz subjects solved more of the attempted questions correctly than low Vz subjects.

Although chi-square analyses with Bonferroni corrections revealed no significant differences in the problem solving strategies between high- and low-Vz subjects, chi-square analyses without Bonferroni corrections did provide some interesting trends. First, low Vz subjects were more likely to use movements of body parts and/or surrounding objects while solving the mental rotations problems. Second, low Vz subjects were more concerned about time, that is finishing all task questions, than they were about answering the identification questions correctly. The tendency for low Vz subjects to offload cognitive work onto external perceptual-motor processes suggests that they may have difficulties with storage or transformation of mental representations, which may contribute to their poor task performance. Furthermore, low Vz subjects may be more prone to errors while performing the anatomy task, as suggested by their tendency to focus on the quantity, rather than the quality, of their answers. Further studies with large sample sizes are needed to determine whether these strategies actually contribute to differences in task performance.

Limitations and future directions

We recognize that experiment 2 has some limitations. First, after correcting for multiple chi-square test analyses, a p-value of less than 0.002 (= 0.05 divided by 21 comparisons) was needed to detect a significant difference. As a result, the chances of finding a difference on any of the multiple choice questions posed on the self-reflective questionnaire was extremely low, especially with such the small sample size (i.e., N = 42). Future studies are warranted to decrease the number of questions posed on the self-reflective questionnaire and/or increase the sample size in order to enhance the ability to detect strategy differences between high- and low-Vz individuals. Future studies are also warranted to increase the sample size. With a larger sample size, it is possible to partition subjects into three Vz groups (high, intermediate, and low) and then removing the intermediate group in order to achieve a larger spread between individuals of high- and low-Vz. Such an approach should increase the chance of finding strategy differences between high and Vz individuals.

4.5 Summary

Experiment 2 demonstrated that Vz influences performance on the SAT. In addition to scoring higher and spending less time on the task, high Vz subjects also solved more of the attempted questions correctly than their low Vz counterparts. Although there were differences in the ways subjects approached answering the SAT, these differences did not contribute to the variations observed in SAT performance. Therefore, in the absence of instructional aids, Vz is the main contributor of variations in SAT performance.

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Chapter 5

5 Experiment 3

5.1 Introduction

Stereoscopic displays have found their way into wide variety medical fields including anatomy teaching and training, diagnosis, preoperative planning, and minimally invasive surgery (Beurden et al., 2009). Although there is substantial evidence that stereoscopic displays benefits the execution of surgical tasks (Peitgen et al., 1996; Falk et al., 2001; Byrn et al., 2007), there is limited evidence that they facilitate the acquisition of visuospatial anatomical knowledge. The purpose of experiment 3 was to examine the role of computer-implemented stereopsis in comprehending visuospatial anatomical information.

Experiment 1 demonstrated that the effects of spatial visualization ability (Vz) on spatial anatomy task performance could be modulated by instruction with different computer visualizations. While static representations of the aorta, trachea, and esophagus augmented the SAT scores of high- and low- Vz subjects equally, animations of these structures rotating in virtual space enhanced the performance of high Vz subjects more than low Vz subjects.

Both the static representation and animation used in experiment 1 relied on monocular depth cues for inferring the visuospatial information of anatomy. These cues require the visual input of one eye and are generally broken down into two categories depending on whether they are present in a static picture (called pictorial cues) or a dynamic picture (called motion cues) (Schwartz, 2010). Pictorial cues include relative size, familiar size, linear perspective, texture, interposition, light, shading, and shadow, while motion cues include motion parallax. The perception of depth from monocular cues is based on the concept that the size of the retinal image of an object is proportional to the object's size and inversely proportional to the distance of the object (Schwartz, 2010). Hence, an object that casts a smaller retinal image is perceived as being farther away than an object that casts a larger retinal image.

While the visuospatial information of anatomy was noted monocularly in experiment 1, it is generally enhanced when viewed binocularly, especially at near distances. On average, the human eyes are separated by approximately 6.4 cm in the horizontal direction (Ware, 2004). Due to this separation, the two eyes receive slightly different images of world and the brain uses the disparity between these images to recover information about relative depth and distance of objects in the visual world (Steinman et al., 2000). This process is called stereopsis and its sole basis is the horizontal disparity between the two retinal images (Poggio and Poggio, 1984). While stereopsis occurs naturally in animals with overlapping visual fields (Ware, 2004), the effect can be achieved using a standard computer monitor with a high refresh rate (100 Hz or better) coupled with stereo-glasses (Bowman et al., 2005). The monitor is used to display the disparate images (one for each eye) while the stereo glasses are used to filter the screen images so that each eye receives only one screen image.

Stereo glasses can either be active or passive (Bowman et al., 2005) in their approach to keeping left and right eye visual input separate. Active (or shutter) stereo glasses are synchronized to open and close their shutters to match the images generated on the screen. Passive stereo glasses are based on polarization or spectral multiplexing. Polarization multiplexing filters the overlaid images with polarized filters that run in opposite directions (e.g., one filter could be horizontally polarized while the other vertically polarized). Spectral multiplexing (or anaglyph stereo) displays the two overlaid images in two different colours (e.g., blue and red). The coloured filters are used so that light from any colour other than the filter's colour is washed out. Although active stereo produces the highest stereo quality, it is expensive and requires synchronization between the glasses and the images generated on the monitor. Passive stereo is relatively inexpensive but colour polarization reduces the overall quality of the images.

The purpose of experiment 3 was to examine the role of computer-implemented stereopsis in spatial anatomy comprehension. Since the additional depth cues incorporated in stereoscopic displays better communicate the visuospatial properties of anatomical structures, we hypothesized that stereoscopic displays will augment spatial anatomy task performance. The resolution of this question has important implications for the way anatomical information is best presented in learning situations. Furthermore, it provides a rational basis for discussing and implementing stereoscopic displays in anatomy courses.

5.2 Materials and methods

5.2.1 Participants

A total of 40 undergraduate and graduate students from The University of Western Ontario participated in the study (Female = 22, Males = 18; Mean age = 25.45 ± 6.0 years). Participants were selected from a pool of 42 potential participants on the basis of their stereoscopic vision (see below). This study was granted ethics approval by The Research Ethics Board at The University of Western Ontario. Participation in the study was voluntary and students could opt out at any time during the course of the study.

5.2.2 Instructional materials

The object of instruction used in experiment 3 was the same as that used in experiments 1. The object is a computer-generated representation of the aorta, trachea, and esophagus. Four separate computer files were developed to show the visuospatial properties of the anatomical structures. The first was an animation of the anatomical structures rotating continuously in the x-, y-, and z-axes. The second showed static representations of the anatomical structures switching between the six canonical orientations. The third and fourth were similar to the first two files except anaglyph stereo was implemented and red-cyan stereo glasses were needed to view the content.

5.2.3 Performance measures

Stereovision Test. The Stereo Butterfly Test (Stereo Optical Co., Inc., Chicago, IL) was used to assess participants' stereopsis. The test was presented with the use of polarized glasses at approximately 16-inch testing distance. Participants were asked to examine a random dot pattern without the help of any monocular depth cues. Intact stereopsis was recorded if the participant reported seeing a butterfly. Participants who did not have intact stereopsis were excluded from the study.

Mental Rotations Task (MRT). The MRT (Vandenberg and Kuse, 1978; Peters et al., 1995) was used to assess participants' Vz. The task involves mentally rotating three-dimensional block figures. The test consisted of 24 items. Each item was made up of one target figure and four option figures (two are rotated images of the target and two are distractors). Participants had to determine as quickly and accurately as possible which two of the four option figures were rotations of the target figure. Participants were given 360 seconds to complete as many questions as possible. A credit was given if both correct stimuli were identified. The maximum score a participant could receive on the MRT was 24.

Spatial Anatomy Task (SAT). The same anatomy task used to assess spatial anatomical comprehension in experiments 1 and 2 was used again in the present study. The task consisted of 30 multiple-choice questions - 10 involving the mental rotations of the anatomical structures, 10 involving the identification of the structures in two-dimensional cross-sections, and 10 involving the localization of planes corresponding to selected cross-sections. For each group of questions, participants were given 120 seconds to complete as many questions as possible. A countdown timer appearing on the top right-hand corner of the computer screen recorded the amount of time participants spent on the task. For the mental rotations questions, a single credit was given if both correct stimuli were identified. For the identification and localization task questions, a credit was given for each correct answer. The maximum score a participant could receive on the SAT was 30. The maximum time a participant could spend on the SAT was 360 seconds.

5.2.4 Study design

The research design is illustrated in Figure 5.1 and described below. The entire study took approximately 30 minutes to complete. Participants were tested on an individual basis at a computer in a quiet laboratory setting. All participants completed three pre-tasks, a study phase, and a post-task (see below for details). Matlab (The MathWorks, Natick, MA, USA) was used for implementation of all phases of the study. Participants' responses to individual items on MRT and SAT were automatically recorded. The amount of time (in seconds) spent on the SAT was also recorded.

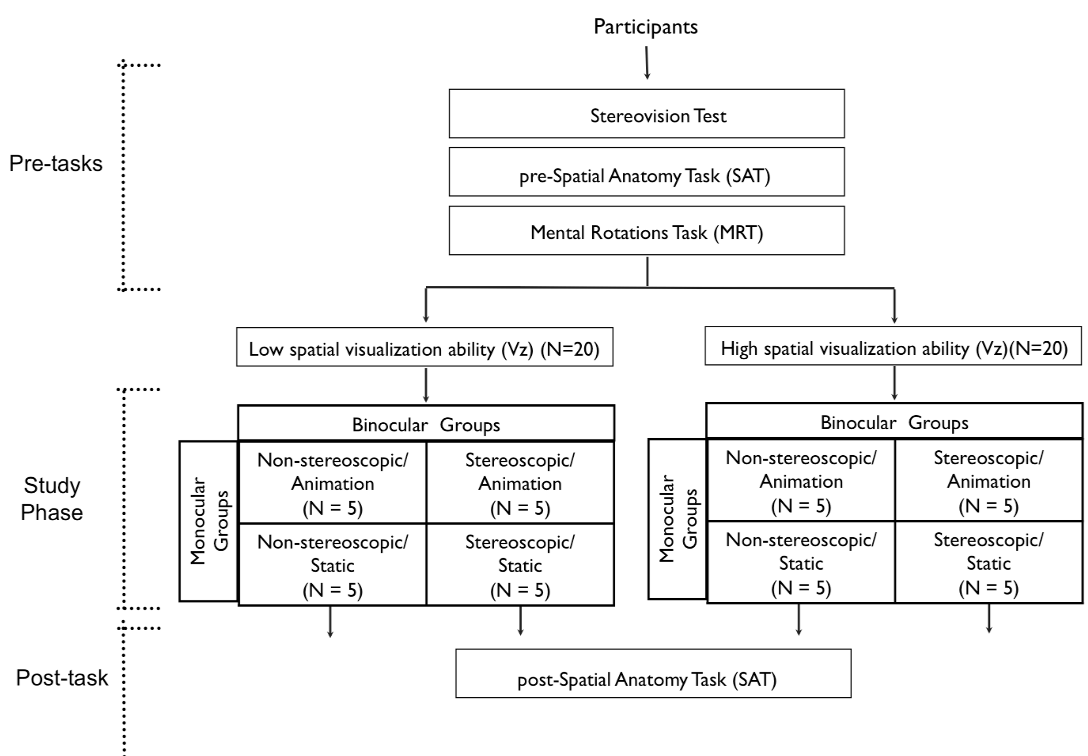


Figure 5.1: Flowchart illustrating the procedure for the study. All participants had to complete three pre-tasks (i.e., the stereovision test, mental rotations task and spatial anatomy task), a study phase, and a post-task (i.e., the spatial anatomy task).

Pre-tasks. Forty-two students completed the stereovision test, MRT and SAT at the start of the study. Of the 42 students, two lacked stereopsis and were excluded from the study. Based on the scores obtained on the MRT, the remaining 40 students were allocated to one of two spatial visualization ability (Vz) groups – low Vz (N = 20, lower median group) or high Vz (N = 20, higher median group).

Study Phase. Participants in each Vz groups were randomly assigned to one of two binocular display groups (non-stereoscopic or stereoscopic) and then to one of two monocular display groups (static, animated). Participants in the non-stereoscopic/animated group watched an animation of the anatomical model continuously rotating around the x-, y-, and z-axes, while those in the stereoscopic/animation group watched the anaglyph version of the animation. Participants in the non-stereoscopic/static group viewed static representations of the anatomical model switching between the six canonical views, while those in the stereoscopic/static group viewed the anaglyph version of the static representations. The duration of exposure to the anatomical model was the same for all participants (150 seconds).

Post-task. Subsequently, the same spatial anatomy task 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.

5.2.5 Data analyses

Descriptive statistics for the MRT, pre-SAT, and post-SAT were computed. Separate 2x2x2 completely randomized factorial (CRF) analyses were used to determine whether there were there any main or interaction effects between Vz (low, high), binocular displays (stereoscopic, non-stereoscopic), and monocular displays (static, animated) on post-SAT scores and total time spent on the post-SAT. Covariates appearing in the CRF analyses were mean scores and mean time on the pre-SAT, respectively.

5.3 Results

Descriptive statistics for the MRT and SAT are presented in Table 5.1.

	MRT score	Pre-SAT score	Time spent on the pre-SAT(in seconds)	Post-SAT score	Time spent on the post-SAT (in seconds)
High Vz	16.50 ± 4.44	17.85 ± 5.93	311.84 ± 42.55	20.25 ± 4.43	297.62 ± 44.07
Low Vz	7.35 ± 2.89	13.40 ± 4.91	340.69 ± 26.72	16.90 ± 4.93	307.33 ± 38.62

Table 5.1: Descriptive statistics for the MRT, pre-SAT, and post-SAT for high Vz (N = 20) and low Vz (N = 20) subjects.

The F-statistics for the CRF analysis of post-SAT scores (with pre-SAT scores as a covariate) are listed in Table 5.2. The CRF analysis revealed a significant interaction effect between monocular and binocular displays.

Effect	F-statistics
Vz	$F(1, 32) = 0.09, p > 0.05$
Monocular displays	$F(1, 32) = 1.01, p > 0.05$
Binocular displays	$F(1, 32) = 0.64, p > 0.05$
Vz x monocular displays	$F(1, 32) = 2.14, p > 0.05$
Vz x binocular displays	$F(1, 32) = 0.04, p > 0.05$

Monocular displays x binocular displays	$F(1, 32) = 7.93, p < 0.05$*
Vz x monocular displays x binocular displays	$F(1, 32) = 1.45, p > 0.05$

Table 5.2: F-statistics for completely randomized factorial analysis of post-SAT scores.

Table 5.3 and Figure 5.2 show the mean post-SAT scores for all monocular by binocular display level combinations. Following the significant interaction, simple main effect tests revealed a significant difference in post-SAT scores for subjects viewing the non-stereoscopic animation and non-stereoscopic static representations, but not for those viewing the stereoscopic animation and stereoscopic static representations. For the non-stereoscopic displays, subjects viewing static representations scored significantly higher on the post-SAT than those viewing the animation. For the stereoscopic displays, mean post-SAT scores were not significantly different between subjects viewing the static representations and those viewing the animation.

Binocular displays	Monocular displays	Mean score ± standard error
Non-stereoscopic	Static	[a] 21.18 ± 1.14*
	Dynamic	[a] 16.83 ± 1.10*
Stereoscopic	Static	[a] 17.07 ± 1.08
	Dynamic	[a] 19.22 ± 1.07

Table 5.3: Mean post-SAT scores for all binocular by monocular display level combination.
[a] Covariates appearing in the model are evaluated at a mean pre-SAT score of 15.22
* $p < 0.05$

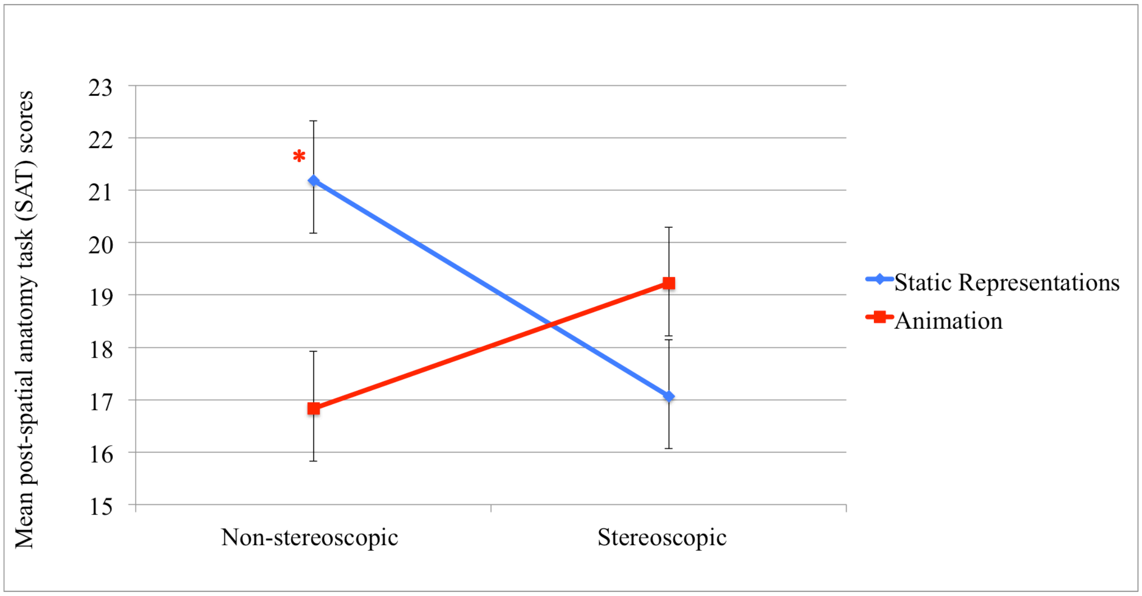


Figure 5.2: Profile plot of mean post-SAT scores. The plot shows an interaction between monocular (static and dynamic) and binocular (non-stereoscopic and stereoscopic) cues. The two lines represent the static and dynamic groups. The crossing of the lines indicates an interaction effect.

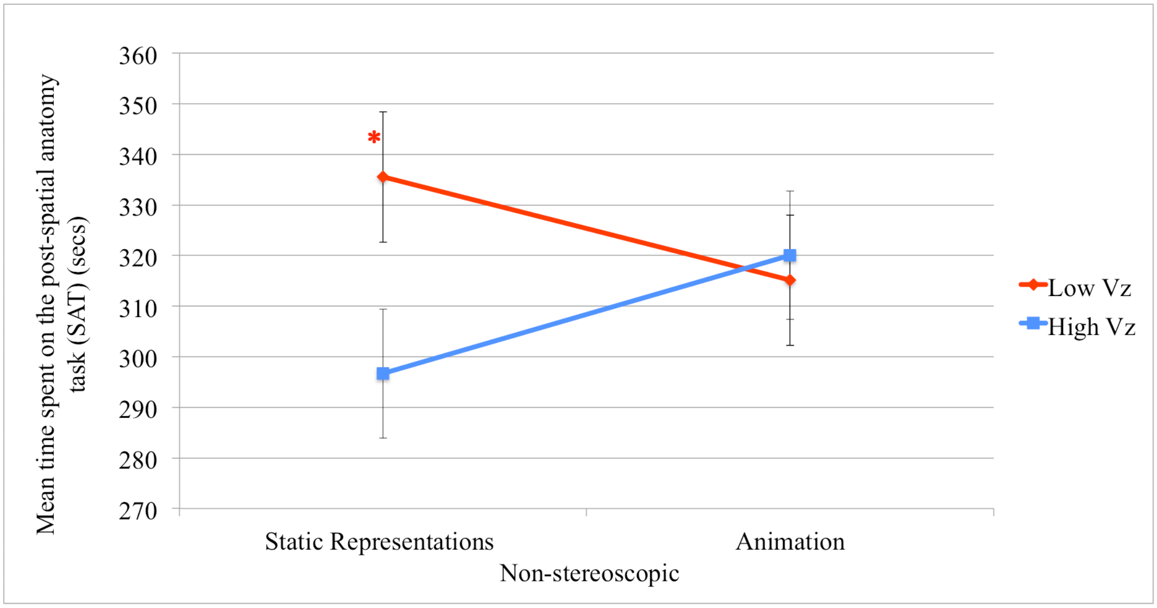
F-statistics for the CRF analysis of time spent on the post-SAT (with time spent on the pre-SAT as a covariate) are shown in Table 5.4. The analysis revealed a significant three-way interaction effect between the factors. Table 5.5 and Figure 5.3 show the mean time spent on the post-SAT for all monocular display by binocular display by Vz level combination. Following the significant interaction, simple main effect tests revealed a significant difference in the amount of time spent on the post-SAT for high and low-Vz subjects viewing the non-stereoscopic static representations. High Vz subjects spent significantly less time on the post-SAT than their low Vz counterparts.

Effect	F-statistics
Vz	F (1, 32) = 1.77, p > 0.05
Monocular displays	F (1, 32) = 1.12, p > 0.05
Binocular displays	F (1, 32) = 0.04, p > 0.05
Vz x monocular displays	F (1, 32) = 0.06, p > 0.05
Vz x binocular displays	F (1, 32) = 0.20, p > 0.05
Monocular displays x binocular displays	F (1, 32) = 1.49, p > 0.05
Vz x monocular displays x binocular displays	F (1, 32) = 7.24, p < 0.05*

Table 5.4: F-statistics for completely randomized factorial analysis of time spent on the post-SAT.
* p< 0.05

Binocular displays	Monocular displays	Spatial visualization ability (Vz)	Mean time ± standard error
Non-stereoscopic	Static	Low Vz	[a] 335.56 ± 12.90*
		High Vz	[a] 296.69 ± 12.77*
	Animated	Low Vz	[a] 315.15 ± 12.90
		High Vz	[a] 329.10 ± 12.71
Stereoscopic	Static	Low Vz	[a] 320.26 ± 12.86
		High Vz	[a] 337.71 ± 13.00
	Animated	Low Vz	[a] 326.19 ± 12.78
		High Vz	[a] 290.79 ± 13.09

Table 5.5: Mean time spent on the post-spatial anatomy task (SAT) for all binocular cue x monocular cue x spatial visualization ability (Vz) level combination.
[a] Covariates are evaluated at a mean pre-SAT time of 326.28 seconds.
*p < 0.05



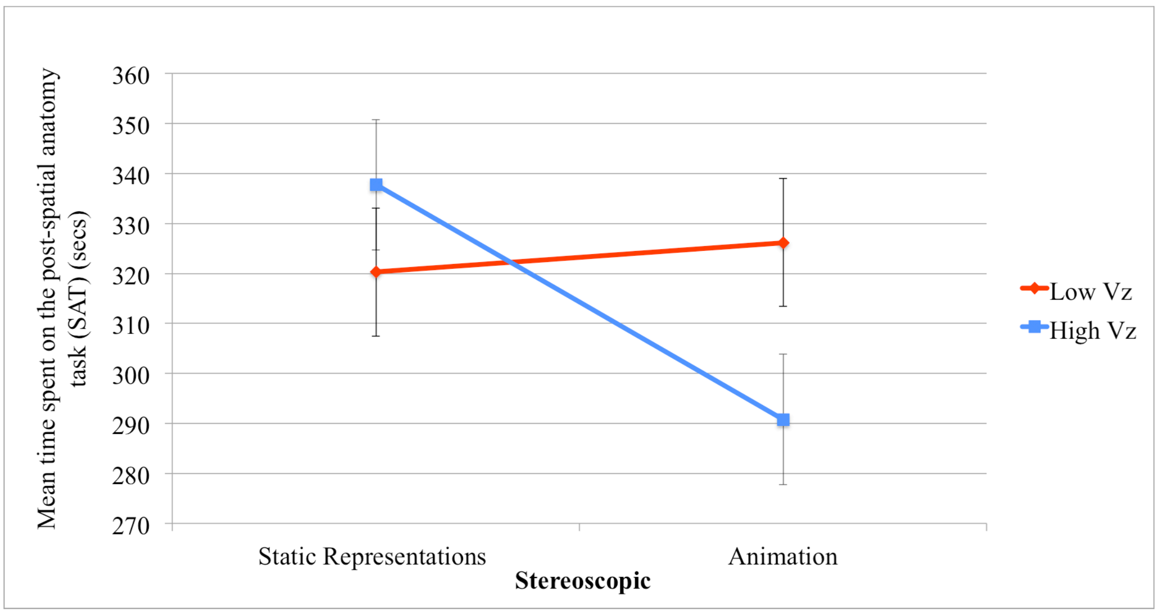


Figure 5.3: Profile plot of mean time spent on the post-SAT. There was a three-way interaction between spatial visualization ability (high, low), monocular depth cues (static, animated), and binocular depth cues (non-stereoscopic, stereoscopic). The two plots represent the non-stereoscopic (above) and stereoscopic groups (below). The two lines represent the high Vz and low Vz groups. The crossing of the lines indicates an interaction effect.

5.4 Discussion

The purpose of this study was to examine the role of computer-implemented stereopsis in spatial anatomy comprehension. Compared to the monocular depth cues offered by conventional animations and static representations, the binocular depth information afforded by stereoscopic animations and static representations more accurately communicate the depth and three-dimensionality of anatomical structures. As a result, it was hypothesized that instruction with stereoscopic displays will improve SAT performance. However, the results of this study did not support this hypothesis, as both SAT scores and time spent on the anatomy task were not significantly different for subjects who received instruction with stereoscopic displays and those receiving instruction with the non-stereoscopic displays.

This finding contradicts the results of earlier studies that found stereoscopic feedback benefits the execution of surgical tasks (Peitgen et al., 1996; Falk et al., 2001; Byrn et al., 2007) and acquisition of anatomical knowledge in virtual learning environments (Luursema et al., 2006; Luursema et al., 2008). There are two possible reasons for this contradictory result. First, previous studies assessing the role of stereopsis used active shutter techniques to generate the stereoscopic image while the present study used passive anaglyph method. The anaglyph method has the advantage of being inexpensive and easy to use (i.e., does not require synchronization of the stereo glasses with the images generated on the screen); however, the stereo image produced is poor quality and does not retain the original colours (Bowman et al., 2005). Thus, the reduced quality stereo images generated in this study might have masked any potential benefits of stereopsis. Second, previous studies assessing the role of stereopsis often used performance tasks that required reaching and grasping movements (i.e., prehension), while the present study used a performance task that required no reaching and/or grasping. Therefore, it appears that stereopsis contributes positively to visuomotor task performance but not visuospatial task performance. This assumption is supported by a number of studies that found binocular depth cues play a critical role in the programming and execution of prehension (Servos et al., 1992; Bradshaw and Elliott, 2003), and prehension is crucial to surgical procedures.

While the present study failed to show a main effect for stereopsis, two significant interaction effects were found. The first was a two-way interaction between binocular and monocular displays on SAT score (see Table 5.3 and Figure 5.2). In the absence of stereopsis, individuals viewing the static representations scored significantly higher than those viewing the animation. However, when stereopsis was implemented, the instructional advantage that static representations had over animation disappeared, and those viewing the animation had similar post-SAT scores as those viewing the static representations. The second interaction effect was a three-way interaction between Vz, binocular and monocular cues on the amount of time spent on the post-SAT (see Table 5.5 and Figure 5.3). In the absence of stereopsis, high Vz subjects viewing the static representations spent significantly less time on the post-SAT than their low Vz counterparts. However, the addition of stereopsis to the static representations eliminated the time difference between high- and low-Vz subjects, as those with low Vz spent approximately the same amount of time on the anatomy task as those with high Vz. Concerning the animations, there was no difference in the amount of time spent on the post-SAT for subjects viewing the non-stereoscopic animation or those viewing the stereoscopic animation (see Table 5.5 and Figure 5.3). Taken together, the results of this study demonstrate that instruction using stereopsis alone did not contribute to post-SAT performance; however, in situations where there was a difference in post-SAT score (see Table 5.3 and Figure 5.2) or time spent on the post-SAT (see Table 5.4 and Figure 5.3), the implementation of stereopsis to the display abolished the difference and brought students' performance to a similar level.

Limitations and future directions

This study has some limitations. First, the lower quality stereo images generated by anaglyph stereo technique might have eliminated any potential benefits of stereopsis. Hence, further studies are warranted to determine whether the stereo images produced by other stereo projection methods such as active shutter or autostereoscopic techniques contribute to performance on the spatial anatomy task. Active shutter stereo has the advantage of producing high quality stereo images and autostereoscopy has the advantage of displaying the images without the use of special headgear or stereo glasses (Bowman et al., 2005). We speculate that the stereo images produced by active shutter stereo and autostereoscopic stereo will contribute positively to performance on the SAT. Second, the material used in this study (aorta, esophagus, and trachea) contains little visuospatial information as it consists essentially of three tubes. The authors suggest further studies be conducted to examine the contribution of stereopsis to learning more spatially complex areas in the body, such as the head and neck or abdomen. Finally, further experiments are also warranted to increase the number of participants. For this study 40 participants were assigned to 8 experimental groups, resulting in five participants in each experimental group. Such an increase in sample size would help to validate our results.

5.5 Summary

In conclusion, stereoscopic displays can potentially improve many aspects of medicine, from anatomy education to surgical training. Although there is substantial evidence that stereoscopic viewing benefits the execution of surgical tasks, there is limited evidence that it facilitates the acquisition of spatial anatomical knowledge. The present study revealed that stereoscopic displays had no additional advantages over non-stereoscopic displays. Further experiments with larger sample size are needed to confirm the results of this study. Further experiments are also needed to determine whether stereopsis contributes to learning more spatially complex areas in the body. The results of these experiments can be used to provide a rational basis for discussing the implementation of stereoscopic visualizations into anatomy education.

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Chapter 6

6 General discussion

The overarching aim of this dissertation was to explore the relationship between internal and external visualizations and the implications of this relationship for comprehending visuospatial anatomical information. Four factors were examined – three are properties of computer visualizations used in anatomy courses and one is an inherent property of the learner. In regards to computers, dynamism (static versus animated), interactivity (interactive versus non-interactive), and stereopsis (stereoscopic versus non-stereoscopic) were examined. On the learner side, spatial visualization ability (Vz) was explored. In all three experiments the same experimental approach was used, Vz was assessed with the standardized Mental Rotations Task (MRT) (Vandenberg and Kuse, 1978; Peters et al., 1995) and comprehension of visuospatial anatomical information was measured with a novel Spatial Anatomy Task (SAT).

6.1 Empirical contributions

Experiment 1 (Chapter 2) established that Vz positively influences performance on the SAT. High Vz subjects scored significantly higher and spent significantly less time on the SAT than low Vz subjects. Experiment 1 demonstrated that instruction with different computer visualizations modulates the effects of Vz on SAT scores. While static representations benefited high and low Vz subjects equally, animations particularly benefited high Vz subjects, as their mean score on the SAT was significantly higher than the mean score of low Vz subjects. Finally, experiment 1 revealed that interactive visualizations offered no additional advantages over non-interactive displays. Both interactive and non-interactive displays provided the same benefits to high- and low-Vz subjects.

Experiment 2 (Chapter 3) explored the problem solving strategies of high- and low-Vz subjects in order to determine whether differences in strategies contributed to differences in SAT performance. Experiment 2 reaffirmed that Vz is a strong predictor of success on the SAT. In addition to scoring higher and spending less time on the SAT, high Vz subjects were also more accurate than low Vz subjects. Strategy reports revealed that there were in fact a number of ways to approach solving the SAT problems; however, differences in strategies did not contribute significantly to differences in SAT performance. Therefore, in the absence of external computer visualizations, Vz is the main contributor of variation in SAT performance.

Experiment 3 (Chapter 4) examined whether improving the depth and realism of computer visualizations (i.e., through computer-implemented stereopsis) would inherently improve its educational effectiveness. Although there is substantial evidence that stereoscopic feedback benefits the execution of surgical tasks (Peitgen et al., 1996; Falk et al., 2001; Byrn et al., 2007), results from experiment 3 revealed that stereopsis alone did not improve SAT performance.

Effects of Vz

Given that the spatial anatomy task involved encoding, storing and mentally manipulating visuospatial information in three-dimensions and two-dimensional cross-sections, it was hypothesized that individuals with high Vz would perform significantly better on the SAT than those with low Vz. The results of experiments 1 and 2 supported this hypothesis by indicating a positive correlation between Vz and SAT score, a negative correlation between Vz and amount of time spent on the SAT, and a positive correlation between Vz and accuracy on the SAT. Individuals with high Vz scored higher, spent less time, and were more accurate than those with low Vz.

Effects of dynamism

Intuitively, one might expect that animations will offer advantages over static representations, especially since the additional depth cues incorporated in these displays better communicate the visuospatial properties of anatomical structures (Keehner et al., 2008b). However, experiment 1 demonstrated that animations did not offer additional advantages over static representations, and that the effectiveness of animations depended on participant's Vz. Experiment 1 revealed that static anatomical representations augmented performance equally for participants of high- and low-Vz. By contrast, animation of the anatomical model particularly benefited participants of high Vz, as their mean score on the SAT was significantly higher than those with low Vz.

Since Vz is partially related to speed of processing visuospatial information (Salthouse, 1996), this might have affected speed of encoding information in the animation, such that only participants with high Vz were able to keep up with the pace of the animation. Since Vz is partially 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 visuospatial 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 animation.

Effects of interactivity

Intuitively, one might also expect that interactive visualizations will offer advantages over non-interactive displays, especially since interactivity enables the viewer to adapt the presentation to his or her own cognitive needs by actively deciding what is presented on the screen and when it is presented (Schwan and Riempp, 2004). However, experiment 1 demonstrated that interactive visualizations did not offer additional advantages over non-interactive displays, and that instruction with interactive and non-interactive visualizations improved performance equally for high- and low-Vz subjects.

One possible reason for not finding an advantage for interactivity is the nature of the user control interface. The key-press control interface implemented in experiment 1 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 learner to be exactly mirrored in the movements of the visualization should be especially beneficial in helping learners create an integrated visuospatial mental representation of any object he or she is viewing. Another possible reason for not finding an advantage for interactivity is the quality of the visuospatial information received from active control. Keehner et al. (2008a) proposed that 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 visuospatial information is stored in memory. Some authors suggest that visuospatial information is not remembered in 3-D, but rather in specific 2-D views in the canonical orientations, and that unfamiliar orientations are recognized by mental rotation of these 2-D views (Garg et al., 1999; 2001; 2002). Therefore, permitting interactivity does not guarantee that users will discover the most effective way to manipulate the visualization to achieve the most task-relevant information.

Effects of stereopsis

Intuitively, one might expect that stereoscopic displays will offer additional advantages over non-stereoscopic display, especially because the binocular information offered by stereoscopic displays increases the realism and three-dimensionality of visuospatial anatomical information (Scaife and Rogers, 1996). However, experiment 3 demonstrated that stereoscopic visualizations did not offer additional advantages over non-stereoscopic displays, and that instruction with stereoscopic and non-stereoscopic displays improved performance equally for high- and low-Vz subjects. One possible reason for not finding an instructional advantage for stereoscopic displays is the quality of the stereo images produced by the anaglyph technology. Although anaglyph stereo has the advantage of being inexpensive and easy to use, colour polarization reduces the colour quality of the stereo images (Bowman et al., 2005). Thus, the poor quality stereo images produced in experiment 3 might have masked any potential benefits of stereopsis.

It is important to acknowledge that the results observed in experiment 3 are specific to performance on the SAT, which required mental manipulation of visuospatial anatomical information. This does not imply that stereopsis would not facilitate performance on another task. For example, previous studies assessing the role of stereopsis often used performance tasks that involved reaching and grasphing movements (i.e., prehension) (Peitgen et al., 1996; Falk et al., 2001; Byrn et al., 2007). In all of these studies, the implementation of stereopsis augmented task performance. Therefore, it appears that stereopsis contributes positively to visuomotor task performance but not visuospatial task performance.

6.2 Contributions to anatomy education

One of the biggest challenges in education is the tendency for educators to assume that the newest and latest technology is going improve pedagogy over historically salient practices. For example, when motion picture was developed, Thomas Edison advocated,

> "I believe that the motion picture is destined to revolutionize our educational system and that in a few years it will supplant largely, if not entirely, the use of textbooks." - Thomas Edison, 1922 (cited in Cuban, 1986, p. 9)

More recently in medical education, similar claims have been made for dynamic, interactive, and stereoscopic computer visualizations. There is an inherent belief that increasing the educational effectiveness of computer visualizations is a mere question of making them dynamic, interactive, and/or realistic. However, experiments 1, 2, and 3 clearly demonstrate that this is not the case, and that the benefits of computer visualizations vary according to learner characteristics, particularly spatial visualization ability. What this suggests is that the value of computer visualizations, either static pictures or technologically-advanced animations, cannot be assessed adequately on the basis of our intuitions alone. Instead, visualizations, and their incorporation into curricula, need to be tested both empirically and qualitatively for impact on student learning in order to provide a rational basis for discussing their implementation in anatomy courses.

There is increasing evidence that instructional value of computer visualizations depends on how well its design reflects our understanding of human cognitive architecture (Chandler, 2004; Plass et al, 2009). Extensive research demonstrates that working memory and long-term memory and the interaction between these two memory structures plays a crucial role in learning (Sweller et al., 1998). In the domain of anatomy education, research indicates that Vz plays an important role in acquiring anatomical knowledge. Therefore, instructional techniques in anatomy not only need to be sensitive to the severe limitations of working memory but also need to be aware of variations in learners' ability to apprehend, encode, and manipulate mental representations. As anatomy educators we need to be aware of these cognitive limitations in order to guide us in the design, evaluation, and selection of computer visualizations that are appropriate for the individual learner, educational setting, and/or problem-solving task in question.

Given the importance of spatial visualization ability in the comprehension of visuospatial anatomical information, questions arise about the extent to which spatial visualization ability is mutable. There is evidence that spatial visualization ability could be improved through practice (Peters et al., 1995; Lufler et al., 2012) and training (Terlecki et al., 2008). Therefore, early testing of anatomy students for their spatial visualization abilities would allow intervention with the appropriate training tools that are recommended to help reduce the gap between high- and low-Vz learners. This would ensure that all learners, whatever their innate Vz, have the best chance to acquire sufficient understanding of visuospatial anatomical information.

6.3 Future directions

The approach taken to understand anatomy comprehension through the interaction of internal and external visualizations has exposed a number of potential avenues for further research. Below is a list of potential topics for future research in this field.

One potential future direction is to compare the effects of different user control interfaces. As mentioned in the literature review, the ability to interact with computer visualizations can be achieved through various input devices, ranging from traditional key button presses to a more naturalistic interface such as six degrees of freedom motion trackers that allow the manipulations made by the user to be mirrored by the movements of the visualization. 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 interaction with a user control interface. Directness 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 or direct engagement with the object of interest. According to Hutchins et al. (1985), 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. Therefore research comparing the effectiveness of different user control interfaces can be used to guide the selection of appropriate user control interfaces that will aid comprehension of visuspatial anatomical information.

A second potential direction is to examine the effects of different computer visualizations on other aspects of performance such as motivation. One of the main appeals of animations and stereoscopic display is that they are novel, aesthetically appealing, attractive, and therefore can pique a person's curiosity. According to Malone (1981), curiosity is one of the three most important characteristics of intrinsically motivating instructional environments; the others two factors being challenge and fantasy (Malone, 1981). *Intrinsic motivation* is described as the motivational value of the content itself without the provision of external incentives to induce participation (Rieber, 1991). In other words, a person must be willing to engage in the instructional activity without external incentives such as grades, money, or status. Measures of continuing motivation, such as choosing to either return to an instructional task in a free-choice situation, or the expressing desire to do so have been used successfully to estimate the constructs of intrinsic motivation (Kinzie and Sullvan, 1989; Rieber, 1991).

Finally, an important issue for future research is the influence of learner characteristics on comprehension. In this dissertation, the focus was Vz, which is one of five sub-factors of spatial ability. It would be warranted to examine whether the remaining four factors – spatial relations, closure speed, closure flexibility, and perceptual speed – influence performance on the spatial anatomy task. Another learner characteristic that might influence anatomy task performance is prior knowledge. Experienced or high-knowledge learners are considered learners who have substantial previously acquired knowledge in a specific domain (Kalyuga, 2005). At the perceptual level, prior knowledge can influence how a learner directs his or her visual attention while viewing a visual display. For example, whereas a low-prior knowledge (or novice) learner may direct his or her attention towards features of display that are physically salient (i.e., larger or brighter) but not directly relevant to the learning task, a high-prior knowledge learner may direct his or her attention to only features of the display that are relevant to the learning task (Kriz and Hegarty, 2007; Hegarty and Kriz, 2008). At the cognitive level, prior knowledge can influence how information is treated in working memory. Human working memory is severely limited in duration and capacity when dealing with new and unfamiliar information (Sweller et al., 1998; Kalyuga, 2008). However, in familiar domains, the available knowledge stored in long-term memory (in the form of knowledge structures called schemas) allows us to combine or 'chunk' large amounts of information and treat it as a single element, thus reducing working memory limitations (Sweller et al., 1998; Kalyuga, 2008). In many learning situations, instructional tools that help high-knowledge learners may not help or even hinder low-knowledge learners, and vice-versa.

6.4 Conclusion

In anatomy, any display (e.g., static diagrams or animations) that depicts the human body is an external visualization of the body. In contrast, cognitive processes such as apprehending, encoding, and manipulating mental representations can be thought of as manifestations of internal spatial visualization ability. Thus, visuospatial anatomy comprehension can be framed in terms of the interplay between the perception of external visualizations and the ability to maintain and manipulate internal visualizations. In the absence of external computer visualizations, spatial visualization ability is the main contributor of variation in spatial anatomy task performance. In the presence of external computer visualizations, task performance depends on the interaction between spatial visualization ability and visuospatial characteristics of the external visualization. As we continue to design computer visualizations for anatomy education, it is important to recognize that dynamic, interactive, and stereoscopic visualizations may not always be better than static, non-interactive, and non-stereoscopic displays. Therefore, anatomy educators need to move beyond the presumption that technologically-advanced visualizations are superior to simple images, to assessing what conditions must be in place for these visualizations to be effective.

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Appendices

Appendix A: Ethics approval notice

Research Western

Use of Human Participants - Ethics Approval Notice

Principal Investigator: Dr. Tim Wilson
Review Number: 17332E
Review Level: Delegated
Approved Local Adult Participants: 240
Approved Local Minor Participants: 0
Protocol Title: Development and evaluation of computer-generated visuals for education
Department & Institution: Anatomy & Cell Biology, University of Western Ontario
Sponsor:
Ethics Approval Date: September 01, 2011 **Expiry Date:** May 31, 2012
Documents Reviewed & Approved & Documents Received for Information:

Document Name	Comments	Version Date
Revised UWO Protocol		
Advertisement		
Advertisement	Announcement	
Revised Letter of Information & Consent		2011/08/30

This is to notify you that The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects (HSREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the Health Canada/ICH Good Clinical Practice Practices: Consolidated Guidelines; and the applicable laws and regulations of Ontario has reviewed and granted approval to the above referenced revision(s) or amendment(s) on the approval date noted above. The membership of this REB also complies with the membership requirements for REB's as defined in Division 5 of the Food and Drug Regulations.

The ethics approval for this study shall remain valid until the expiry date noted above assuming timely and acceptable responses to the HSREB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time you must request it using the UWO Updated Approval Request Form.

Members of the HSREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the HSREB.

The Chair of the HSREB is Dr. Joseph Gilbert. The UWO HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Ethics Officer to Contact for Further Information

___ Janice Sutherland	✓ **Grace Kelly**	___ **Shantel Walcott**

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The **University** ***of*** **Western Ontario**
Office of Research Ethics

Western

Office of Research Ethics

The University of Western Ontario

Website: www.uwo.ca/research/ethics

Use of Human Subjects - Ethics Approval Notice

Principal Investigator: Dr. T.D. Wilson
Review Number: 17332E **Review Level:** Expedited
Review Date: August 11, 2010 **Approved Local # of Participants:** 210
Protocol Title: Development and evaluation of computer-generated visuals for education
Department and Institution: Anatomy, University of Western Ontario
Sponsor: None
Ethics Approval Date: November 15, 2010 **Expiry Date:** May 31, 2012
:uments Reviewed and Approved: UWO Protocol, Letter of Information. Announcement. Online Poster.
uments Received for Information:

s is to notify you that The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human jects (HSREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research olving Humans and the Health Canada/ICH Good Clinical Practice Practices: Consolidated Guidelines; and the applicable laws and ılations of Ontario has reviewed and granted approval to the above referenced study on the approval date noted above. The nbership of this REB also complies with the membership requirements for REB's as defined in Division 5 of the Food and Drug ;ulations.

: ethics approval for this study shall remain valid until the expiry date noted above assuming timely and acceptable responses to the ꓤEB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time must request it using the UWO Updated Approval Request Form.

·ing the course of the research, no deviations from, or changes to, the protocol or consent form may be initiated without prior tten approval from the HSREB except when necessary to eliminate immediate hazards to the subject or when the change(s) involve y logistical or administrative aspects of the study (e.g. change of monitor, telephone number). Expedited review of minor nge(s) in ongoing studies will be considered. Subjects must receive a copy of the signed information/consent documentation.

estigators must promptly also report to the HSREB:

a) changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;
b) all adverse and unexpected experiences or events that are both serious and unexpected;
c) new information that may adversely affect the safety of the subjects or the conduct of the study.

ıese changes/adverse events require a change to the information/consent documentation, and/or recruitment advertisement, the vly revised information/consent documentation, and/or advertisement, must be submitted to this office for approval.

mbers of the HSREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in :ussion related to, nor vote on, such studies when they are presented to the HSREB.

Chair of HSREB: Dr. Joseph Gilbert
FDA Ref. #: IRB 00000940

Ethics Officer to Contact for Further Information			
Janice Sutherland	☐ Elizabeth Wambolt	☑ Grace Kelly	

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Appendix B: Permission approval notice

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Appendix C: Instructions for the Spatial Anatomy Task - Mental Rotations

Spatial Task

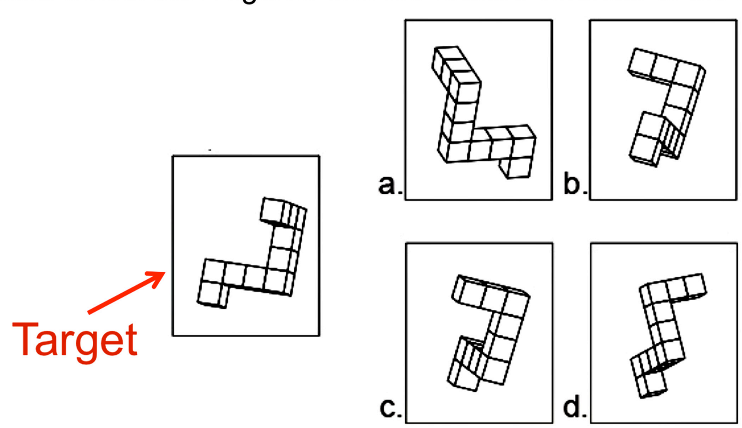
Part 1

PRESS ANY KEY TO CONTINUE

The first SPATIAL TASK consists of 10 questions. The questions are similar to the Mental Rotation Task questions.

Recall: Each Mental Rotations Task question consists of 5 figures – 1 target and 4 choice figures.

Task: Select the 2 figures that are rotated versions of the target.

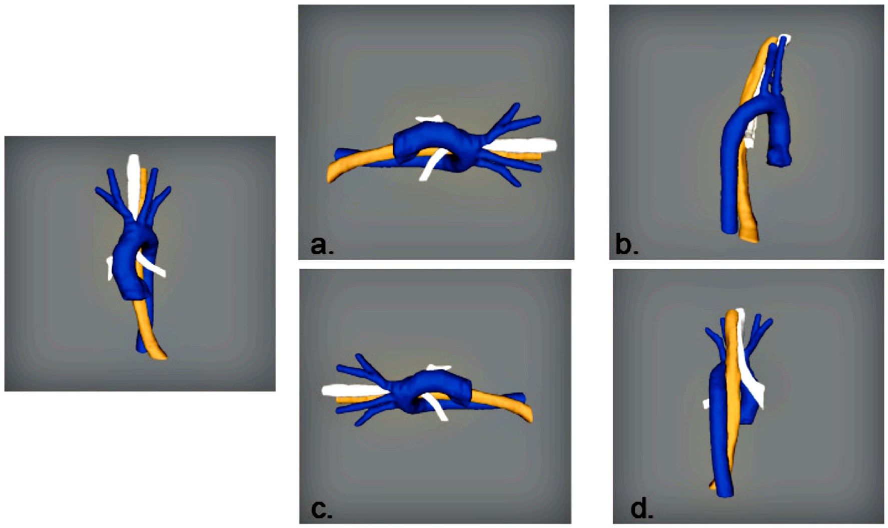


PRESS ANY KEY TO CONTINUE

Answers: a and c

Here is an example of a Spatial Task question for you to try.

Task: Select the 2 figures that are rotated versions of the target.



PRESS ANY KEY TO CONTINUE

Answers: a and d

Once you start the task, you will be given 10 questions. You will have 2 minutes to complete as many questions as possible.

When you do the task, please remember that for each question, there are **2 correct answers**. You will be given a point if you select both correct matching figures. Selecting only 1 of these will result in no points.

Please use the keys labeled **'a, b, c, d'** to make your selections.

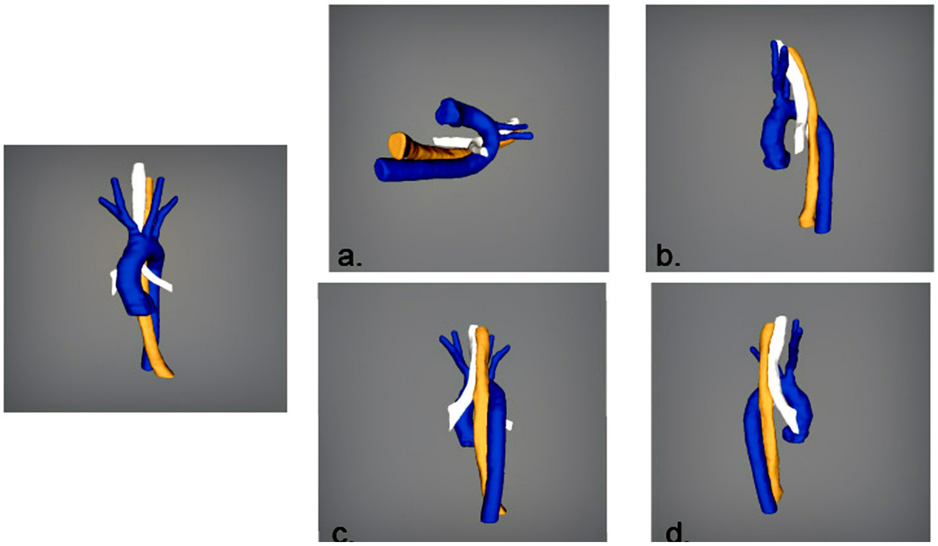
You will not be able to change your answers after they have been selected so please be careful when inputting your answers.

PRESS ANY KEY TO BEGIN TASK

Appendix D: Spatial Anatomy Task - Mental rotations questions

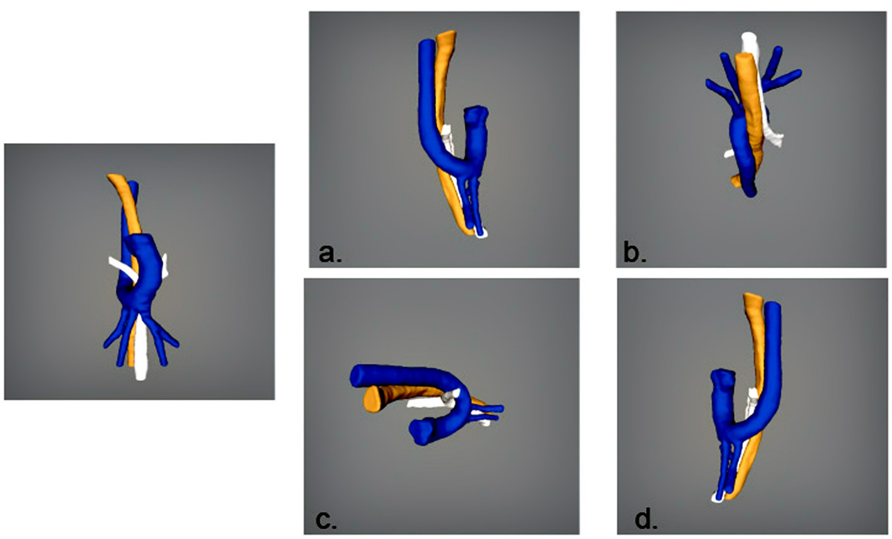
Q1.

Select the **2 figures** that are rotated versions of the target.



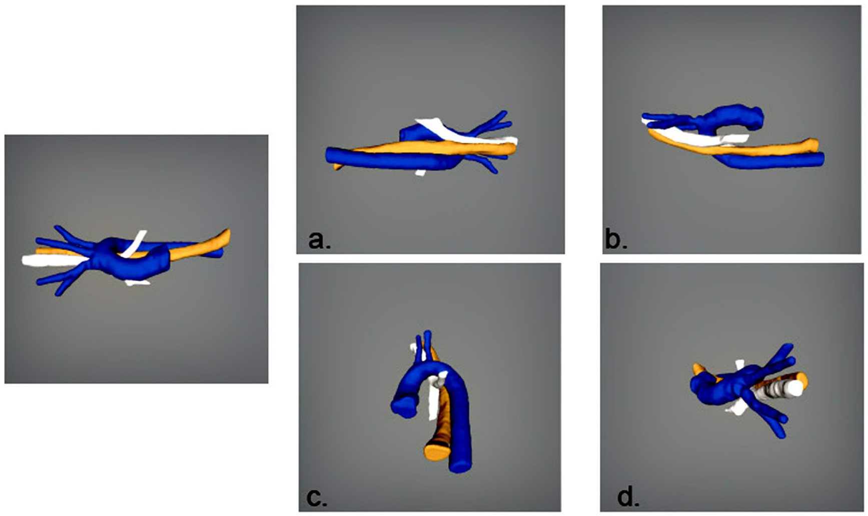
Q2.

Select the **2 figures** that are rotated versions of the target.



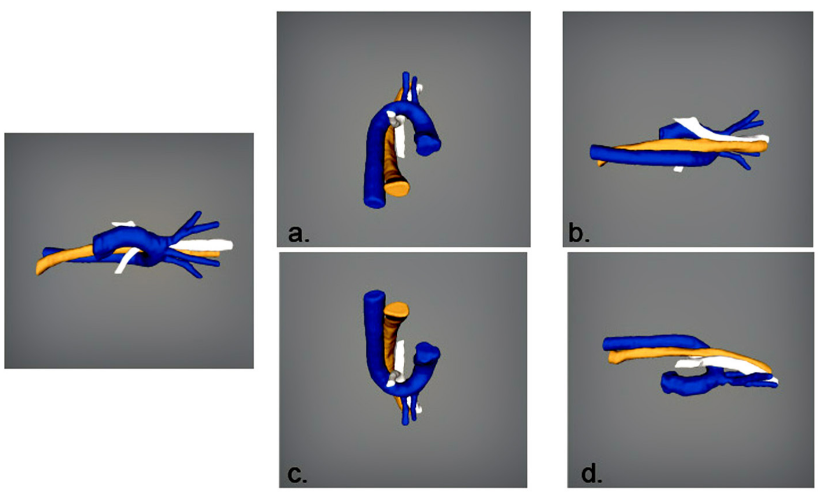
Q3.

Select the **2 figures** that are rotated versions of the target.



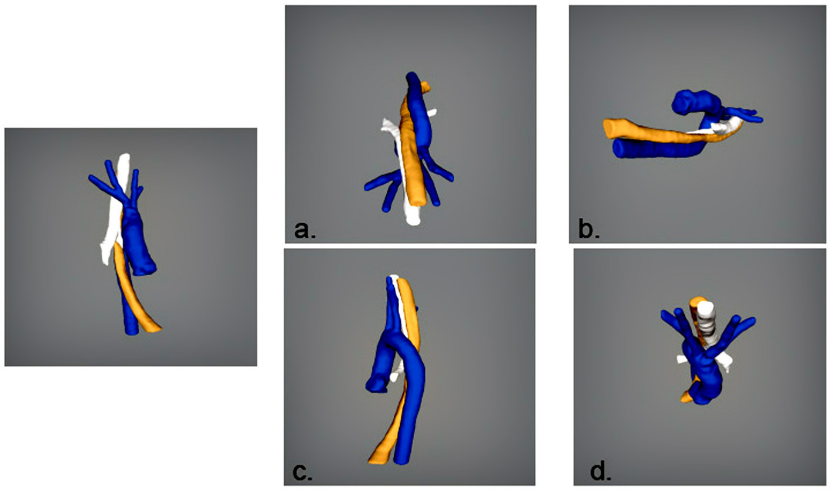
Q4.

Select the **2 figures** that are rotated versions of the target.



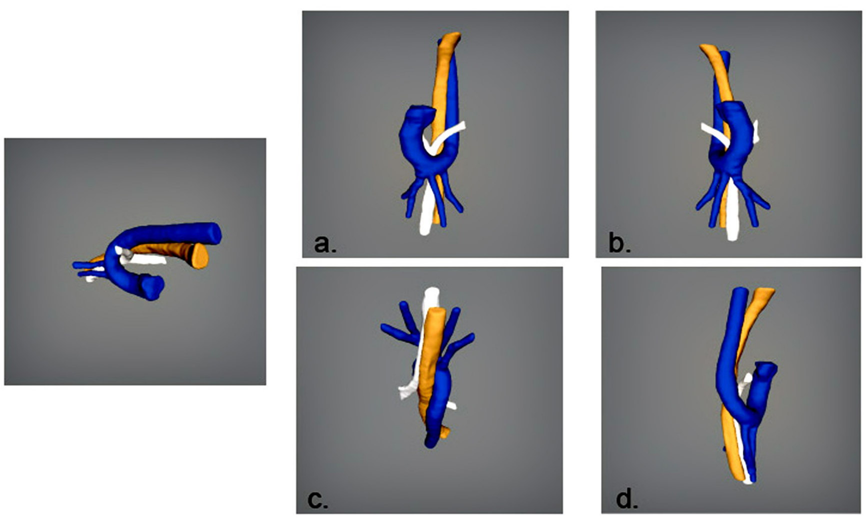
Q5.

Select the **2 figures** that are rotated versions of the target.



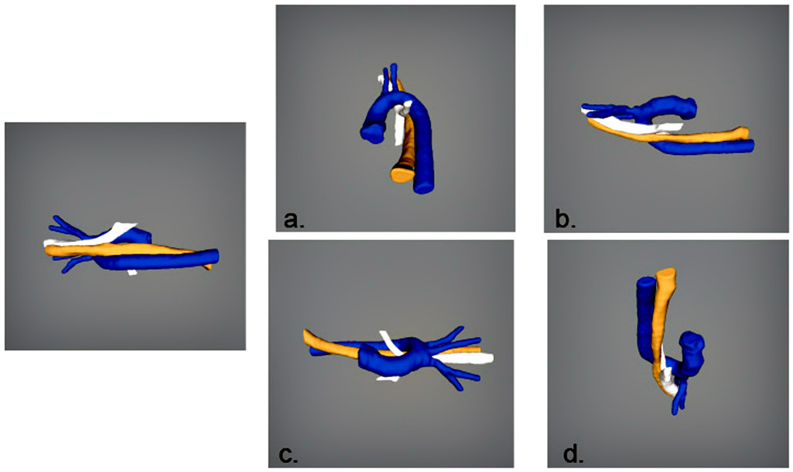
Q6.

Select the **2 figures** that are rotated versions of the target.



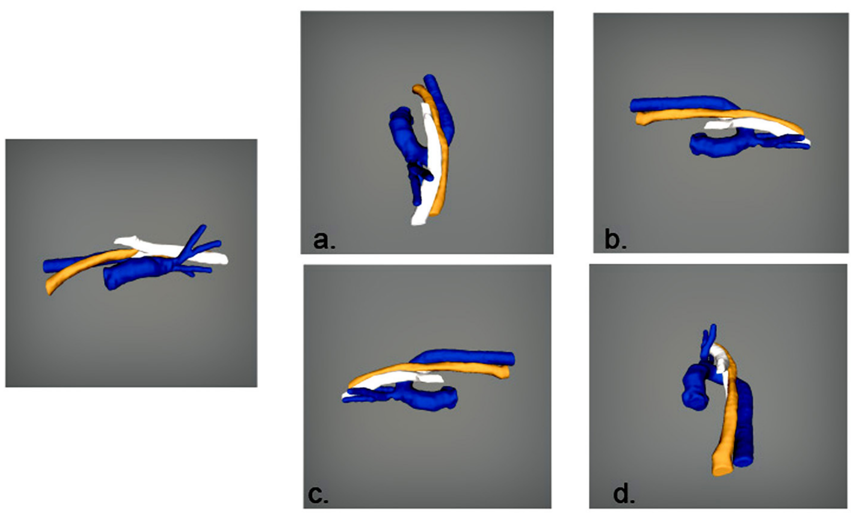
Q7.

Select the **2 figures** that are rotated versions of the target.



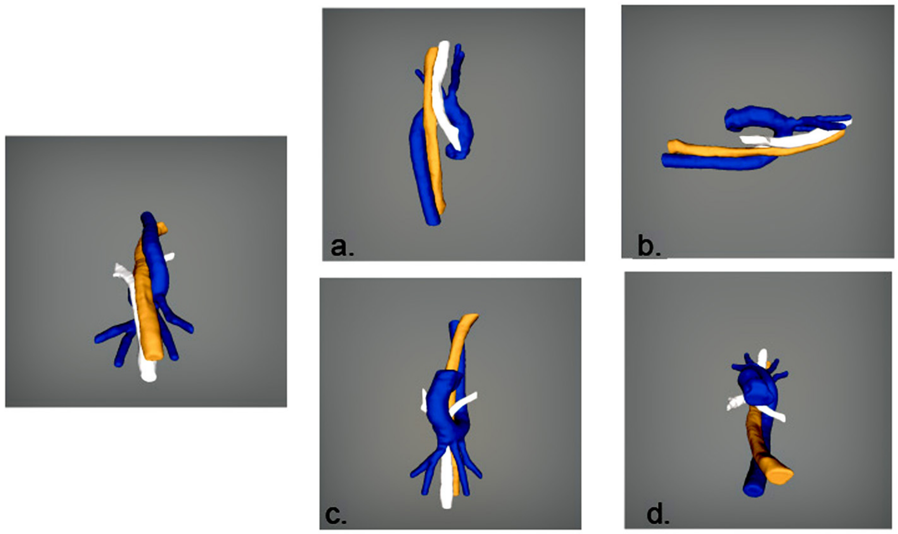
Q8.

Select the **2 figures** that are rotated versions of the target.



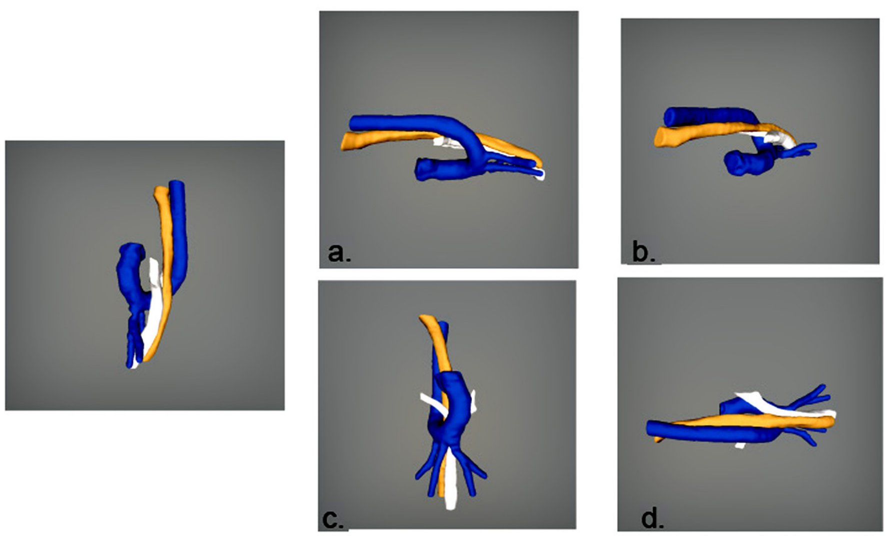
Q9.

Select the **2 figures** that are rotated versions of the target.



Q10.

Select the **2 figures** that are rotated versions of the target.



Appendix E: Instructions for the Spatial Anatomy Task - Identification

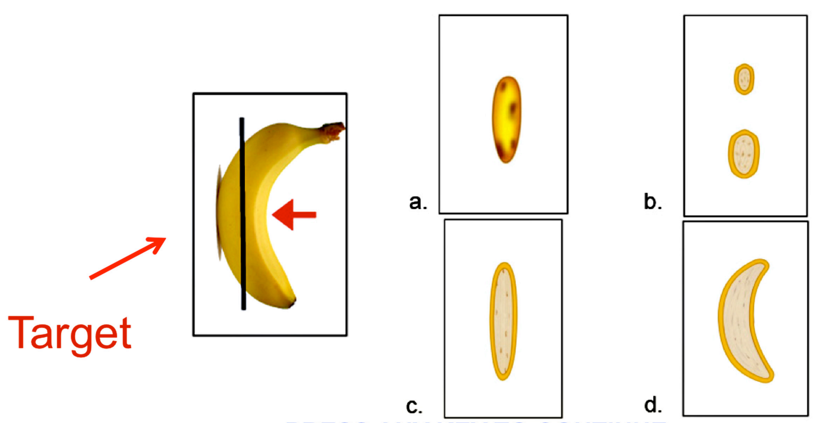
Spatial Task

Part 2

PRESS ANY KEY TO CONTINUE

The second SPATIAL TASK consists of 10 questions. Each question consists of 5 figures – 1 target figure and 4 choice figures. The target figure consists of an object (e.g., a banana or tubes) with a superimposed horizontal (or vertical) line and an arrow pointing towards the line (See example below).

Task: Select the cross-section that would result if the object was sliced at the line and you are looking at the resulting cross-section from the direction of the arrow.



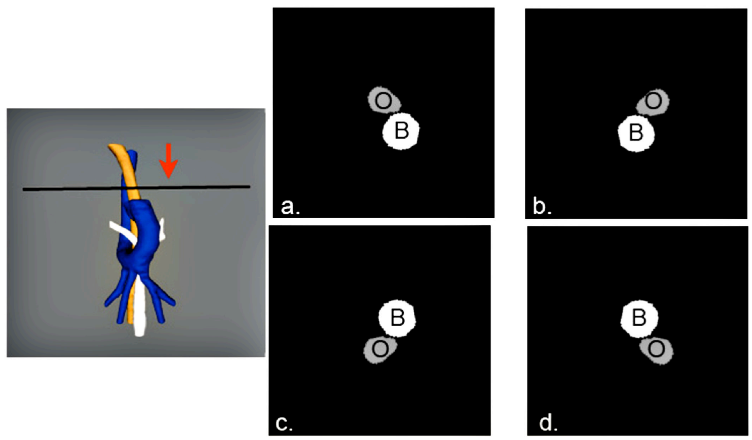
PRESS ANY KEY TO CONTINUE

Answer: c

Here is an example of a SPATIAL TASK question for you to try.

Task: Choose the cross-section that would result if the tubes were sliced at the line and you were looking at the resulting cross-section from the direction of the arrow.

Note: The cross-sections are grayscale images. The circles represent the sliced tubes. The letters in the circle represent the tube colour (**B= blue, O=orange, W=white**).



Answer: d

PRESS ANY KEY TO CONTINUE

Once you start the task, you will be given 10 questions. You will have 2 minutes to complete as many questions as possible.

When you do the task, please remember that there is 1 correct answer for each question.

Please use the keys labeled **‘a, b, c, d’** to make your selection.

You will not be able to change your answer after they have been selected so please be careful when inputting your answer.

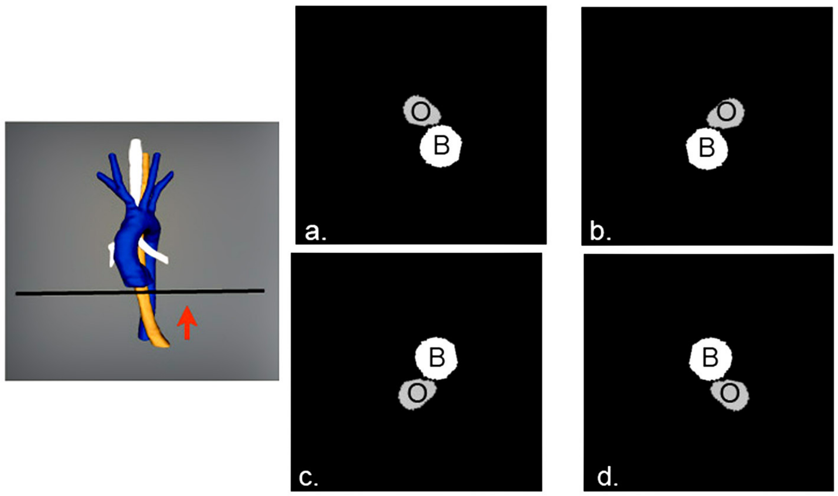
PRESS ANY KEY TO BEGIN TASK

Appendix F: Spatial Anatomy Task - Identification questions

Q1.

Select the cross-section that would result if the tubes were sliced at the line
and you are looking at the resulting cross-section from the direction of the arrow.

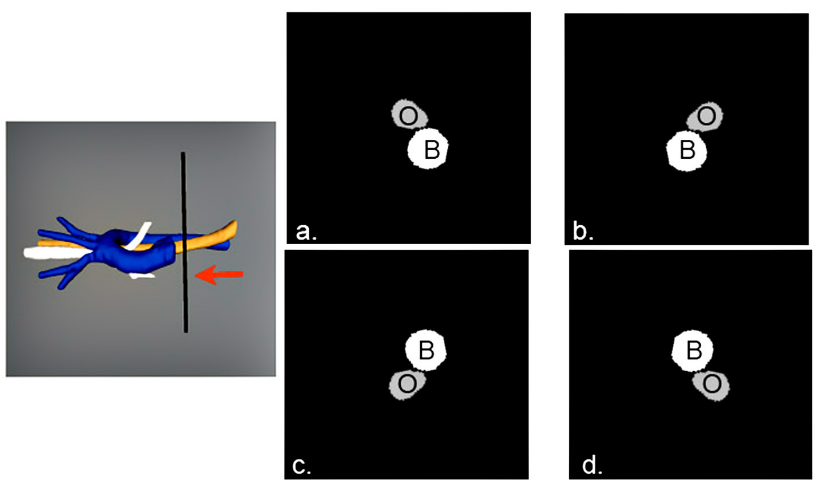
Note: B=blue tube, O=orange tube, W=white tube



Q2.

Select the cross-section that would result if the tubes were sliced at the line
and you are looking at the resulting cross-section from the direction of the arrow.

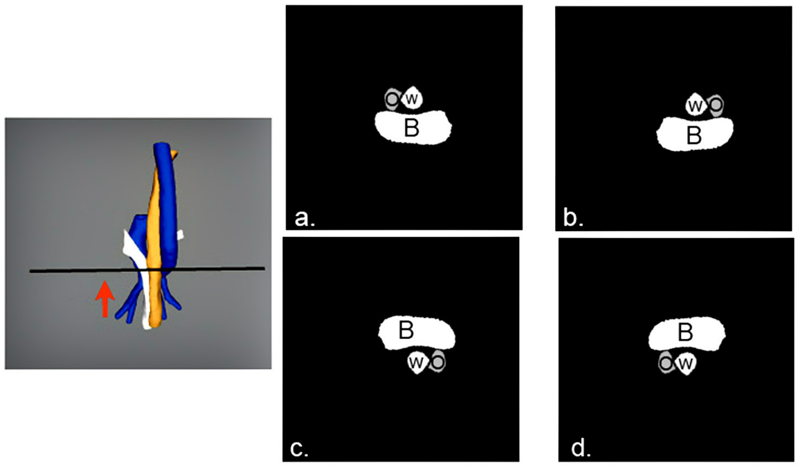
Note: B=blue tube, O=orange tube, W=white tube



Q3.

Select the cross-section that would result if the tubes were sliced at the line
and you are looking at the resulting cross-section from the direction of the arrow.

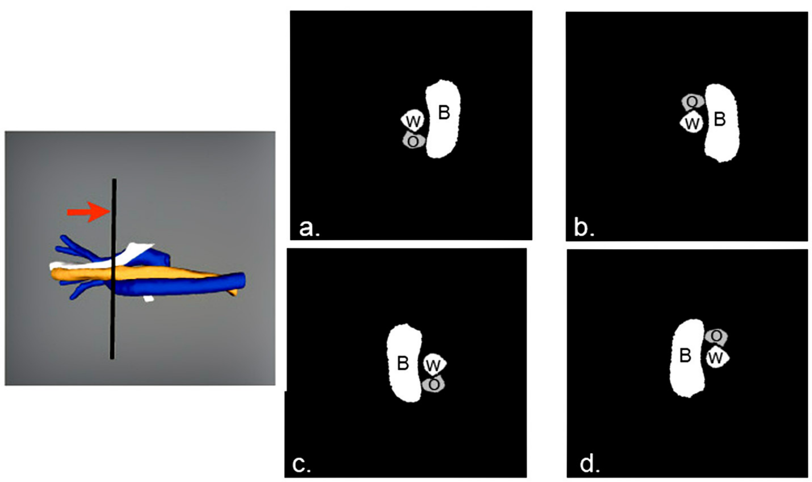
Note: B=blue tube, O=orange tube, W=white tube



Q4.

Select the cross-section that would result if the tubes were sliced at the line
and you are looking at the resulting cross-section from the direction of the arrow.

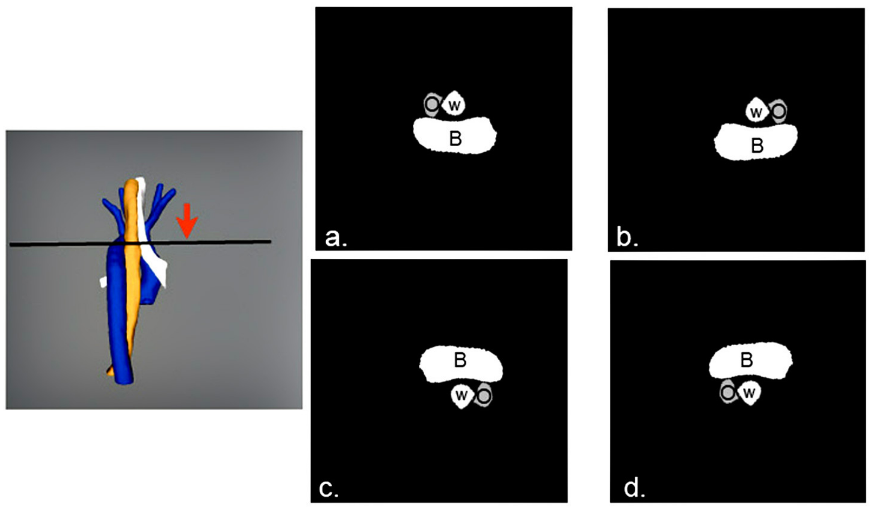
Note: B=blue tube, O=orange tube, W=white tube



Q5.

Select the cross-section that would result if the tubes were sliced at the line and you are looking at the resulting cross-section from the direction of the arrow.

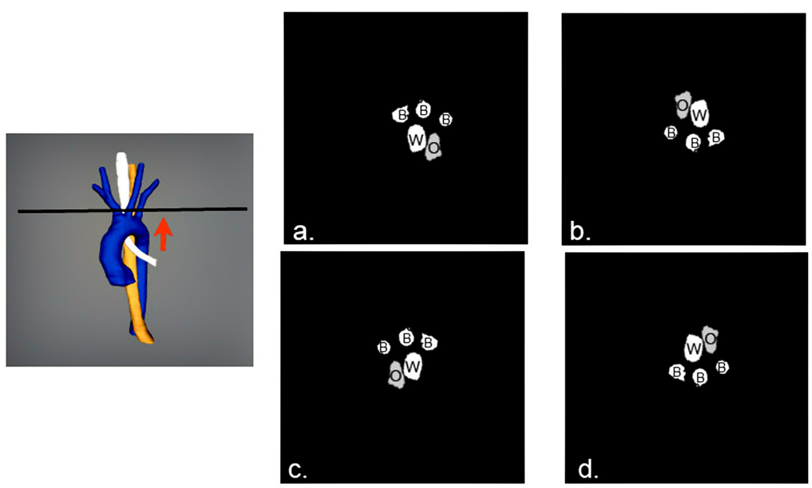
Note: B=blue tube, O=orange tube, W=white tube



Q6.

Select the cross-section that would result if the tubes were sliced at the line and you are looking at the resulting cross-section from the direction of the arrow.

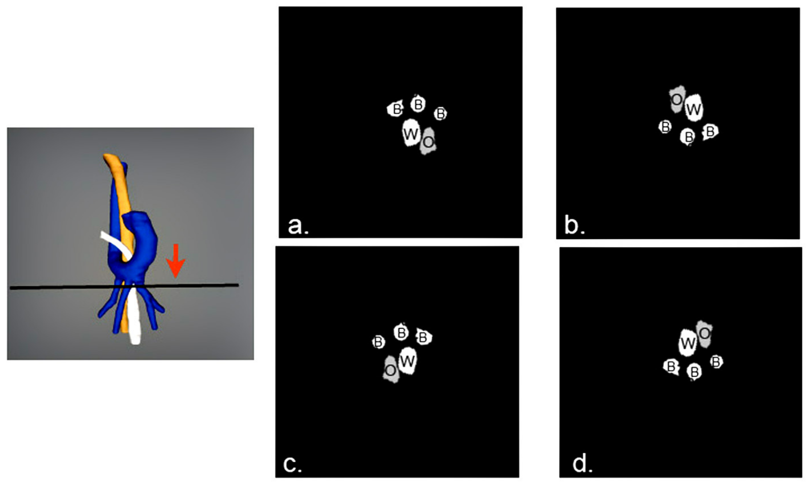
Note: B=blue tube, O=orange tube, W=white tube



Q7.

Select the cross-section that would result if the tubes were sliced at the line
and you are looking at the resulting cross-section from the direction of the arrow.

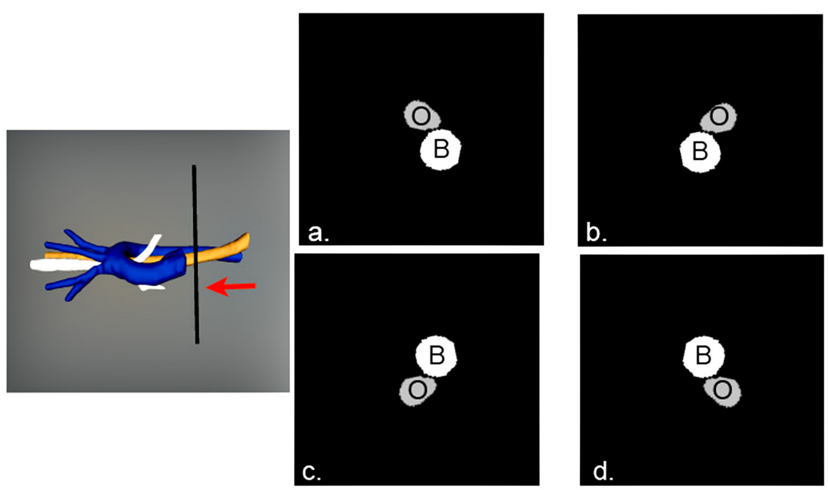
Note: B=blue tube, O=orange tube, W=white tube



Q8.

Select the cross-section that would result if the tubes were sliced at the line
and you are looking at the resulting cross-section from the direction of the arrow.

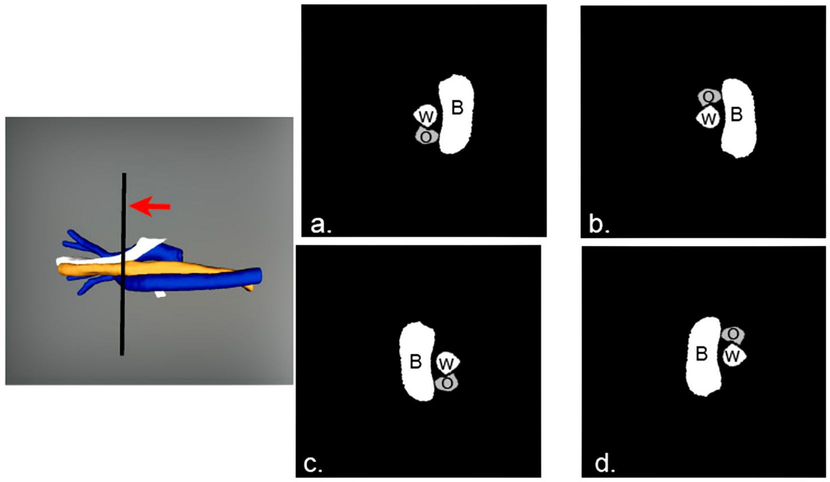
Note: B=blue tube, O=orange tube, W=white tube



Q9.

Select the cross-section that would result if the tubes were sliced at the line
and you are looking at the resulting cross-section from the direction of the arrow.

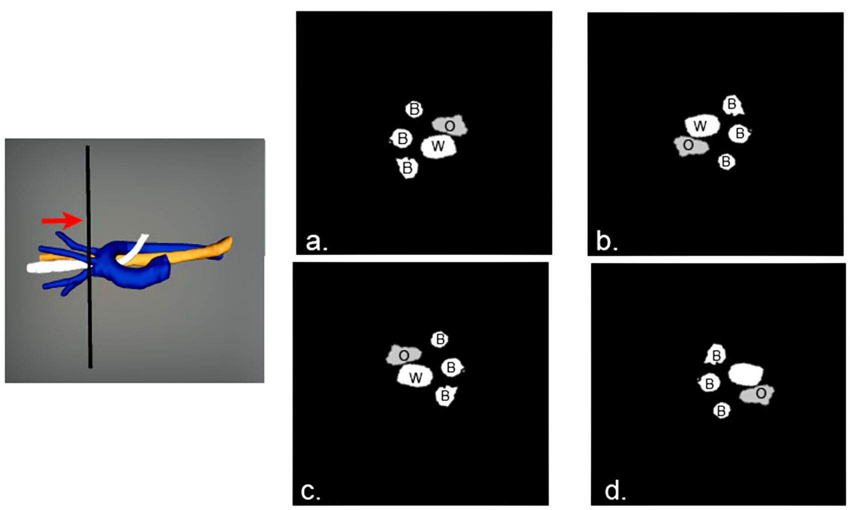
Note: B=blue tube, O=orange tube, W=white tube



Q10.

Select the cross-section that would result if the tubes were sliced at the line
and you are looking at the resulting cross-section from the direction of the arrow.

Note: B=blue tube, O=orange tube, W=white tube



Appendix G: Instructions for the Spatial Anatomy Task - Localization

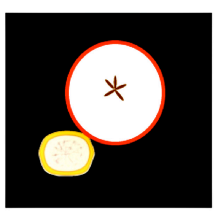
Spatial Task

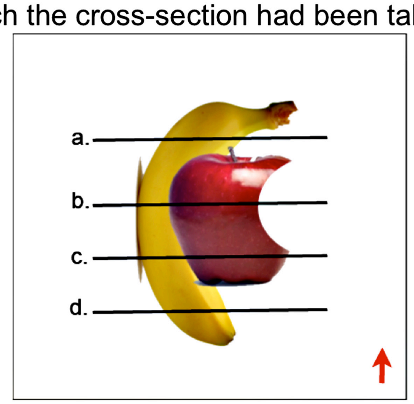
Part 3

PRESS ANY KEY TO CONTINUE

The third SPATIAL TASK consists of 10 questions. For each question, you are given a cross-section of an object. The task is to choose (from 4 answer choices) the correct horizontal or vertical line that represents the level at which the cross-section has been taken.

Example 1: The left image below represents a cross-section of an apple and banana viewed from the direction of the arrow (i.e. below). Please choose the correct line on the right image that represents the level at which the cross-section had been taken.





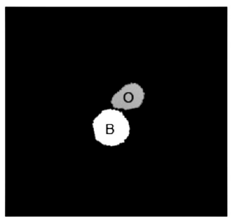
PRESS ANY KEY TO CONTINUE

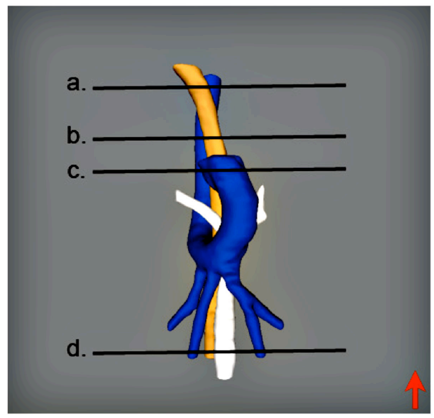
Answer: c

Here is an example of a SPATIAL TASK question for you to try.

Task: Choose the line on the right image that represents the level at which the cross-section has been taken.

Note: The cross-section is a grayscale image. The circles represent the sliced tubes. The letters in the circle represent the tube colour (**B= blue, O=orange, W=white**).





PRESS ANY KEY TO CONTINUE

Answer: b

Once you start the task, you will be given 10 questions. You will have 2 minutes to complete as many questions as possible.

When you do the task, please remember that there is 1 correct answer for each question.

Please use the keys labeled **‘a, b, c, d’** to make your selection.

You will not be able to change your answer after they have been selected so please be careful when inputting your answer.

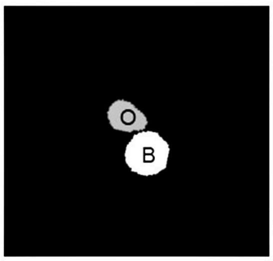
PRESS ANY KEY TO BEGIN TASK

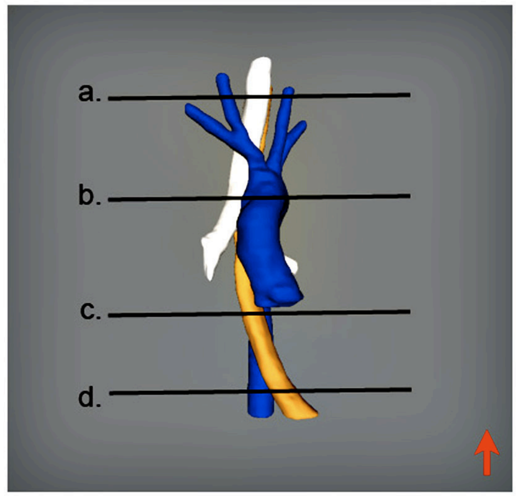
Appendix H: Spatial Anatomy Task - Localization questions

Q1.

Select the line on the right image that represents the level at which the cross-section was taken.

Note: B=blue tube, O=orange tube, W=white tube

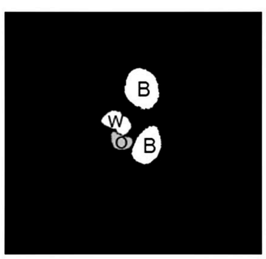


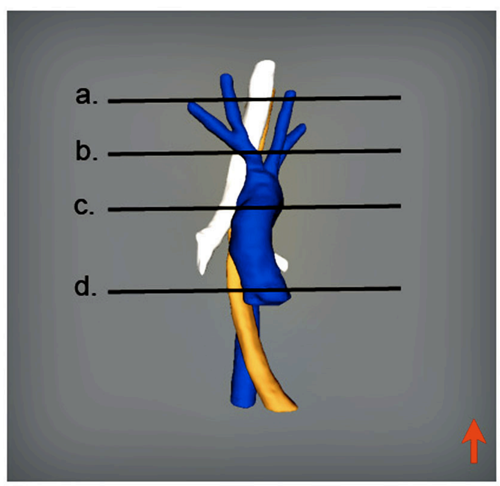


Q2.

Select the line on the right image that represents the level at which the cross-section was taken.

Note: B=blue tube, O=orange tube, W=white tube

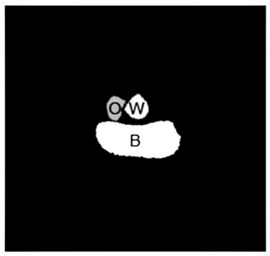


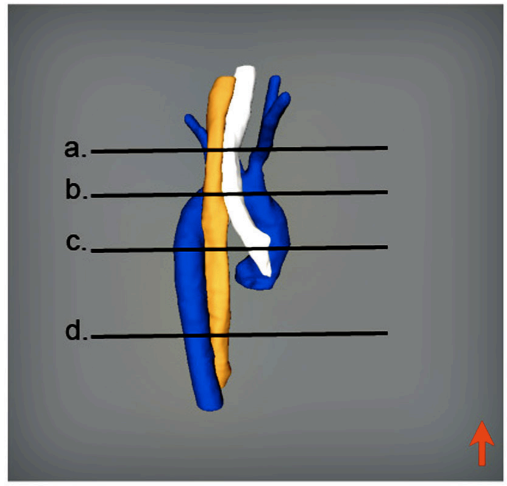


Q3.

Select the line on the right image that represents the level at which the cross-section was taken.

Note: B=blue tube, O=orange tube, W=white tube

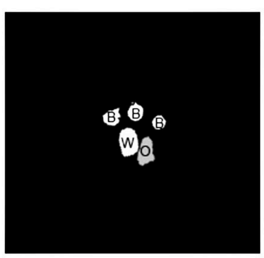


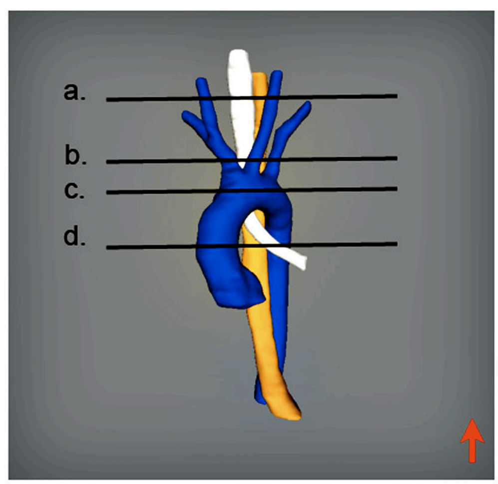


Q4.

Select the line on the right image that represents the level at which the cross-section was taken.

Note: B=blue tube, O=orange tube, W=white tube

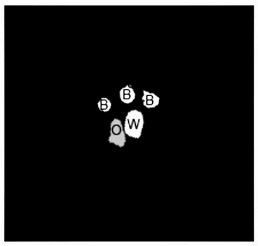


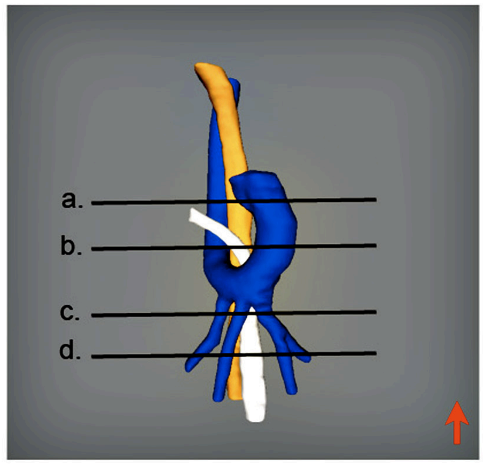


Q5.

Select the line on the right image that represents the level at which the cross-section was taken.

Note: B=blue tube, O=orange tube, W=white tube

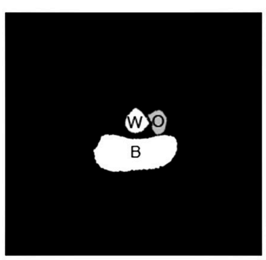


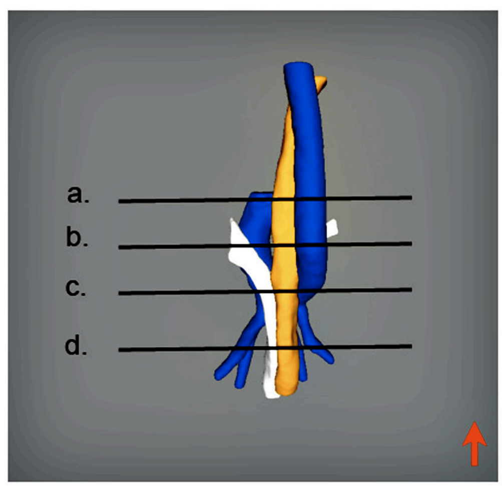


Q6.

Select the line on the right image that represents the level at which the cross-section was taken.

Note: B=blue tube, O=orange tube, W=white tube

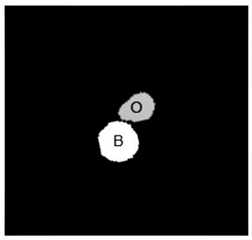


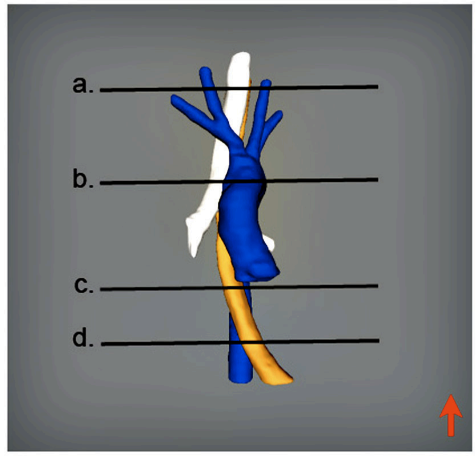


Q7.

Select the line on the right image that represents the level at which the cross-section was taken.

Note: B=blue tube, O=orange tube, W=white tube

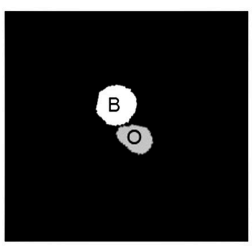


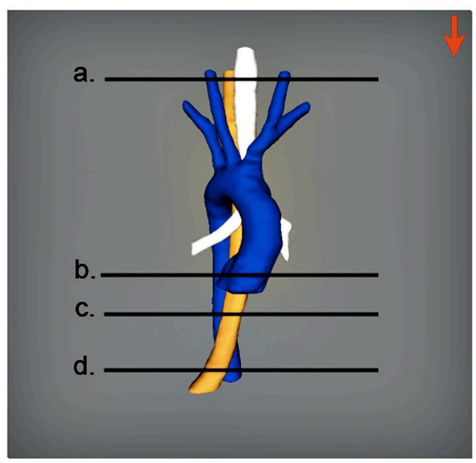


Q8.

Select the line on the right image that represents the level at which the cross-section was taken.

Note: B=blue tube, O=orange tube, W=white tube

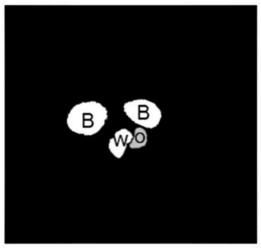


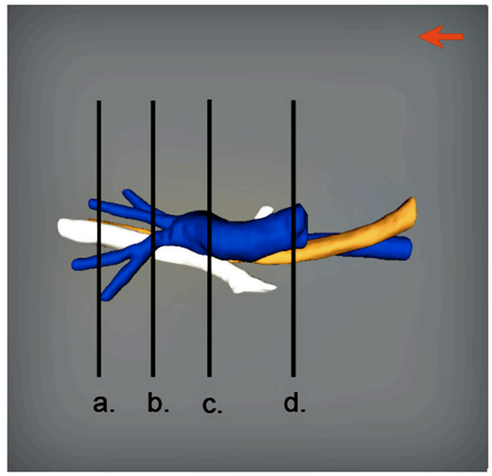


Q9.

Select the line on the right image that represents the level at which the cross-section was taken.

Note: B=blue tube, O=orange tube, W=white tube

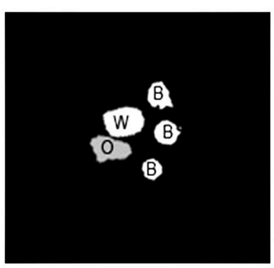


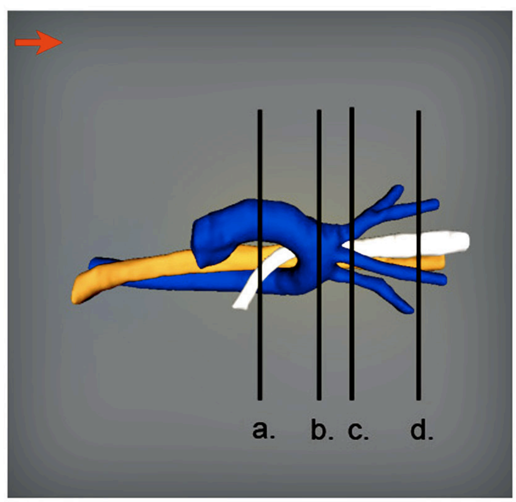


Q10.

Select the line on the right image that represents the level at which the cross-section was taken.

Note: B=blue tube, O=orange tube, W=white tube





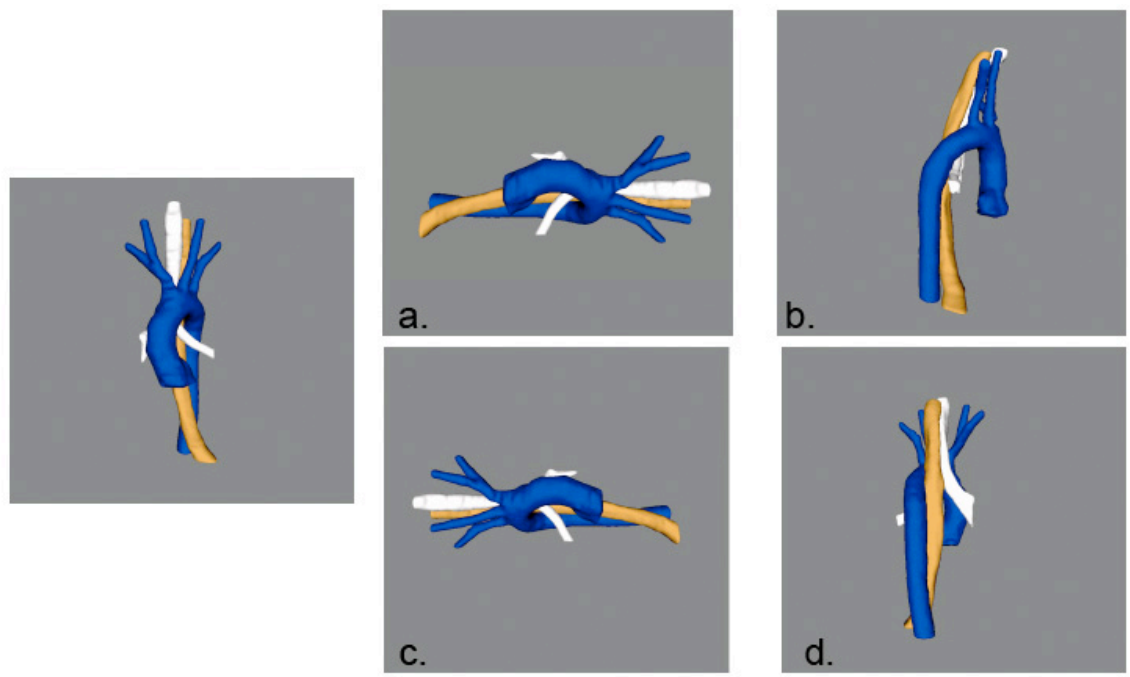
Appendix I: Self-reflective questionnaire

Participant #:____

Self-reflective Questionnaire

The following 22 questions involve self-analysis about the processes and strategies used while answering the spatial task questions. Please select the most appropriate answer for each of the following questions.

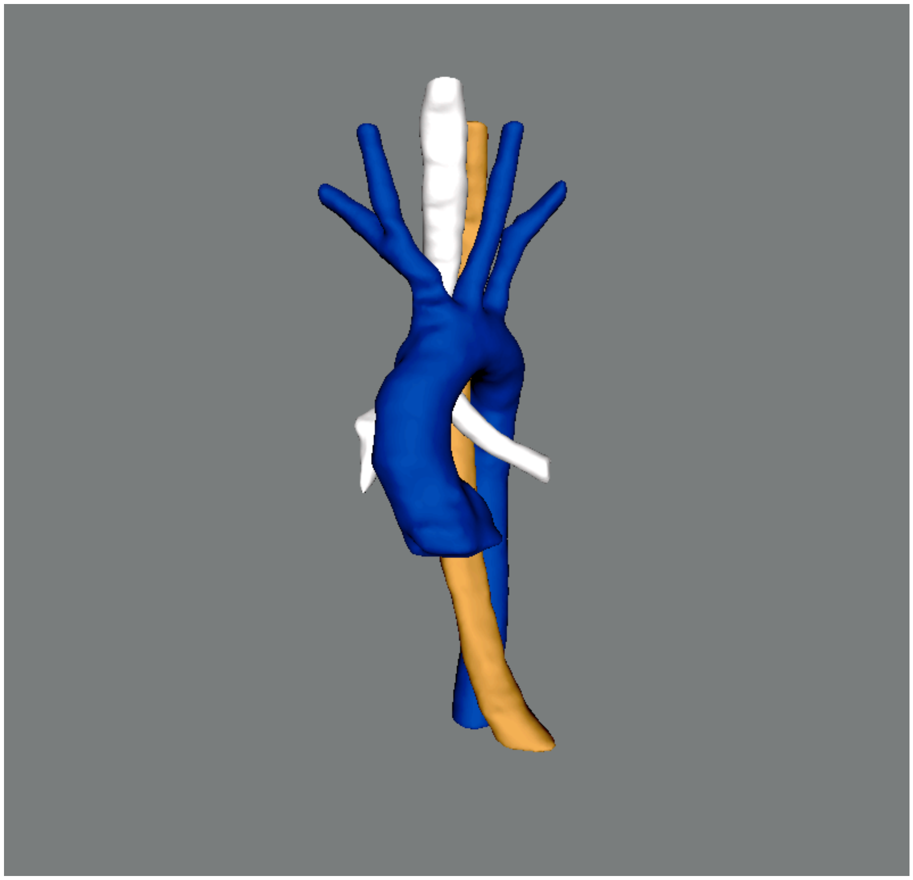
Questions 1-9 are related to the mental rotations task. Recall: this task consisted of 10 problems. Each problem was made up of 5 figures (shown below). Your task was to select the 2 figures that are rotated versions of the target. You were given 2 minutes to complete as many questions as possible.



Answers: 'a' and 'd'

Q1. When answering the **mental rotations task** questions:
a. I imagined rotating all 3 tubes in my mind when making the comparison
b. I imagined rotating 2 of the 3 tubes in my mind when making the comparison
c. I imagined rotating 1 of the 3 tubes in my mind when making the comparison
d. I imagined rotating part(s) of 1 or more tube(s) when making the comparison (e.g., the curvature of the blue tube, or the 'Y' shape branch coming off the blue tube)
e. Other (explain)____

Q2. Please explain or mark on the image below which tube(s) or tube feature(s) you used when making the comparison.



____

____

____

Q3. When answering the **mental rotations task** questions:
a. I imagined rotating the tubes
b. I imagined rotating myself
c. I imagined rotating both the tubes and myself
d. Other (explain)____

Q4. When answering the **mental rotations task** questions:
a. I thought through the steps verbally in my mind (e.g., “rotate tube to the right then up”)
b. I relied mainly on visualizing the figures and did not talk myself through the steps
c. Other (explain)____

Q5. When answering the **mental rotations task** questions:
a. I used movements of my body (e.g., finger, head, hand) and/or objects around me to help me with the task
b. I did NOT use movements of my body (e.g., finger, head, hand) and/or objects around me help me with the task
c. Other (explain)____

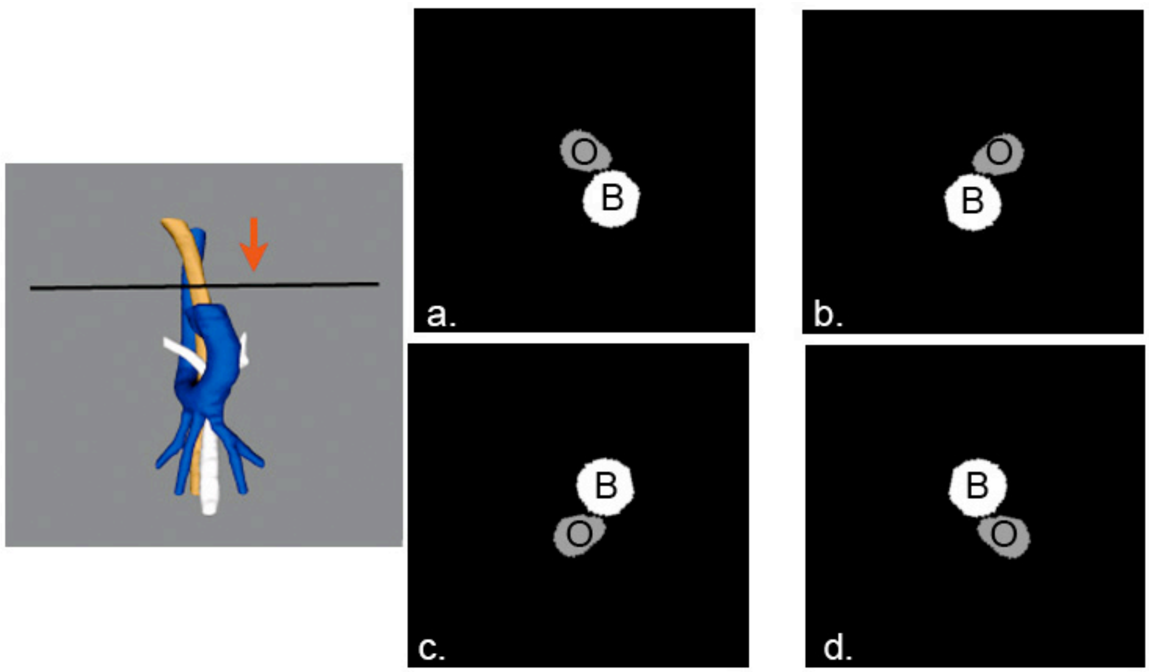
Q6. When answering the **mental rotations task** questions:
a. I scanned the option figures for the most likely match and then made my choices
b. I scanned the option figures systematically, trying the first, then the second etc.
c. I scanned the option figures in a haphazard nonsystematic way
d. Other (explain)____

Q7. When answering the **mental rotations task** questions:
a. I always compared the option figures to the target figure
b. Once I found a match, I compared the rest of the option figures to the match instead of the target
c. I did a bit of both
d. Other (explain)____

Q8. When answering the **mental rotations task** questions:
a. I developed a specific approach to solve the questions
explain ____
b. I tried various approaches to solve the questions
explain ____
c. I had no specific approach
d. Other (explain)____

Q9. When answering the **mental rotations task** questions:
a. I was more concerned with getting the right answers than I was about the time limit
b. I was more concerned with getting all the answers completed than I was about getting the correct answers
c. I did not care how I did it
d. Other (explain)____

Questions 10 -16 are related to the identification task. Recall: this task consisted of 10 problems. For each problem you were given an image of the tubes with a superimposed horizontal (or vertical) line and an arrow pointing towards the line (shown below). Your task was to choose (from 4 answer choices) the correct cross-section that would result if the tubes were sliced at the line and you were looking at the resulting cross-section from the direction of the arrow. You were given 2 minutes to complete as many questions as possible.



Note: The cross-sections are grayscale images. The circles represent the sliced tubes. The letters inside the circles represent the tube colour, B=blue, O=orange, and W=white.

Answer: ‘d’

10. When answering the **identification task** questions:
a. (1) I sliced the tubes, (2) rotated the resulting image to match the orientation of the cross-sections, and (3) selected a cross-section
b. (1) I rotated the tubes to match the orientation of the cross-sections, (2) sliced the tubes, and (3) selected a cross-section
c. (1) I selected a cross-section, (2) rotated the cross-section to match the line on the tube image, (3) repeated steps (1) and (2) until I found the correct cross-section
d. Other (explain)____

Q11. When answering the **identification task** questions:
a. I imagined rotating the tubes
b. I imagined rotating myself
c. I imagined rotating the tubes and myself
d. Other (explain)____

Q12. When answering the **identification task** questions:
a. I scanned the cross-sections for the most likely match and then made my choice
b. I scanned the cross-sections systematically, trying the first, then the second etc.
c. I scanned the cross-sections in a haphazard nonsystematic way
d. Other (explain)____

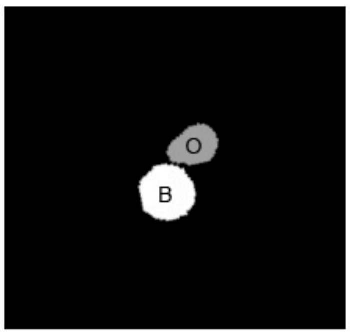
Q13. When answering the **identification task** questions:
a. I thought through the steps verbally in my mind (e.g., "slice then rotate")
b. I relied mainly on visualizing the images and did not talk myself through the steps
c. Other (explain)____

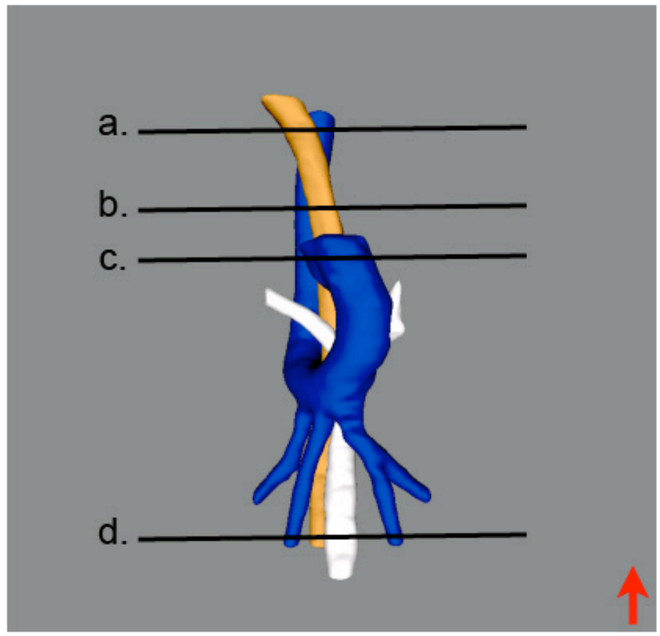
Q14. When answering the **identification task** questions:
a. I used movements of my body (e.g., finger, head, hand) and/or objects around me to help me with the task
b. I did not use movements of my body (e.g., finger, head, hand) and/or objects around me to help me with the task
c. Other (explain)____

Q15. When answering the **identification task** questions:
a. I developed a specific approach to solve the problems
explain ____
b. I tried various approaches to solve the problems
explain ____
c. I had no specific approach
d. Other (explain)____

Q16. When answering the **identification task** questions:
a. I was more concerned with getting the right answers than I was about the time limit
b. I was more concerned with getting all the answers completed than I was about getting the correct answers
c. I did not care how I did it
d. Other (explain)____

Questions 17-22 are related to the localization task. Recall: this task consisted of 10 problems. For each problem you were given a cross-section of the tubes (shown below). Your task was to choose (from 4 answer choices) the correct horizontal or vertical line that represents the level at which the cross-section has been taken. You were given 2 minutes to complete as many questions as possible.





Answer: 'b'

Q17. When answering the **localization task** questions:
a. I imagined rotating the cross-section to match the orientation of the lines
b. I imagined slicing then rotating the tubes to match the orientation of cross-section
c. I imagined rotating then slicing the tubes to match the orientation of the cross-section
d. Other (explain)____

Q18. When answering the **localization task** questions:
a. I thought through the steps verbally in my mind (e.g., "rotate then superimpose")
b. I relied mainly on visualizing the images and did not talk myself through the steps
c. Other (explain)____

Q19. When answering the **localization task** questions:
a. I scanned the horizontal/vertical lines for the most likely match and then made my choice
b. I scanned the horizontal/vertical lines systematically, trying the first, then the second etc.
c. I scanned the horizontal/vertical lines in a haphazard nonsystematic way
d. Other (explain)____

Q20. When answering the **localization task** questions:
a. I used movements of my body (e.g., finger, head, hand) and/or pencil to help me with the task
b. I did not use movements of my body (e.g., finger, head, hand) and/or pencil to help me with the task
c. Other (explain)____

Q21. When answering the **localization task** questions:
a. I developed a specific approach to solve the problems
explain ____
b. I tried various approaches to solve the problems
explain ____
c. I had no specific approach
d. Other (explain)____

Q22. When answering the **localization task** questions:
a. I was more concerned with getting the right answers than I was about the time limit
b. I was more concerned with getting all the answers completed than I was about getting the correct answers
c. I did not care how I did it
d. Other (explain)____

Appendix J: Answer key to the Spatial Anatomy Task questions

Spatial Anatomy Task		
Mental rotations	Identification	Localization
1ad	1a	1c
2ab	2c	2c
3bc	3b	3b
4cd	4c	4b
5ac	5d	5c
6bd	6a	6c
7ab	7b	7d
8ab	8c	8c
9ad	9a	9c
10bc	10c	10c

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