Embodied Cognition and Virtual Reality in Learning to Visualize Anatomy

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Abstract

This study examines the facilitative effects of embodiment of a complex internal anatomical structure through three-dimensional ("3-D") interactivity in a virtual reality ("VR") program. Since Shepard and Metzler's influential 1971 study, it has been known that 3-D objects (e.g., multiple-armed cube or external body parts) are visually and motorically embodied in our minds. Such findings confirm the theory that our mental images, and rotations of these images, are in fact confined by the laws of physics and biomechanics, because we perceive, think and reason in an embodied fashion. With the advancement of new technologies, virtual reality programs for medical education now enable users to interact directly in a 3-D environment with internal anatomical structures. Given that such structures are not readily viewable to users and thus not previously susceptible to embodiment, coupled with the VR environment affording all possible degrees of rotation, how people learn from these programs raises new questions. If we embody external anatomical parts we can see, such as our hands and feet, can we embody internal anatomical parts we cannot see? Does manipulating the anatomical part in virtual space facilitate the user's embodiment of that structure and therefore the ability to visualize the structure mentally?

Medical students grouped in yoked-pairs were tasked with mastering the spatial configuration of an internal anatomical structure; only one group was allowed to manipulate the images of this anatomical structure in a 3-D VR environment, whereas the other group could only view the manipulation. The manipulation group outperformed the visual group, suggesting that the interactivity that took place among the manipulation group promoted visual and motoric embodiment, which in turn enhanced learning. Moreover, when accounting for spatial ability, it was found that manipulation benefits students with low spatial ability more than students with high spatial ability.

Keywords: Embodied cognition; Virtual reality; Visualization.

Introduction

Virtual reality programs have the potential to be the most dramatic change in the way anatomy is taught since Vesalius's richly illustrated volumes of the human body based on careful and intricate cadaver dissections. Although computer technology has undoubtedly transformed the manner in which doctors evaluate and treat their patients (e.g., CT scans, robotic surgery), the methods used to teach medical students have been in place for centuries (e.g., lectures, anatomy textbooks, cadaver dissection). Some believe this is all about to change. Virtual reality ("VR") programs for medical education now enable users to interact directly with, as well as view, anatomical parts in three-dimensions, with the potential to change the way medical students learn anatomy, perform dissections and even practice surgical procedures.

The advent of these programs raises questions for cognitive psychologists, some of which this study aims to address. At the broadest level: how are complex, internal anatomical structures learned through 3-D viewing and interactivity? What factors, from both a cognitive and human-computer interaction perspective, contribute to the learning of anatomy through these VR programs?

This study considers the above-mentioned factors under the framework of embodied cognition: that cognition is inextricably linked to our physical interactions with our environment (Wilson, 2002). Using the embodied cognition framework, this study explores the following research questions: 1) Does the physical manipulation of, versus solely viewing, a complex internal anatomical structure in a virtual reality program facilitate a better visualization of the structure? 2) Does spatial ability affect participants' visualizations in this particular study?

Theoretical Background

The theoretical framework underlying and informing the questions in this study bridges two distinct areas of cognitive psychology through the lens of embodied cognition: mental rotation and imagery and multimedia learning.

Studies in mental rotation and imagery provide some of the most compelling evidence of how cognition is rooted in our bodily interactions with the environment. Shepard & Metzler's seminal research showed that people mentally manipulate objects similarly to the way they would with actual objects in physical space, and that the time it takes to rotate the image increases linearly with the degree of rotation (Shepard & Metzler, 1971; Shepard & Cooper, 1982). Subsequent research using the Shepard & Metzler paradigm has confirmed the proposition that motor processes are involved in mental rotation (Wexler et al., 1998) and that motor cortices (primary/M1 or premotor cortex) are activated when performing the task (Kosslyn et al., 1998).

Additional research in mental rotation and imagery has helped to clarify and refine the nature and extent to which motor processes are connected to mental rotation and imagery. For example, it is known that there are differences in the way we conduct mental rotations of an object as compared with a body part. This difference arises because the trajectory imagined, for example, for the observer's hand or foot is strongly influenced by the biomechanical constraints specific to the actual movement of the hand and foot. For example, people are faster and more accurate at performing mental rotations of drawings of hands or identifying which hand is pictured when they are asked to imagine rotating the hand that does not require difficult bodily movements (Parsons, 1987a, b; Schwoebel et al., 2001). Given the details of the way the body actually works, the motor imagery system actively facilitates or constrains how quickly mental imagery is executed. Neuropsychological studies have proven that motor processes are recruited when we imagine and manipulate complex 3-D structures in our mind but also that the body's biomechanical constraints actually affect our ability to conduct mental rotations (Amorim et al., 2006).

Research in the area of multimedia learning endeavors to complement the research discussed above in embodied cognition and mental rotation and imagery by analyzing how multimedia programs may be designed to maximize learning and understanding. Recent theories and studies have focused on how the motor or haptic channel, through direct tactile manipulation and feedback can aid in deeper learning and understanding and the degree to which interactivity of any kind is productive (Meyer & Kieras, 1997; Chan & Black, 2006; Black, in press). For example, Chan & Black (2006) investigated how seventh graders are better at visualizing complex concepts such as Newtonian mechanics if they are able to interact with a technology-rich environment allowing for direct-manipulation animation ("DMA"). DMA allowed learners to interact directly with navigation controls, determine their viewing direction and to control the pace of the navigation of the content. Chan & Black found that DMA, which incorporated the haptic channel in the learning process, provided learners with a superior learning experience as compared with those who were in the non-haptic groups (narrative-only, narrative-and static visuals, narrative and animation) about causal interactions and functional relations in systems.

Despite the ubiquity of computer programs that exist for 3-D visualizations of anatomy, there are very few empirical investigations on what makes such programs effective. These studies have started to investigate, from a human-computer interaction and cognitive perspective, what factors contribute to developing successful visualizations of complex anatomy (or anatomy-like) structures from various 3-D visualization programs. From the corpus of these studies, the following variables have emerged as being significant: 1) manipulation (or interactivity) of the 3-D object versus just viewing, 2) the importance of having access to certain views and/or orientations of the structure, and 3) spatial ability of the learner. The most significant studies were conducted by Garg and his colleagues (Garg et al., 1999, 2001, 2002) and Keehner and her colleagues (2008a, b), who concluded that developing accurate visualizations of an anatomical (or anatomical-like) structure has more to do with participants' access the critical views and orientations of the structure than being able to interact with it, and furthermore, that such programs should be used carefully with those with lower spatial ability were found to have had a harder time learning from such programs.

Yet, it is curious that the exact opposite findings have been found in some studies where active exploration appeared to benefit those participants with low spatial ability scores over those with higher spatial ability scores. In a study conducted by Luursema et al. (2006), participants were divided into groups viewing the same computer-generated 3-D images of anatomical parts of the abdomen, but with half of the group viewing the images stereoptically (using shutter-glasses), providing actual depth perception, and the other half of the group viewing the images binocularly (without shutter glasses). Luursema et al. found that a "combination of computer-implemented *stereopsis* (visual depth through seeing with both eyes) and *dynamic exploration* (being able to continuously change one's viewpoint with respect to objects studied in real-time) is beneficial to anatomical learning" (p. 455), and that participants with low visuo-spatial ability benefited more from this combination than participants with high visuo-spatial ability. In a more recent study, Meijer & van den Broek (2010) also found that active exploration actually improved low spatial participants' 3-D mental representations of complex 3-D objects (and had no effect on middle or high spatial participants' representations).

Research Design and Questions

This study builds from, as well as aims to overcome some of the potential confounds of the previous studies, in investigating the effects of interactivity and embodiment in a VR system when learning a complex, internal anatomical structure. First, the computer 3-D visualization program used in this study is more intuitive from a visual and motor processing standpoint. This VR system provides the user with stereoscopic vision with 3-D goggles, allowing for full depth perception of the object of study. In addition, this system has a joystick that allows the user to interact physically/motorically with the virtual object in a similar manner as one would outside of a virtual environment. Both these elements would, in theory, foster a stronger sense of embodiment because of the more realistic and natural aspects of visual and motor information in the VR system. Therefore, it is possible that if the interface of the VR program allows for a more intuitive mechanism for viewing and rotating the virtual object, and is compatible with the human body's natural movements, a participant might be able to develop a better internal 3-D visualization of a complex anatomical structure.

Second, the stimulus used in this study is an internal anatomical structure (as opposed to a fictitious structure or external body part) – the inner ear. In Garg et al.'s studies, it is possible that the findings were confounded by the stimulus material – the carpal bones – because it is a part of the body that people are very familiar with both visually and motorically. That is, the wrist falls on two natural planes, and people are used to seeing as well as feeling their wrists in those two common positions. Therefore, it is not surprising that there are canonical views of the wrist that would naturally transfer to canonical views of the carpal bones within the wrist. Furthermore, using an internal anatomical structure free of any joint articulation or specific visual cues to orient the structure allows us to begin to investigate how (if at all) and which canonical views users develop of this structure during their study time. In essence, it is addressing the issue of whether the user literally embodies (or maps onto him/herself) the internal anatomical structure.

With these changes, this study addresses the following research questions:

1) Does the physical manipulation of, versus solely viewing, a complex internal anatomical structure in a virtual reality program facilitate a better visualization of the structure? If so, is there a difference in visualizing: a) different sub-structures within the larger structure that have different shapes, i.e., line (e.g., the path of a nerve) versus circles (e.g., semi-circular canals protruding off a surface); and b) the structure from different vantage points (i.e., anatomical planes)?

2) Does spatial ability affect participants' visualizations in this particular study? If so, does it have a different effect for: a) participants who manipulate versus view the structure; and/or b) participants with differing spatial abilities (i.e., low versus high)?

Method

Participants

Seventy-six medical students between the ages of 20-38 years at the University of Medicine and Dentistry of New Jersey, Newark, participated in this study. None of the participants had formal instruction of the inner ear or prior exposure to the VR machine.

Materials

The VR system and target anatomical structure

The VR machine is housed at the University of Medicine and Dentistry, Newark. It generates a stereoscopic 3-D environment that is viewed through stereoscopic 3-D goggles. It has a free-moving, non-mounted joystick, enabling the user to hold, control and manipulate the movement (by rotating on an x-, y-, and z- axis) of the 3-D representation of the anatomical structures in a similar manner as one would be able to with a tangible object outside of a virtual environment.

The target anatomical structure is the inner ear. The inner ear is a structurally complex system concentrated in a very small area in the human skull. The virtual ear model was developed by an otolaryngologist at UMDNJ in conjunction with the engineers of the VR program to ensure accuracy of the model.

Pre-test measures

Participants took the following pre-tests prior to working on the VR machine: 1) a background questionnaire which includes questions on comfort level of using a joystick and playing video games, as well as any prior use of working with 3-D modeling programs; 2) an ear anatomy questionnaire; 3) Vandenberg & Kuse (1978) Mental Rotation Test ("MRT"). This is a standardized test of spatial ability that assesses one's ability to rotate and visualize a 3-D structure; and 4) Ekstrom et al.'s Building Memory Test. This standardized test was used assess participants' ability to remember the location of an object within a map.

Post-test measure

A series of snapshots of the virtual ear model were taken in the following anatomical planes: lateral, superior, inferior, anterior and posterior. The purpose of using all these anatomical planes is to create a 3-D "voxel" of the area of study. For each plane, two snapshots were produced, one without the facial nerve and another without the semi-circular canals. Therefore, the post-test consisted of a total of 10 snapshots.

Procedure

Each participant was tested individually. First, each participant completed all four pre-test measures. Next, the participant was randomly assigned to one of the two conditions (*manipulation, visual)*. The *manipulation* participant was given a brief training period with the joystick in the VR machine. Once the participant indicated that he/she felt comfortable using the joystick, the target anatomical structure (inner ear model) was presented. After providing a brief explanation of the inner ear and how it was positioned in a surgical position, the participant was asked to study the spatial configuration of two sub-structures within the inner ear: the facial nerve and the semi-circular canals. The *manipulation* participant was informed that he/she could use the joystick to rotate the ear model, and was given 5 minutes to study. Each *manipulation* participant's study of the inner ear, based on his/her own joystick movements, was recorded in the VR machine, which was then shown to the yoked, *visual* participant. After the study period, each participant was given the 10 post-test snapshots (randomized order by sub-structure) and asked to draw in, to the best of his/her ability, the missing sub-structure.

Coding

The drawings were assessed for accuracy of visual representation on the following criteria: parts, angle and placement and size. The various individual criterions were summed to derive the following TOTAL scores: 1) overall TOTAL; 2) TOTAL for each anatomical plane; 3) TOTAL for facial nerve; 4) TOTAL for semi-circular canal. The researcher and an independent coder coded the post-test.

Both coders were blind to the identity of the participants and condition assignment each coded all 760 drawings.

Analysis and Results

Participants in the *manipulation* condition scored higher than those in the *visual* condition on all the TOTAL scores (Table 1).

Table 1. Mean score analysis on all dependent measures

	Manipulation Mean (s.d.)	Visual Mean (s.d.)	t(37), p
TOTAL	72.47 (7.303)	60.76 (11.391)	6.437, <.001
TOTAL by sub-structure			
facial nerve	32.39 (5.900)	26.71 (6.375)	4.870, <.001
semi-circular canals	39.74 (3.020)	33.82 (6.673)	5.029, <.001
TOTAL by anatomical plane			
lateral	15.11 (2.051)	13.58 (2.937)	3.153, =.003
superior	13.92 (1.440)	11.63 (2.562)	5.663, <.001
inferior	13.79 (2.183)	10.74 (2.565)	6.481, <.001
anterior	14.18 (2.078)	12.13 (2.622)	4.830, <.001
posterior	15.03 (2.175)	12.45 (2.738)	4.700, <.001

A correlational analysis of all the pre-test measures with TOTAL score showed that only MRT was correlated (r = .0325). A one-way analysis of covariance (ANCOVA) was conducted using MRT as the covariate. A significant interaction effect was found between MRT and condition on TOTAL score, F (1, 35) = 5.168, p < .029. Simple group main effects tests were conducted to assess differences between those who scored lower on the MRT (1 *SD* below the mean = 11.274) and those who scored higher on the MRT (1 *SD* above the mean = 27.166) (Figure 1).

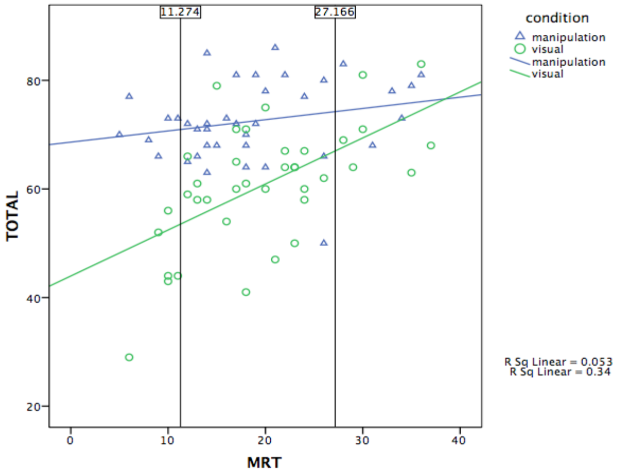

Figure 1. Differences on TOTAL score performance between the two conditions on two levels (high versus low) of the covariate (spatial ability).

Given that the statistical analysis revealed that those in the *manipulation* condition had more accurate 3-D visualizations of the inner ear over those in the *visual* condition, some ancillary questions arose with respect to what the participants in the *manipulation* group were doing. For example, were there certain strategies used by the *manipulation* participants that enabled better embodiments of the inner ear? That is, were there common characteristics of the manner in which *manipulation* participants rotated the structure that led to highly successful performance on the post-test? Or, conversely, what were the common characteristics among *manipulation* participants who performed relatively poorly on the post-test?

A qualitative video profile of the top and bottom performing manipulation participants showed that common characteristics might exist on either end. First, among the top performing manipulation participants, they quickly oriented the structure into the posterior plane, which when put in context of the human body means positioned in an upright manner, standing up and looking forward. In addition to standing the model upright, the top manipulators often went back to this posterior view after exploring other views (as though it grounded them in some way), suggesting this view was the one they were most comfortable with. In contrast, the lowest scoring manipulators did not position the structure in an upright position as quickly as those in the top scoring group. There was no particular familiar or comfortable perspective that developed among the low scorers. Second, all the high scoring participants spent more time studying still positions as opposed to moving the object continuously. In contrast, the low scoring manipulators generally spent their time moving and rotating the object in various, haphazard directions and not holding it still.

Third, and perhaps most interestingly, when the high scoring manipulators moved between these still positions, they moved in a "wiggling" manner between these two planes. There were two kinds of wiggling among the top scoring *manipulation* participants. One type was a wiggling that constituted alternating between two still positions, in what appeared to be a comparison and analysis of the two positions. Another strategy demonstrated a different type of wiggling: choosing one "still" position and varying the view of that position by only a few degrees in either direction.

Discussion and Conclusions

The main finding of this study is that manipulating, rather than viewing, an internal anatomical structure in virtual space strengthens the embodiment of that structure and therefore the ability to visualize the structure. As demonstrated in the analysis (Table 1), the *manipulation* group outperformed the *visual* group regardless of whether the participants were visualizing different anatomical sub-structures or from different orientations (i.e., anatomical planes). Participants who are afforded the opportunity to manipulate in virtual space 3-D images of anatomical structures with which they are not familiar outperform participants who are only given the opportunity to watch the 3-D images being rotated. Such results support the general framework of embodied cognition, that there is an intimate connection between our motor and visual processes, and the more explicit the connection, the better the learning.

Beyond this main finding that the motor and visual processes are connected and provide stronger learning, it is posited that the participants may literally have tried to embody (to varying degrees) the inner ear model by mapping it onto their own bodies. Results of TOTAL scores by anatomical plane, combined with the video analysis, support the theory that the virtual inner ear was embodied by the participants in this study in a more literal sense of the term embodiment – that is, that they mapped the structure onto (or within) their own bodies. The results from the mean score analysis (Table 1) show that regardless of condition, participants performed better on the planes we are more familiar with seeing ourselves and others in (lateral, posterior and anterior) over less familiar planes (superior, inferior). As a general matter, we are much more comfortable and familiar with looking at others face-to-face rather than looking down a person's head (superior) or up a person's chin (inferior). This conclusion is similar to ones reached in studies by Parsons and others who have shown that the real world biomechanical constraints on our physical bodies do in fact constrain our mental abilities – specifically the ability to rotate and visualize a body part in our mind. Therefore, it is possible that participants in *both* the manipulation and visual conditions found that visualizing the ear from the superior and inferior planes was a somewhat physically awkward perspective to embody, as it is rare to look into the top of one's head or look up into one's chin. Even though the virtual ear was displayed in the absence of surrounding physical landmarks that would immediately cause the viewer to orient the image in an upright position, there was a way to orient the image (via embodiment) that made it the anatomical plane more familiar and more comfortable to the participants.

Further support for the embodiment theory is that the video analysis revealed that the top manipulators developed a *canonical viewpoint* (Palmer, Rosch & Chase, 1981) for this model. Palmer et al. coined the term canonical viewpoint to describe perspectives in which identification performance of 3-D objects is best. The canonical viewpoint for the ear model appears to be the posterior plane. The qualitative video analysis revealed that the top scoring manipulators started their study with the structure oriented in the posterior plane and often returned to this position as though it was the most stable position. Given that this is their canonical view, it strongly suggests that the manipulators literally embodied – that is, they mapped onto themselves the inner ear from the perspective of their own body schema, or rather that they projected their bodies onto the object in an embodied fashion, maintaining the body axes (head-feet, front-back, and left-right) when doing so ("bodily projection", Lakoff & Johnson, 1999).

The results from this study also illustrate the facilitative effects of interactivity on embodiment and that the development of an internal visual representation of a 3-D structure depends on the spatial ability of the participant. Specifically, the benefits of embodiment in virtual reality appear to be greater for those participants with lower spatial ability. As shown in Figure 1, those who score lower on tests of rotational spatial ability have more to gain from interacting with a 3-D virtual reality environment than those with high rotational spatial ability. There is a greater difference between the two regression lines at a low MRT score versus at a high MRT score, indicating that manipulation, which strengthens embodiment, may help those with lower spatial ability to perform as well as those who have higher spatial abilities (and may not need the manipulation experience).

It is important to note that the main effect of interactivity runs counter to some of the more relevant studies discussed in the literature review (Garg et al., Keehner et al.) who argue that interactivity, which allows for complete freedom of movement and exposure to views from varying perspectives, may overload the learner and prevent effective visualizations. Why is it then that in this study the participants in the *manipulation* condition outperformed the *visual* participants? Perhaps the answer is that this virtual reality program provided a stronger sense of embodiment or "presence" (Usoh et al., 1999) for the *manipulation* participants with the intuitive interface and stereoscopic depth perception of the target structure. Luursema et al. (2006) used a similar program and found that the combination of stereopsis and dynamic exploration to be beneficial for anatomy learning.

There are some limitations in this study. Regarding the dependent measure, the drawing test, it could be argued that assessing the accuracy of visualization by evaluating a participant's drawings may favor participants who have good drawing skills, while disadvantaging participants who may have successfully understood the visual features of the anatomical structures but were less skilled at transmitting their understanding onto several sheets of paper. One way that a future study might be able to address this limitation is to complement the drawing test with an interview of the participant in which the participant would describe his or her understanding of the anatomical structures and/or explain what he or she was trying to draw.

Another potential confound that exists in this study relates to the yoked-pairs design. Although this design is effective in terms of providing the participants in both conditions with the same visual information, it may be argued that certain strategies employed by the *manipulation* participant may make no difference, or may in fact actually hinder the *visual* participant when studying the model. For example, the wiggling that was used by many top performing *manipulators* may have introduced noise or confusion to the yoked, *visual* participant, which in turn made learning less effective. It is possible that a future study where the *visual* participant watches a recording of a high scoring *manipulation* participant without the wiggling could lead to results where learning is equalized.

The findings from this study present significant implications for the potential role of virtual reality in educational settings generally, as well as in field of medical education. Perhaps most significantly, this study suggests that it is possible to embody internal anatomical structures that are not generally visible or familiar to people. While it has been known for some time that we embody wrists and hands, it has not previously been shown that we may be able to embody an internal structure we are not even aware of, such as components of the inner ear. It follows logically that if it is possible to embody the inner ear with its substructures (e.g., semi-circular canals and the facial nerve), perhaps it is also possible to embody the spleen or the liver or the heart. While further research in this area is warranted, if is in fact the case that it is possible to embody other parts of our anatomy, then there may be benefits to approaching the teaching of anatomy with an understanding of embodied cognition in mind.

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