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Direct manipulation is better than passive viewing for learning anatomy in a three-dimensional virtual reality environment

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A B S T R A C T

With the advancement of virtual reality (VR) technologies, medical students may now study complex anatomical structures in three-dimensional (3-D) virtual environments, without relying solely upon high cost, unsustainable cadavers or animal models. When coupled with a haptic input device, these systems support direct manipulation and exploration of the anatomical structures. Yet, prior studies provide inconclusive support for direct manipulation beyond passive viewing in virtual environments. In some cases, exposure to an "optimal view" appears to be the main source of learning gains, regardless of participants' control of the system. In other cases, direct manipulation provides benefits beyond passive viewing. To address this issue, we compared medical students who either directly manipulated a virtual anatomical structure (inner ear) or passively viewed an interaction in a stereoscopic, 3-D environment. To ensure equal exposure to optimal views we utilized a yoked-pair design, such that for each participant who manipulated the structure a single matched participant viewed a recording of this interaction. Results indicate that participants in the manipulation group were more likely to successful generate (i.e., draw) the observed structures at posttest than the viewing group. Moreover, manipulation benefited students with low spatial ability more than students with high spatial ability. These results suggest that direct manipulation of the virtual environment facilitated embodiment of the anatomical structure and helped participants maintain a clear frame of reference while interacting, which particularly supported participants with low spatial ability.

1. Introduction

Virtual reality (VR) systems allow users to explore immersive, three-dimensional (3-D) environments from any location, which could have a profound impact on science education (Merchant, Goetz, Cifuentes, Keeney-Kennicutt, & Davis, 2014).

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Specifically, VR affords investigation of distant locations, exploration of hidden phenomena, and manipulation of otherwise immutable structures (Lee & Wong, 2014). For example, VR can help medical students explore delicate internal organs that would otherwise require cadaver dissection (Nicholson, Chalk, Funnell, & Daniel, 2006). While once a rarity, VR systems are an increasingly commonplace consumer product that may be adopted for instructional use. Yet, currently available, low-cost consumer products typically facilitate observation of virtual environments (e.g., by moving the direction of one's head), support for direct manipulation of structures in the environment is often lacking (Millar, 2016). Without support for direct manipulation, will these systems be effective educational tools? In this manuscript, we explore the role that direct manipulation plays in three-dimensional virtual reality systems by comparing participants who directly manipulate an anatomical structure in a 3-D VR program to those who only view the structure in the same program.

We chose to investigate VR in the context of medical education, because VR programs have the potential to induce the most dramatic shift in anatomy instruction since Vesalius introduced richly illustrated volumes of the human body based on careful, intricate cadaver dissections (Dyer & Thorndike, 2000). While computer technology has undoubtedly transformed the manner in which doctors evaluate and treat their patients, the methods used to teach medical students have been in place for centuries. In particular, cadaver dissection has been considered the gold standard in anatomy instruction dating back to the Renaissance (Dyer & Thorndike, 2000). Although dissection provides students with both a clear view of human organs and their spatial orientation within the body (McLachlan, Bligh, Bradley, & Searle, 2004), the high cost of cadavers and equipment (Robison, Liu, & Apuzzo, 2011; Seymour et al., 2002), the stress placed on medical students (Charlton & Smith, 2000; Finkelstein & Mathers, 1990), and instructional ineffectiveness for small or delicate organs (Hu et al., 2010; Nicholson et al., 2006) present clear limitations. Substituting human cadavers for animals also present ethical challenges and should be minimized (Russell & Burch, 1959; Tannenbaum & Bennett, 2015).

VR represents a promising alternative to cadaver dissection for learning anatomy and practicing surgical procedures (Lee & Wong, 2014). VR systems enable direct interaction with three-dimensional models of anatomical structures. Relative to cadaver dissection, maintenance of a virtual reality 3-D computer model is more cost-effective (after initial development) and sustainable. Likewise, by modeling common physiological processes, such as cancer growth (Jeanquartier, Jean-Quartier, Cemernek, & Holzinger, 2016), computer models have been used to reduce, refine, and replace animal experimentation for biomedical research. Addressing students' comfort working with cadavers, the attitudes of medical school students seem to favor computer models that minimize undue stress (Cabral & Barbosa, 2005; Hariri, Rawn, Srivastava, Youngblood, & Ladd, 2004; Kerfoot, Masser, & Hafler, 2005). Additionally, using virtual 3-D models facilitates magnification of smaller, more delicate structures (e.g., the inner ear) for detailed observation without the physical constraints of cadavers that restrict learner interaction (Nicholson et al., 2006).

Yet, beyond simply providing exposure to relatively inaccessible structures, the potential effectiveness of VR may depend upon the manner in which learners interact with and manipulate represented structures (Lemole, Banerjee, Luciano, Neckrysh, & Charbel, 2007). Specifically, learning anatomy typically requires students to view structures from multiple perspectives, coordinate adjacent structures, and integrate structures into a comprehensive (and potentially hidden) whole (McLachlan et al., 2004). These tasks are highly demanding of spatial cognitive resources (Stull, Hegarty, & Mayer, 2009). Directly manipulating structures in a virtual environment may promote development of “embodied”, multi-modal mental representations of represented structures (Barsalou, 1999). Embodied learning prepares students to engage in mental imagery or simulations in the absence of the physical structures (Barsalou, 1999). For medical students, the ability to imagine and mentally manipulate anatomical structures is a crucial skill (Stull et al., 2009).

In contrast to the embodied view, in which direct manipulation is necessary for learning, it may be that learning anatomy is primarily a function of exposure to optimal information. In this case, video or even still images may be sufficient. Indeed, previous research (e.g., Keehner, Hegarty, Cohen, Khooshabeh, & Montello, 2008) supports an information-processing perspective that de-emphasizes the role of direct manipulation. In the following we survey relevant embodied and information-processing research to explore what features of virtual reality are most likely to promote learning.

1.1. *Embodied cognition and mental imagery*

Standard information-processing theories of cognition view perceptual and motor systems as peripheral to cognition, whereas an embodied view of cognition places elevated significance on these systems (Barsalou, 2008; Clark, 1999; Wilson, 2002). Mounting evidence suggests that what were previously thought to be “purely cognitive” tasks necessarily recruit both perceptual and motor systems. Some of the earliest and most compelling evidence of this comes from the study of mental imagery, which plays a particularly central role in anatomy instruction and medical education (Stull et al., 2009).

Research on mental imagery and rotation has shown that individuals manipulate mental representations much like they would actual objects in physical space, such that the time it takes to mentally rotate an image increases linearly with the degree of rotation (Shepard & Cooper, 1982; Shepard & Metzler, 1971). This research suggests that mental representations not only have perceptual qualities, but that they recruit processes from the motor system, as well (Wexler, Kosslyn, & Berthoz, 1998; Wohlschlager & Wohlschlager, 1998). Neuroimaging studies show that motor cortices (primary/M1 or premotor cortex) are activated when performing mental transformation tasks (Cohen et al., 1996; Kosslyn, DiGirolamo, Thompson, & Alpert, 1998), and that transcranial magnetic stimulation targeted to interfere with neuronal processes in motor regions of cortex reduce mental rotation performance (Ganis, Keenan, Kosslyn, & Pascual-Leone, 2000).