Evaluation of the Effectiveness of 3D Vascular Stereoscopic Models in Anatomy Instruction for First Year Medical Students

Dongmei Cui,[1]* Timothy D. Wilson,[2,3] Robin W. Rockhold,[4] Michael N. Lehman,[1] James C. Lynch[1]
[1]Department of Neurobiology and Anatomical Sciences, University of Mississippi Medical Center, Jackson, Mississippi
[2]Schulich School of Medicine and Dentistry, Department of Anatomy and Cell Biology, Western University, London, Ontario, Canada
[3]Corps for Research of Instructional and Perceptual Technologies (CRIPT), Schulich School of Medicine and Dentistry, Western University, London, Ontario, Canada
[4]Department of Pharmacology and Toxicology, and Health Sciences, University of Mississippi Medical Center, Jackson, Mississippi

The head and neck region is one of the most complex areas featured in the medical gross anatomy curriculum. The effectiveness of using three-dimensional (3D) models to teach anatomy is a topic of much discussion in medical education research. However, the use of 3D stereoscopic models of the head and neck circulation in anatomy education has not been previously studied in detail. This study investigated whether 3D stereoscopic models created from computed tomographic angiography (CTA) data were efficacious teaching tools for the head and neck vascular anatomy. The test subjects were first year medical students at the University of Mississippi Medical Center. The assessment tools included: anatomy knowledge tests (prelearning session knowledge test and postlearning session knowledge test), mental rotation tests (spatial ability; presession MRT and postsession MRT), and a satisfaction survey. Results were analyzed using a Wilcoxon rank-sum test and linear regression analysis. A total of 39 first year medical students participated in the study. The results indicated that all students who were exposed to the stereoscopic 3D vascular models in 3D learning sessions increased their ability to correctly identify the head and neck vascular anatomy. Most importantly, for students with low-spatial ability, 3D learning sessions improved postsession knowledge scores to a level comparable to that demonstrated by students with high-spatial ability indicating that the use of 3D stereoscopic models may be particularly valuable to these students with low-spatial ability. Anat Sci Educ 10: 34–45. © 2016 American Association of Anatomists.

Key words: gross anatomy education; medical education; anatomy assessment; 3D stereoscopic models; 3D virtual models; vasculature of the head and neck; spatial ability; anatomy knowledge test; anatomy teaching

INTRODUCTION

The medical school curriculum has been under constant pressure for many years to teach more information in less time. Because anatomy classes typically have many hours devoted to laboratories, this trend has especially impacted anatomy education. Many medical schools have reduced laboratory hours, particularly in gross anatomy classes (Cottam, 1999; Drake et al., 2002; Verhoeven et al., 2002; Moxham and Plaisant, 2007; Yeung et al., 2012; Drake, 2014). This development has highlighted the need to develop teaching techniques that will increase the efficiency of the education process

*Correspondence to: Dr. Dongmei Cui, Department of Neurobiology and Anatomical Sciences, University of Mississippi Medical Center, 2500 North State Street, Jackson, MS 39216, USA. E-mail: dcui@umc.edu

Received 2 December 2015; Revised 4 May 2016; Accepted 4 May 2016.

Published online 6 June 2016 in Wiley Online Library (wileyonlinelibrary.com). DOI 10.1002/ase.1626

© 2016 American Association of Anatomists

(Drake, 1998; Drake et al., 2009; Alpern et al., 2011; Hopkins et al., 2011).

Much of traditional anatomy education is centered around cadaveric dissection, augmented by two-dimensional images in textbooks and on projection screens, with the goal of enabling the student to construct an internal, mental, visuospatial representation of the skeleton, the internal organs, the circulatory system, and the nervous system of the human body. These internal images, that can be mentally rotated and viewed from different angles, are important in many branches of medicine, particularly in surgery.

One strategy for increasing the efficiency of anatomy education is to use computer-aided learning (CAL) techniques (Schwartz and Reilly, 1980; Ackerman, 1998; Carmichael and Pawlina, 2000; Verhoeven et al., 2002; Vernon and Peckham, 2002; Moxham and Plaisant, 2007; Drake et al., 2009; Tam et al., 2009). The CAL techniques that are currently receiving the most attention involve presenting three-dimensional (3D) images of complex anatomical structures and relationships either by utilizing stereoscopic images in a virtual reality-like environment or, in simulated 3D images, utilizing rotating images on a computer monitor (GMC, 1993, 2009; Aziz et al., 2002; McLachlan et al., 2004; McLachlan and Patten, 2006; Luursema et al., 2006, 2008; Nguyen and Wilson, 2009; Held and Hui, 2011; Brewer et al., 2012; Brown et al., 2012; de Ribaupierre and Wilson, 2012; Anderson et al., 2013; Foo et al., 2013; Cui et al., 2015; Ferdig et al., 2015; Kockro et al., 2015). It is anticipated that the CAL techniques can enable students to develop the internalized mental images of anatomical structures and relationships more efficiently than when using traditional teaching techniques. There is some evidence that stereoscopic 3D displays may aid in the rapid acquisition of this information, although the results are not yet conclusive. Three-dimensional models in anatomy instruction have generally received positive responses from students and faculty (Qayumi et al., 2004; Nicholson et al., 2006; Brown et al., 2012), However, there is not yet compelling empirical evidence to demonstrate that stereoscopic 3D models are educationally superior to traditional 2D images in textbooks and PowerPoint presentations (Tam et al., 2009; Brewer et al., 2012; Foo et al., 2013; Khot et al., 2013). For example, Garg and colleagues used stereoscopic 3D images in a study of the acquisition of knowledge about the bones of the wrist (Garg et al., 2002) and found that 3D virtual models of the wrist did not improve learning. However, in that study, the anatomical structures involved were relatively simple and perhaps not challenging enough for the 3D representations to be helpful. In contrast, Luursema and colleagues used stereoscopic 3D models of the organs of the abdomen and found that when subjects were able to interact with the stereoscopic 3D images, i.e., to rotate the images at will, their performance on identification tasks and localization tasks was significantly better than that of subjects who were presented only with traditional 2D images (Luursema et al., 2006). However, when the same investigators did a similar study using only stereoscopic viewing of virtual anatomical models, without simultaneous active manipulation of the models, the results were more equivocal and not clearly significant (Luursema et al., 2008).

The first goal of the present study was to investigate whether 3D virtual models will have a greater learning benefit when more complex anatomical structures, such as models of the vasculature of the head and neck are used. A second related issue concerns the natural differences in the visuospatial ability that exist among individuals. There is much evidence that, in general, individuals who score higher on tests of visuospatial ability, such as the mental rotation test (MRT) of Vandenberg and Kuse (1978) and Peters et al. (1995) or the Revised Minnesota Paper Form Board Test (RMPFBT) of Likert and Quasha (1995) perform better in anatomy courses (Rochford, 1985; Guillot et al., 2006; Lufler et al., 2012; Berney et al., 2015), anatomy-related identification tasks (Garg et al., 2001; Luursema et al., 2006, 2008; Nguyen et al., 2012, 2014), and interpretation of ultrasound images (Clem et al., 2013) than do individuals with lower scores on visuospatial tests. Differences in visuospatial ability have also been shown to be predictive of success in some fields of surgery (Schueneman et al., 1984; Risucci, 2002; Wanzel et al., 2002; Clem et al., 2013).

Evidence exists suggesting that learning anatomical relationships in a stereoscopic 3D virtual reality environment compensates, to some extent, for the disadvantage of having low initial visuospatial ability. Luursema and colleagues developed 3D virtual models of the organs of the abdomen and trained subjects to identify and localize organs in CT slices (Luursema et al., 2006). All subjects took a test of visuospatial ability (Vandenberg and Kuse, 1978). One group was trained using only traditional 2D illustrations; a second group was trained using stereoscopic 3D images. Subjects in the 3D group were able to interact with the images, rotating them at will. Performance on the identification task and the localization task was better in the stereoptic/interactive group than in the 2D group. Furthermore, the results indicated that the subjects in the low visuospatial ability group benefited more from the stereoptic/interactive training than did the subjects in the high visuospatial ability group. However, when the same investigators did a similar study where one group of subjects viewed stereoscopic 3D images, but did not have the ability to interact with the images, this relationship was only borderline significant (Luursema et al., 2008). A similar study by Berney and colleagues had subjects study the scapula and associated shoulder flexion movements utilizing either a dynamic 3D reconstruction of the scapula or a series of static views of the scapula in different stages of its movement (Berney et al., 2015). In this study, the 3D images themselves did not provide an advantage, but the dynamic movement of the model did provide a measure of assistance to the low-visuospatial ability subjects in the study.

In all of the aforementioned studies, the anatomical relationships were relatively simple, this may have been a factor in the small differences seen between 3D presentations and traditional 2D presentations. In contrast, the vasculature in the head and neck represents some of the most complex regions of the human body. In order to test the possible advantage of stereoscopic 3D images in anatomical education, 3D stereoscopic vascular models of the head and neck were developed from CT angiograms (CTA) (Cui et al., 2015). These models were used to test the effectiveness of 3D models in the learning of the details of the vasculature of the head and neck by first year medical students enrolled in a gross anatomy class, and to examine the possible relationship between 3D anatomical instruction and the visuospatial ability of the students.

METHODS

Computer-Generated 3D Anatomical Models

The construction of the virtual 3D models used in this study has been described in detail in an earlier publication (Cui et al., 2015). Briefly, Amira software, version 5.6 (FEI Corp., Hillsboro, OR) was used to create virtual 3D models of the major arterial circulation of the head and neck, using deidentified routine CTA data supplied by the Department of Radiology, University of Mississippi Medical Center (UMMC). In developing the models, both surface rendering and volume rendering techniques were used, and in some models, a combination of both techniques was used. Volume rendered 3D models are based on variations of tissue density (Martin et al., 2013; Cui et al., 2015). This technique is quick, but does not permit the separation of different structures that have similar densities. Surface rendered 3D vascular models are created based on the identification and marking of anatomical structures observed in the CTA images (Cui et al., 2015). This technique is time consuming, as some models required the identification and marking of anatomical structures in hundreds of axial CTA images, but does permit the construction of highly selective and detailed models of complex anatomical structures. A Dell Precision T7600 computer workstation (Dell Inc., Round Rock, TX) with an NVIDIA Quadro K6000 video card (NVIDIA Corp., Santa Clara, CA) was used to run the Amira software during both the development of the models and the projection of the final products during the experiments.

Stereoscopic 3D Projection and Viewing

The basic technique of projecting and viewing stereoscopic 3D images has been well-described in the literature (Poggio and Poggio, 1984; Nguyen and Wilson, 2009; Sergovich et al., 2010; Cui et al., 2015) and will only be summarized here. Because the eyes are separated by 6–7 cm in humans, each eye sees a slightly different image of its surroundings. When the brain puts these two images together, a profound impression of three-dimensionality results (Poggio and Poggio, 1984). In the present study, the Amira software, version 5.6 (FEI Visualization Sciences Group, Burlington, MA), produced a “left-eye image” and a “right-eye image” of the computer-constructed model. The two images were projected by a pair of high-definition InFocus IN3128HD digital projectors (L and R, Fig. 2) (InFocus Corp., Wilsonville, OR). A linearly polarized filter (Polarizer film; Edmond Optics America, Barring, NJ) was placed in the light path of each projector; the axis of polarization of the two filters was offset by 90° (Fig. 2). The projectors were supported and aligned using Da-Lite 21400 commercial stacker (Da-Lite Corp., Warsaw, IN). Images were projected onto a screen with a metallic surface which does not depolarize light waves as do normal projection screens (Fig. 2) (Da-Lite Model C 100″ diagonal, silver matte finish; Da-Lite Corp., Warsaw, IN). To view the image stereoscopically, an observer wears glasses that have polarized lenses that match the polarization axes of the projector filters of the projector, so the observer’s left eye sees only the projected left eye image and the observer’s right eye sees only the projected right eye image (American Paper Optics, Bartlett, TN). In 3D movie theaters, circular polarization is typically used instead of linear polarization because circular polarization reduces the visual interaction between the two channels when the observer tilts his/her head. Head tilt was not found to be a problem during the short viewing periods in this study.

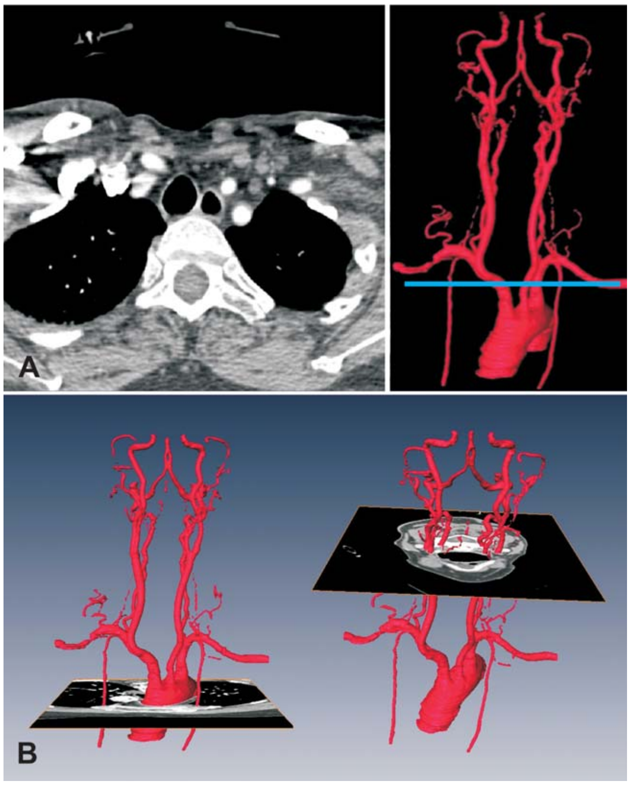

Figure 1.

Examples of images used in the 2D learning session. (**A**) CT angiography slice images (left) and 2D image captured from 3D model (right) with level of plane indicated by the blue solid line; (**B**) examples of images used in the 3D learning session. 3D models were superimposed upon CT angiography slice images.

Participants

All 149 first-year medical students from UMMC were invited to enroll in the study. A total of 39 students elected to participate (17 men, 22 women). These students were enrolled in the first year gross anatomy course, in the head and neck block, while the study was ongoing. Participation in the study did not affect their academic grades. Subjects received a small compensation ($5.00 cafeteria gift card) at the completion of the experimental session. The protocol for this study was approved by the Institutional Review Board (IRB) at the University of Mississippi Medical Center (IRB # 0241).

Learning Sessions

All participants were given a short introductory overview on the major arteries of the head and neck. Students were randomly assigned to receive either a 2D or a 3D learning session on the more detailed aspects of the vasculature of the head and neck (Fig. 3).

The introductory lecture was 5 minutes in length, and consisted of the presentation of a series of simple drawings of major arteries in the head and neck, including the cerebral vasculature. The structures studied included the aortic arch, brachiocephalic trunk, subclavian arteries, common carotid arteries, vertebral arteries, internal carotid arteries, external

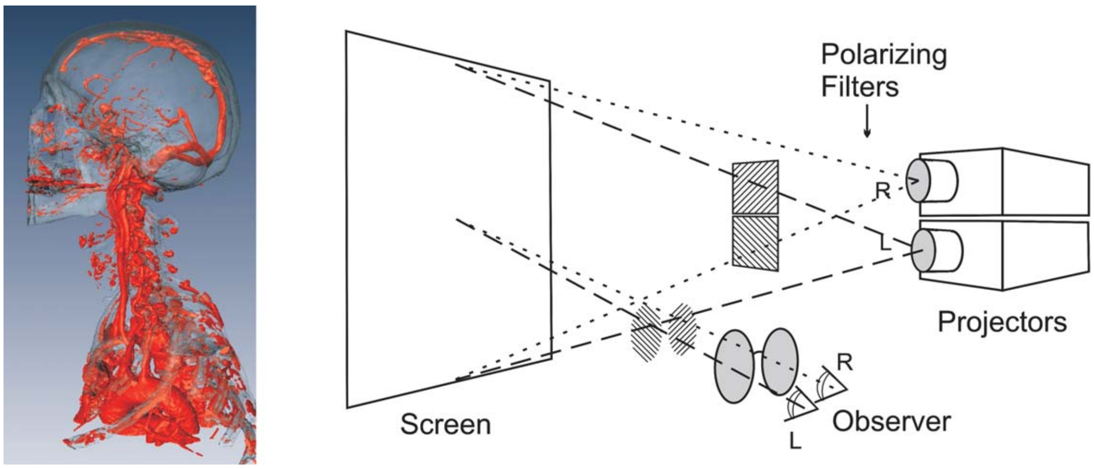

Figure 2.

Three-dimensional projection and viewing. Two high-definition LCD projectors were controlled by the Dell T7600 workstation. One projected an image of the virtual model that would be seen by the right eye (R) and the other projected the slightly different image that would be seen by the left eye (L). A linear polarizing filter was placed in front of each projector; the axis of polarization of the two filters was separated by 90°. The observer wore special polarizing glasses in which the polarizing angle of the left lens matched that of the "left" projector and the polarizing angle of the right lens matched the polarizing angle of the "right" projector, so that the observer would see the "right" image with his right eye and the "left" image with his left eye, resulting in the perception of three-dimensionality.

carotid arteries, basilar artery, anterior cerebral arteries (ACA), middle cerebral arteries (MCA), and posterior cerebral arteries (PCA). The purpose for the introduction of vascular anatomy in the head and neck was to provide a baseline of knowledge for all students who participated in the study. This introductory approach using simplistic drawings provided initial preknowledge for the learner and enabled further cognitive scaffolding of new anatomical detail (Wilson, 2015).

The 2D learning session of about 20 minutes utilized 2D images captured as snapshots, thus identical, from the 3D stereoscopic models, as well as radiographic images from the data originally used to create the 3D models (Fig. 1A). These images were viewed by projecting 2D images on a screen in the same room as the 3D learning sessions. 2D group students received 2D images of the 3D visualization, and 2D images of the original data slices. An instructor gave a description of the anatomical structures while showing the projected flat screen images. During the 2D learning session, students viewed the radiographic images at the levels of the sections indicated on the diagrams while the instructor provided a scripted explanation and description of the anatomy.

The 3D learning session was also 20 minutes in duration and utilized the 3D stereoscopic models created in our previous work (Cui et al., 2015), as well as techniques described previously (Nguyen and Wilson, 2009). In this session, 3D models could be rotated 360° in all axes, and could be made larger or smaller. The instructor controlled the movement of the models. Students wore glasses with linear polarizing filters and viewed the 3D models as images that appeared to float in the center of the room (Figs. 1B and 2). Students reported that they felt "almost able to reach out and touch the images." The same basic normal and abnormal vascular anatomy was presented in the 3D learning sessions as was presented in the 2D learning sessions. The 3D models were projected, and the same instructor who gave the 2D lecture provided the same scripted explanation and descriptions.

Anatomy Knowledge Tests and MRT

Since this was a pretest and posttest experimental design with a control group, both anatomical knowledge and mental rotation ability were tested at the commencement and the end of the study. For the anatomy pretest and posttest, questions were randomly selected from a question bank created for this study by instructors who routinely provide examination questions for first year medical students. The questions included identifying structures based on images derived from the snapshots from the 3D models, functional and structural related questions, and spatial relationship questions. The questions addressed knowledge-relevant to anatomical and clinical facts. Learner knowledge was first assessed after the introductory lecture but prior to the 2D and 3D learning sessions and again after the 2D and 3D learning sessions (Fig. 3). Prelearning session tests and postlearning session tests each contained 15 questions. These questions addressed structure, function, and spatial relationships. Less than 50% of the questions (7 out of 15 questions) on the postlearning session knowledge test were also on the prelearning session knowledge test. Among these questions, five were repeated questions and two asked about the same structures, but used different images in different spatial orientations. Although these questions were repeated, correct answers were not given to students after the preknowledge test. Participants had 30 seconds for each question, for a total of about 8 minutes for each knowledge test. Tests were scored with a maximum of 15 points for each test. One point was given when the answer was entirely correct. Students, for example, were asked to give the name of the structure and which side of the patient the image represented. If the structure was named

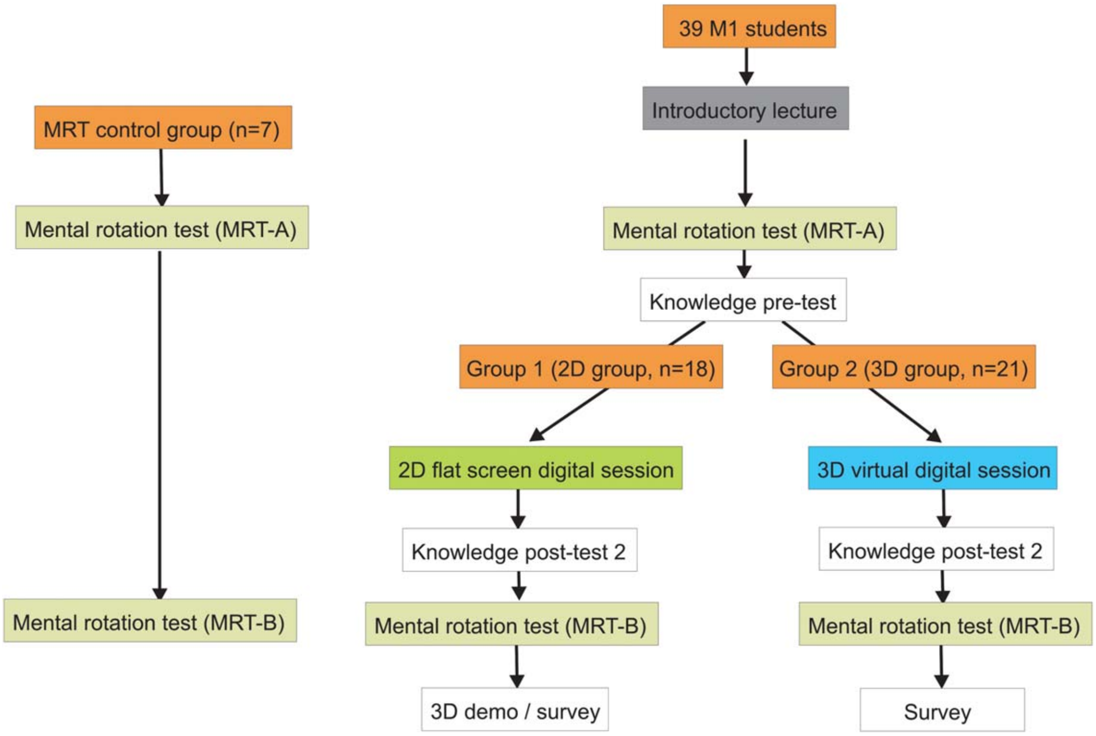

Figure 3.

Flowchart for experimental evaluation of the effectiveness of 3D stereoscopic vascular models in anatomy learning. First year medical students (M1) in the 3D virtual group used 3D stereoscopic models when learning vasculature of the head and neck (3D learning session). Students in the 2D group used 2D flat screen projected digital images (2D snapshots from 3D models) when learning the head and neck vasculature (2D learning session). Both groups were given an introduction to the vascular anatomy of the head and neck prior to any other intervention. All students took MRT-A and then MRT-B tests. A preknowledge test and a post-knowledge test were also administered. Students in the 2D group were given a 3D demonstration (similar to the 3D learning session) after they finished the post-knowledge test. A survey was administrated to both groups of students at the end of the laboratory.

correctly, but the side of the patient was wrong, only a half point was given for that question. If the side of the patient's image was answered correctly, but the structure was wrong, no point was given for that question.

MRT, which measure students' spatial visualization ability (SA) (Shepard and Metzler, 1971; Vandenberg and Kuse, 1978) were administered before and after the 2D (flat screen images) and the 3D sessions. The redrawn MRT figures were used, it involves participants determining which two of four drawings are the same as a sample drawing but are viewed from a different angle (Peters et al., 1995). This test can be administered in different versions, the MRT-A version was used before the learning session and the MRT-B version was used after the learning session. The post-MRT (MRT-B) consists of the same items as MRT-A, but the items are rearranged in a different order. Peters et al. (1995) found no significant differences in performance on the two test version, thus qualifying the MRT-B as an alternate to MRT-A. In these MRT tests, six sets of figures on one page were projected at a time. Twenty-four sets were presented in total. Students had 2 minutes for each page (6 questions), giving a total of 8 minutes for 24 questions. There was a short break of 30 seconds in the middle of the test. Each MRT test was scored with a maximum of 24 points. One point was given if both of the stimulus figures that matched the target figure were identified correctly. No credit was given for an answer that had only one correct identification (Peters et al., 1995). Post experiment, students' initial MRT scores (presession MRT scores/MRT-A) were statistically divided into two categories: (1) MRT-high (high-spatial ability) group: scores above median (> 12); (2) MRT-low (low-spatial ability) group: scores below the median (< 12). MRT scores equal to 12 will be excluded from the study. The group with the high MRT scores and the group with the low MRT scores were used to compare whether students who had a lower 3D spatial ability were helped by the use of 3D models when learning the head and neck vasculature.

Experimental Design

A total of 39 student volunteers were randomly assigned to one of two groups: 2D group (students who were given the 2D learning session) or 3D group (students who were given the 3D learning session) (Fig. 3). A schedule of 2D sessions and 3D sessions was then given to the students and they participated in their respective experimental session as their academic schedule permitted. All participants received a short introductory lecture on the vascular anatomy of the head and neck and cerebrum.

Students in the 2D group ($n = 18$) then received the 2D learning session consisting of a lecture using 2D images

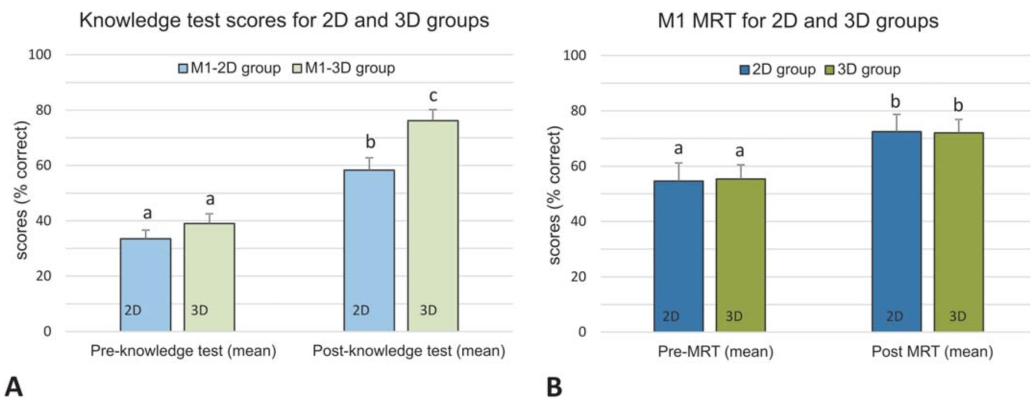

Figure 4.

Comparison of the first year medical students' preknowledge test scores and postknowledge test scores between the 2D and the 3D groups (**A**).Comparison of first year medical students' pre-MRT scores and post-MRT scores between 2D and 3D groups (**B**). The statistical relationship between groups is indicated by lower-case letters. Groups that share a common letter do not differ at the $P < 0.05$ level.

projected on a flat projection screen. The images were captured as snapshots from the 3D stereoscopic models, and images of the CTA radiographic images from the data used to create the 3D models. The radiographic images were shown with referenced images of the vascular models with indications of levels from each transverse plane.

Students in the 3D group ($n = 21$) received a 3D virtual anatomy learning session consisting of a lecture using projected stereoscopic 3D virtual models and a verbal description of vascular anatomy. The instructor and the dimly lit learning environment were the same as for the 2D learning session. Both the 2D and 3D learning sessions also provided the same basic vascular anatomy and learning objectives.

MRTs preceded and followed the preknowledge and postknowledge tests for each group. The purpose of the test was to assess each student's spatial ability, and to determine whether students' spatial ability was correlated with their anatomical knowledge test scores. The prelearning session and postlearning session anatomy knowledge tests were given before and after both the 2D and the 3D learning sessions to measure each student's knowledge of anatomy and to document any improvement. In addition, a questionnaire soliciting general questions and feedback from students was given at the end of the 2D and 3D sessions. A postexperimental survey was conducted at the end of each learning session. The questionnaire was designed to collect general information about the participants and their feedback on 3D stereoscopic models.

Finally, a MRT control group was used to determine whether there was a test-retest bias caused by multiple uses of the MRT. Here, we could determine how the MRT test scores may have changed simply as a result of repeated testing, without the intervening 2D digital learning or 3D stereoscopic virtual learning experiences. Participants were asked to do the MRT-A, followed by a brief break equal in time to the 2D or 3D session, then to take the MRT-B.

Statistical Analysis

A power analysis was performed to determine the necessary sample size to statistically test for differences between the 2D and 3D groups on their prelearning session knowledge test and postlearning session knowledge test. Based on this analysis, the estimated required sample size (number of participants) was a minimum of 36 ($n_1 = 18$ and $n_2 = 18$, accepting an alpha of 0.05 and a power of 0.80). The results of this study were statistically analyzed using STATA, version 14, a data analysis and statistical software (StataCorp LP, College Station, TX). A Wilcoxon rank-sum test (Mann-Whitney *U* test) was used to assess potential differences between groups on the postlearning session knowledge tests. In consultation with the Center for Biostatistics at UMMC, the Wilcoxon rank-sum (Mann-Whitney *U* test) test was chosen because the sample distribution deviated from a normal distribution. A two-way linear regression analysis was used to calculate the regression coefficient and determine whether the students' initial level of spatial ability was correlated with increased test scores after using 3D models in a virtual learning environment. A scatter plot with a fitted line was used to visualize the correlation between the postsession knowledge test scores and initial MRT scores among different groups.

RESULTS

Comparison of Content Examination and MRT Scores for the 2D and 3D Groups

Students were randomly assigned to either the 3D group ($n = 21$) or 2D group ($n = 18$). Figure 4A shows that the mean score of the prelearning session knowledge test for the 2D group was 33.52% (SD ±13.16) while the mean score of the postknowledge test was 58.33% (SD ±18.76). The mean score of the prelearning session knowledge test for 3D group was 39.05% (SD ±15.82) while the mean score of the postknowledge test was 76.19% (SD ±18.57). The difference of the prelearning session knowledge test between the 2D and 3D groups was not statistically significant (Wilcoxon rank-sum, $P = 0.2695$). However, the difference of the postknowledge test between the 2D and 3D groups was statistically significant (Wilcoxon rank-sum, $P = 0.0033$). The difference between the preknowledge test and postknowledge test for

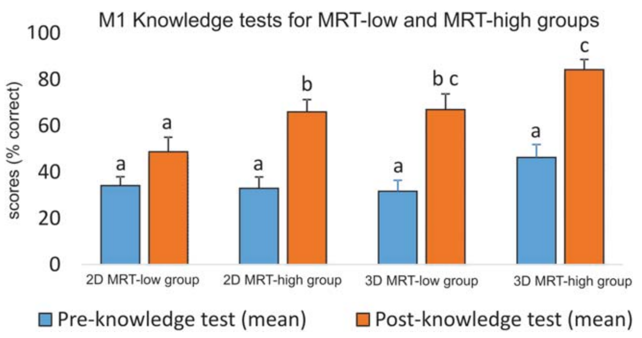

Figure 5.

Mean scores for the prelearning and postlearning session knowledge test scores for the students with low and high-spatial ability (MRT-low/high) in 2D and 3D learning session groups. The statistical relationship between groups is indicated by lower-case letters. Groups that share a common letter do not differ at the $P < 0.05$ level.

the 2D group was significant ($P < 0.001$), and for the 3D group it was also significant ($P < 0.001$).

Figure 4B shows the mean of the presession MRT scores in the 3D group was 55.36% (SD ±23.65); while the mean of the postsession MRT scores was 72.02% (SD ±22.33). For students in the 2D group, the mean of the presession MRT scores was 54.63% (SD ±27.86) and the mean of the postsession MRT scores was 72.45% (SD ±26.74). The difference of the presession MRT scores between the 2D and 3D groups was not significant ($P = 0.8212$), while the difference of the postsession MRT scores between the 2D and 3D groups was also not significant ($P = 0.6208$). The control group also showed no significant difference ($P = 0.3029$) between the first and second administered test.

Comparison of Content Examination and MRT Scores for MRT-Low and MRT-High in the 2D and 3D Groups

For the purpose of distinguishing spatial ability among the students who participated in this study, those who scored below the median on the presession MRT test were assigned to a MRT-low group, while students who scored above the median were assigned to a MRT-high group. Figure 5 shows the mean scores of the prelearning session anatomy knowledge test scores of the MRT-low and MRT-high subgroups in the 2D and 3D groups shown on the left panel. The postlearning session knowledge test scores of the MRT-low and MRT-high subgroups in the 2D and 3D groups appear on the right panel of Figure 5. The differences of the prelearning session knowledge test scores among these groups were not significant: 2D MRT-low vs. 3D MRT-low: $P = 0.5303$, 2D MRT-high vs. 3D MRT-high: $P = 0.129$, 2D MRT-low vs. 2D MRT-high: $P = 0.6220$, 3D MRT-low vs. 3D MRT-high: $P = 0.1188$. After a 2D learning session, the postknowledge test scores in the students with high-spatial ability (MRT-high) group were significantly higher than the students with low-spatial ability (MRT-low) group (2D MRT-low vs. 2D MRT-high: $P = 0.0259$). However, following the 3D learning sessions, postknowledge test scores in the students with high-spatial ability (MRT-high) group were not significantly higher than the students with low-spatial ability (MRT-low) group (3D MRT-low vs. 3D MRT-high: $P = 0.0899$) (Fig. 5). Consequently the 3D learning sessions enabled students with low-spatial ability to perform as well as students with high-spatial ability. Regardless of spatial ability, the 3D learning groups consistently outscored the 2D learning groups on the postlearning session tests. Among the high-spatial ability students, postlearning session knowledge test scores were greater when instructed with 3D than 2D (2D MRT-high vs. 3D MRT-high: $P = 0.0259$). Similarly, students with low-spatial ability (MRT-low) in the 3D group outperformed the 2D group (2D MRT-low vs. 3D MRT-low: $P = 0.0610$). For all students in the 3D group, test scores increased from the preknowledge mean (31.67%, SD ±14.93) to the postknowledge mean (67%, SD ±21.34). In contrast, among all students in the 2D group, test scores increased from the preknowledge mean (34.17% SD ±10.80) to the postknowledge mean (48.75%, SD ±17.63).

Correlation Between Postlearning Test Scores and MRT Scores

Linear regression analysis was used to determine the relationship between the postlearning session knowledge test score and each student's initial MRT (prelearning session MRT) scores for the MRT-low and MRT-high subgroup in both the 2D and 3D experimental groups. Two-way scatter plots indicating the linear regression line demonstrate this relationship: 3D MRT-low, 3D MRT-high, 2D MRT-low, and 2D MRT-high (Fig. 6).

In the 3D MRT-low group, regression analysis indicated almost none ($R^2 = 0.0017$) of the total variation in scores on the postlearning session knowledge test could be explained by their spatial ability as judged by students' initial MRT scores. There was no significant correlation between the initial MRT score and postlearning session knowledge test score in the 3D MRT-low group ($P > 0.05$, $r = 0.042$).

In the 3D MRT-high group, 31% ($R^2 = 0.3131$) of the total variation in postlearning session knowledge test scores could be explained by students' spatial ability as judged by students' initial MRT scores. There was a moderate positive linear relationship between the students' initial MRT score and postknowledge test score in the 3D MRT-high group ($P > 0.05$, $r = 0.5596$).

In the 2D MRT-low group, 27% ($R^2 = 0.2701$) of the total variation in postlearning session knowledge test scores could be explained by their spatial ability as judged by students' initial MRT scores. There was a weak negative linear relationship between the initial MRT and the postlearning session knowledge test in the 2D MRT-low group ($P > 0.05$, $r = 0.5197$).

In the 2D MRT-high group, 78% ($R^2 = 0.7775$) of the total variation in postlearning session knowledge test scores could be explained by their spatial ability as judged by students' initial MRT scores. The regression analysis demonstrated a high positive correlation between student's MRT score and their anatomy knowledge scores ($P < 0.05$, $r = 0.8818$).

Comparing students in the control group (without 2D and 3D learning sessions) for their pre-MRT scores and post-MRT scores, there was no significant difference (Wilcoxon

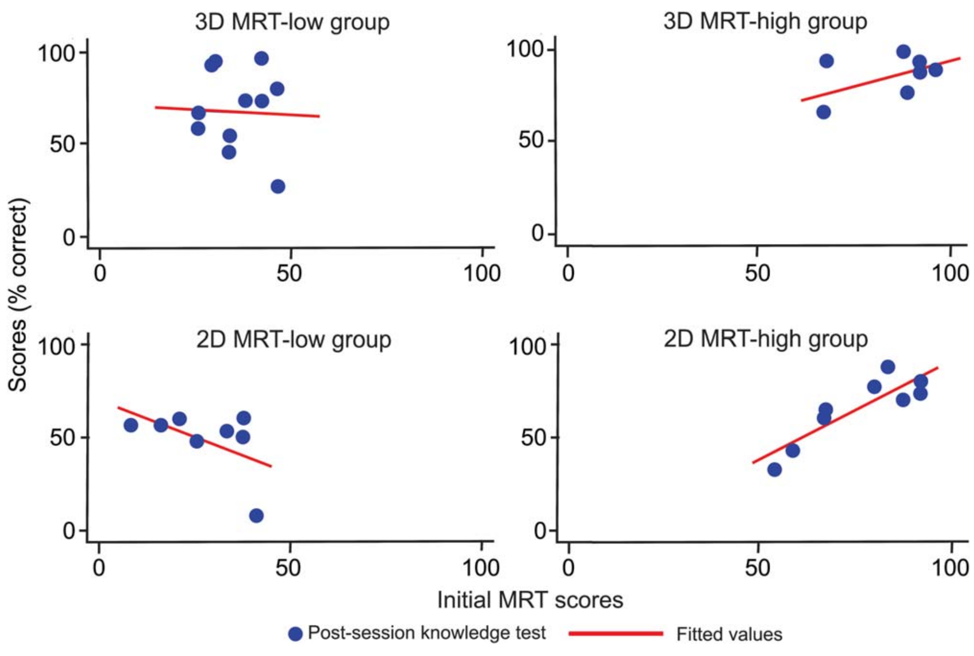

Figure 6.

Correlation between postknowledge test scores and students' initial MRT. Plot with linear regression line of correlation between postknowledge test scores and students' initial MRT (prelearning session MRT) scores in the MRT-low and MRT-high groups of first year medical students. The maximum score on the MRT test is 24 (100%).

rank-sum, $P = 0.3029$) ($n = 7$) between pre-MRT and post-MRT scores.

Survey

A total of 39 students participated in the survey. In a pseudo-cross over fashion, a 3D demonstration was also given to all the students in the 2D group after they completed the knowledge and MRTs. Students rated the 3D virtual models highly favorably as 97% of students either strongly agreed, or agreed, with the statement, "The 3D model was interesting, and engaged me in learning the materials." Furthermore 100% of students either strongly agreed, or agreed, with the statement, "The 3D model showed orientation of the materials better than the flat screen image." In addition, 100% of students either strongly agreed, or agreed, with the statement, "The 3D model is helpful to relate the material that I have learned from the book and the material learned in the laboratory." Specific student comments included: "*I thought the 3D models were amazing. I would love to study using these models.*" "*They were very helpful in learning the spatial relationships.*" "*Really cool, especially when the CT was incorporated.*" Overall, the survey results showed a high degree of interest and enthusiasm by the students for these 3D virtual models.

DISCUSSION

The present study was designed to investigate two aspects of computer-assisted learning in teaching the structure of the vasculature of the head and neck. First, we examined the effectiveness of stereoscopic presentation of 3D vascular models of the head and neck when learning human anatomy. Our results suggest that 3D viewing during a short lecture improves students posttest knowledge scores more than an identical lesson using identical but 2D images.

Further, earlier studies demonstrated a correlation between students' spatial ability and their performance in learning anatomical structure (Rochford, 1985; Garg et al., 2001; Luursema et al., 2006, 2008; Fernandez et al., 2011; Nguyen et al., 2012, 2014) The results of the current study suggest that spatial ability is mitigated through the use of 3D images as evidenced by low-spatial ability students attaining posttest knowledge scores that were similar to student of high-spatial ability. This was not the case using 2D pictures indicating a potential cognitive advantage for high-spatial ability students that is unrelated to the study of the anatomical materials at hand. In order to test that association, a MRT was given to all students in this study to measure spatial ability, followed by a comparison of the learning capabilities between two groups with high- and low-spatial ability.

Are 3D Stereoscopic Vascular Models a More Effective Learning Tool Than 2D Flat Screen Projected Images When Learning Human Anatomy?

There is some preliminary evidence that suggests stereoscopic 3D models are superior to traditional 2D illustrations such as PowerPoint slides and textbook figures in teaching complex anatomical structures (Luursema et al., 2006, 2008; Nicholson et al., 2006; Nguyen et al., 2014). The 2D flat screen projected images are two-dimensional geometric digital images, such as a standard PowerPoint presentation, which may not adequately permit students to effectively master the complex spatial relationships that exist within human anatomy. Students must be able to visualize this 3D organization in their minds to fully understand the workings of, and relationships that exist, within the human body (Hilbelink, 2009). With routine sagittal and coronal reconstructions now available from multidetector computed tomographic scanners, a detailed three-dimensional understanding of structure is even more important than it used to be (Shaffer, 2004). Stereoscopic presentation of images has the advantage of having additional depth information provided by disparities, making it easier to detect diagnostically relevant shapes and distinguish the relative position of anatomical features (Held and Hui, 2011). However, there is only limited evidence to suggest that 3D stereoscopic virtual models actually increase students' test performance and their understanding of anatomical structures. The first goal of the current study was to compare the effectiveness of 3D stereoscopic models vs. 2D flat screen projected images when learning the head and neck vascular anatomy. The results indicate that although the students' test scores improved after both the 2D and 3D teaching presentations, the improvement after the stereoscopic 3D presentation was significantly greater than after the 2D presentation (Fig. 4). The test results indicated that the 3D stereoscopic presentation helped students acquire anatomical information more efficiently. Furthermore, the addition of 3D images facilitated low-spatial ability students greater than high-spatial ability students. The effect of the addition of 3D to the low-spatial ability group also facilitated students' learning of the material beyond that provided by the 2D version of the same material.

In addition to the effectiveness of the 3D presentations, 2D images from 3D models also provided useful information in helping students to improve their content examination scores for anatomy vasculature in the head and neck. There are several possible explanations for this: (1) 2D images captured from 3D models are more realistic than traditional drawings as they show anterior, posterior, and lateral views of the same structure and their relationship with other structures rather than two-dimensional view provided by most illustrations from textbooks. (2) The 2D images provided some, albeit limited, 3D information by showing the plane and level from which the 2D images were derived (Fig. 1A). However, although test scores improved after exposure to the 2D presentation alone, students in the 3D group performed significantly better on the postsession knowledge test scores when compared with students in the 2D group.

Statistical analysis demonstrated that there was no significant difference in the prelearning session knowledge test scores between the 2D and 3D groups, which indicated that the initial baseline anatomy knowledge level was similar between these two groups. In contrast, there was a significant difference on the postlearning session knowledge tests between the 2D and 3D groups. This indicated that instruction of the vascular anatomy of the head and neck using 3D stereoscopic presentation served as a more effective learning tool than the 2D flat screen presentation.

The head and neck are among the most complex regions in the human body, and this is especially true for the vasculature in these regions. The models created from our studies presented the complexity of vascular anatomy and spatial relationships among the blood vessels and other structures in these regions. Some earlier studies have found no, or only limited differences, in learning the effectiveness between 2D views and 3D models (Garg et al., 1999, 2001). On the other hand, these studies used a relatively simple anatomical structure (the carpal bones of the wrist) in a controlled laboratory setting that did not resemble that of an anatomical learning laboratory. Other studies that used more complex structures in a controlled laboratory setting, using subjects not attending anatomy classes, attained results in line with our own, suggesting spatial ability can be improved through the use of stereoscopic image projection (Luursema et al., 2008; Hoyek et al., 2014). When delicate anatomy is exposed using 3D technology, Nicholson et al. (2006) and Venail et al. (2010), found a significant advantage in using 3D technology to teach middle and inner ear anatomy of the temporal bone. Consequently, 3D virtual anatomy may be more useful as a learning tool not only for teaching anatomy in complex spatial regions, but also in identifying for tiny structures and complex relationships that are difficult for the learner to view or are not accessible during routine anatomy laboratory dissection. Finally, although there is a growing need to study 2D vs. 3D visualizations in education, undoubtedly to maintain equality (Wilson, 2015) and validity (Vorstenbosch et al., 2013) across anatomy education's evolving visualization requirements, it remains challenging both technically and logistically to create virtual environments within the classroom or learning laboratory environment (Hoyek et al., 2014). These field-like experiments, much like the current study, afford the ability to assess environments within the curriculum adding significantly to the face validity of the experiment and undoubtedly the application of their outcomes.

Are 3D Models Particularly Helpful to Students with Lower Spatial Ability?

The second goal of the study was to determine whether 3D models were particularly helpful to students with lower spatial ability. Students were divided into an MRT-low group and an MRT-high group based on their initial 3D spatial ability tests (prelearning session MRT). The results suggested that after the 2D learning experience, students with higher spatial ability demonstrated a more accurate identification of vascular anatomy than did students with a lower spatial ability (2D MRT-low vs. 2D MRT-high: $P = 0.0259$). There was a strong positive correlation between each student's initial spatial ability test (MRT) score and their postlearning session knowledge test score in the MRT-high group after a 2D learning session ($R = 0.8818$). These data support previous results (Rochford, 1985; Garg et al., 2001; Luursema et al., 2008; Nguyen and Wilson, 2009; Nguyen et al., 2012, 2014; Hoyek et al., 2014) that showed high-spatial ability to be associated with higher achievement among students taking anatomy courses, as well as among students learning anatomy-related clinical skills (Clem et al., 2013). Students with high-spatial ability scored consistently higher than the students with low-spatial ability on anatomy examinations. Studies have also suggested that computer-assisted learning materials are associated with a better understanding of spatial anatomy (Silén et al., 2008; Petersson et al., 2009; Clem et al., 2013).

Nevertheless, the results of the Rochford study do not directly apply to our results. After the 3D learning experience, we observed that there was no significant difference in the postlearning session knowledge test scores between students with high-spatial ability and students with low-spatial ability in the 3D group. In fact, the improvement in knowledge test scores had a similar increase for the students in both the 3D MRT-low group and 3D MRT-high group (see Fig. 5). In addition, students with low-spatial ability in the 3D group had a greater increase in test scores than did students with higher spatial ability in the 2D group when they took an identical knowledge test following the learning sessions.

The results of the present study indicate further that students with lower spatial ability did more worse than students with a high-spatial ability in the 2D flat-screen learning experience, as the literature had predicted (Rochford, 1985). In contrast, students with low-spatial ability did far better after taking the 3D learning session and were on par with the students with high-spatial ability. One possible explanation for this discrepancy is that exposure to the 3D model may have allowed all students in the 3D group, even those with low-spatial ability, to do well thereby compensating for any differences in spatial ability among the participants. (Luursema et al., 2006; Roach et al., 2014)

Three-Dimensional Stereoscopic Presentation and Future Stereoscopic Techniques in Anatomy Education

Three-dimensional models have been increasingly used in anatomy education as part of computer-assisted learning (Aziz et al., 2002; McLachlan et al., 2004; Brown et al., 2012; Foo et al., 2013; Anderson et al., 2013), but are often limited to online use and to flat screen images of rotating 3D structures (Spitzer et al., 1996; Temkin et al., 2006; Tam et al., 2009; Tam, 2010). For the most part, few medical schools are currently using stereoscopic projection to present 3D anatomical images for anatomy education (Nguyen and Wilson, 2009; Brown et al., 2012; Anderson et al., 2013; Foo et al., 2013). When stereoscopy is not used, a common practical problem that frequently arises is parallax errors when viewing rotating anatomy structures, such as in computer generated movies. Stereoscopic presentation provides a greater and more accurate perception of depth to each person in the class, regardless of their seating position, within the image. Since these pictures are not normally static they offer the ability to magnify areas of the object, as was used in the current study. Stereo imaging can make complicated shapes and structures easier to identify (Held and Hui, 2011).

Amira is one software system that can be used generate and display 3D visualization and 3D data presentation. The dual projectors present the illusion of depth with slightly different images seen by two eyes (Nguyen and Wilson, 2009; Brewer et al., 2012; Cui et al., 2015). Images of models appear emerging from the two projectors onto a large silver screen, and viewers feel almost able to touch the models. The 3D virtual models can be rotated 360° in all axes, flexible viewing of models and internal structures can be viewed once the models have been created. The 3D virtual images can then be then presented stereoscopically via stereoprojection.

Overall, stereoscopic projection of anatomical vasculature of the head and the neck has received positive comments from the participating students in our study. Three-dimensional (3D) information is known to play an important role in understanding the complex structure of human anatomy in medical education, especially when 3D models are created by combining 2D computed tomography slice data (Nicholson et al., 2006; Tam, 2010). Using 3D views can potentially decrease the learning curve experienced with traditional 2D views by providing a whole representation of the patient's anatomy (Foo et al., 2013). The virtual anatomical models enable visualization, manipulation, and interaction on the computer, as well as stereoscopic 3D presentation in a virtual environment (Nguyen and Wilson, 2009; Adams and Wilson, 2011; Yeung et al., 2011, 2012). The positive comments from the participants in this study may also reflect increased interactions between the students and their instructors when viewing the 3D models. Three-dimensional presentation may also increase their focus and attention on learning anatomical structures. In addition, 3D stereoscopic presentation may have improved their understanding of the spatial relationship between the vascular structures and the skull.

Limitations

Because of the volunteer nature of recruiting subjects during a period when the medical students had a particularly heavy course schedule, the total number of subjects in this study was not as large as we would have liked. A power analysis confirmed that the sample size was sufficient to support our main comparison between students in the 2D and 3D learning sessions. However, because of the small overall sample size, it was not possible to do additional comparisons based on gender, although it is well known that there are gender performance differences in MRTs (Shepard and Metzler, 1971). Additionally, it would be very interesting in the future to analyze grade point scores or MCAT scores with respect to test performance after 3D and 2D experiences. Furthermore, there is strong evidence that the ability to interact with the 3D virtual model, to rotate it and zoom closer or farther away, provides additional strength to the 3D experience compared to watching the stereoscopic virtual model passively (Luursema et al., 2006, 2008). Because the subjects in the present study had to be tested in groups, it was not possible to permit individual subjects to have control over the virtual display. This, again, will be addressed in future research. Finally, although the learning sessions in the present study were based on stereoscopic 3D models, the prelearning and postlearning tests were given in a flat, 2D format. It would be interesting to have some examination questions presented in the 3D mode, since 3D displays are becoming routine in some radiological situations. However, most radiological practice still involves the physician looking at a 2D CT or MRI scan and visualizing where that scan level exists in an internalized 3D image of the organ or system in question.

CONCLUSIONS

Overall, the results of this anatomical learning experiment indicate that stereoscopic presentations of 3D models in a small classroom setting provide a better representation of the spatial relationships of anatomic structures than does 2D images of the same material. Importantly, these results suggest that stereoscopic 3D visualization of a complex region, such as the vasculature of the head and neck, improved the performance of all students on an anatomical knowledge test and, in particular, was more helpful to the students with lower spatial ability.

As earlier studies have suggested, spatial ability predicts individual student anatomy learning outcomes when using 2D images in the traditional 2D environment. However, spatial ability does not predict learning outcomes in studies using 3D models, perhaps due to the positive influence of the 3D learning experience itself, masking or perhaps compensating, for any individual variation in spatial ability. It will be interesting and worthwhile in future studies to examine other individual factors, including motivation and reinforcement, that may play a role in predicting the effectiveness of 3D models in the teaching of anatomy. Finally, our data suggest that the use of 3D stereoscopic models may be particularly useful for improving anatomical performance across all students, particularly those with lower spatial ability, and in the future this should be further tested.

ACKNOWLEDGMENTS

The authors would like to acknowledge Drs. Andrew D. Smith, Tracy C. Marchant, John T. Mccarty, and Anson L. Thaggard, Judd Storrs, Allan R. Sinning, Ranjan Batra, Andrew Notebaert, Jian Chen, Duane E. Haines, Jessica H. Bailey, and William P. Daley for their supports of this project. The authors also thank Jerome Allison, David A. Juergens, and Varie Lynch for their technical and editing support. In addition, the authors are grateful to Drs. Warren L. May, Rui He, Ranjan Batra, and Wanmei Wang for their statistical support. The authors also want to thank Dr. Michael Peters from the University of Guelph for kindly providing the MRTs for us to use in this study. The work reported here was supported by a Faculty Scholarship Exchange Award from the University of Mississippi Medical Center. The authors have no conflicts of interest to disclose.

NOTES ON CONTRIBUTORS

DONGMEI CUI, M.D. (Hon.), Ph.D., is an assistant professor in the Department of Neurobiology and Anatomical Sciences at the University of Mississippi Medical Center. She is course director of Histology for Prematriculation and M4 review of histology and pathology. She teaches in Medical Neurobiology and M4 review of neurobiology. She is investigating and developing digital teaching tools in anatomy education.

TIMOTHY D. WILSON, Ph.D., an associate professor in the Department of Anatomy and Cell Biology at Schulich School of Medicine and Dentistry, at Western University, London, Ontario, Canada. He is the director of the CRIPT Laboratory investigating digital anatomy development, deployment, and efficacy in modern curricula. He teaches gross anatomy at a variety of graduate and undergraduate levels.

ROB W. ROCKHOLD, Ph.D., is a professor in the Department of Pharmacology and Toxicology, and of Health Sciences and Deputy Chief Academic Officer at the University of Mississippi Medical Center in Jackson, MS. In addition to pharmacology and toxicology, he teaches adult learning techniques at the graduate level.

MICHAEL N. LEHMAN, Ph.D., is a professor and Chair of the Department of Neurobiology and Anatomical Sciences at the University of Mississippi Medical Center in Jackson, MS. He teaches Medical Neurobiology and is interim Director of the Graduate Program in Neuroscience. He is a mentor and advisor for graduate students in the Program in Neuroscience and Program in Clinical Anatomy.

JAMES C. LYNCH, Ph.D., is a professor and Vice Chair of the Department of Neurobiology and Anatomical Sciences at the University of Mississippi Medical Center in Jackson, MS. He is Director of Medical Neurobiology for first-year medical students and Review of Neurobiology for fourth-year medical students. He also works in the 3D Virtual Anatomy Laboratory.

LITERATURE CITED

Ackerman MJ. 1998. The visible human project: A resource for anatomical visualization. Stud Health Technol Inform 52:1030–1032.

Adams CM, Wilson TD. 2011. Virtual cerebral ventricular system: An MR-based three-dimensional computer model. Anat Sci Educ 4:340–347.

Alpern RJ, Belitsky R, Long S. 2011. Competencies in premedical and medical education: The AAMC-HHMI report. Perspect Biol Med 54:30–35.

Anderson P, Chapman P, Ma M, Rea P. 2013. Real-time medical visualization of human head and neck anatomy and its applications for dental training and simulation. Curr Med Imag Rev 9:298–308.

Aziz MA, McKenzie JC, Wilson JS, Cowie RJ, Ayeni SA, Dunn BK. 2002. The human cadaver in the age of biomedical informatics. Anat Rec 269:20–32.

Berney S, Bétrancourt M, Molinari G, Hoyek N. 2015. How spatial abilities and dynamic visualizations interplay when learning functional anatomy with 3D anatomical models. Anat Sci Educ 8:452–462.

Brewer DN, Wilson TD, Eagleson R, de Ribaupierre S. 2012. Evaluation of neuroanatomical training using a 3D visual reality model. Stud Health Technol Inform 173:85–91.

Brown PM, Hamilton NM, Denison AR. 2012. A novel 3D stereoscopic anatomy tutorial. Clin Teach 9:50–53.

Carmichael SW, Pawlina W. 2000. Animated PowerPoint as a tool to teach anatomy. Anat Rec 261:83–88.

Clem DW, Donaldson J, Curs B, Anderson S, Hdeib M. 2013. Role of spatial ability as a probable ability determinant in skill acquisition for sonographic scanning. J Ultrasound Med 32:519–528.

Cottam WW. 1999. Adequacy of medical school gross anatomy education as perceived by certain postgraduate residency programs and anatomy course directors. Clin Anat 12:55–65.

Cui D, Lynch JC, Smith AD, Wilson TD, Lehman MN. 2015. Stereoscopic vascular models of the head and neck: A computed tomography angiography visualization. Anat Sci Educ 9:179–185.

de Ribaupierre S, Wilson TD. 2012. Construction of a 3-D anatomical model for teaching temporal lobectomy. Comput Biol Med 42:692–696.

Drake RL. 1998. Anatomy education in a changing medical curriculum. Anat Rec 253:28–31.

Drake RL. 2014. A retrospective and prospective look at medical education in the United States: Trends shaping anatomical sciences education. J Anat 224: 256–260.

Drake RL, Lowrie DJ Jr, Prewitt CM. 2002. Survey of gross anatomy, microscopic anatomy, neuroscience, and embryology courses in medical school curricula in the United States. Anat Rec 269:118–122.

Drake RL, McBride JM, Lachman N, Pawlina W. 2009. Medical education in the anatomical sciences: The winds of change continue to blow. Anat Sci Educ 2:253–259.

Ferdig R, Blank J, Kratcoski A, Clements R. 2015. Using stereoscopy to teach complex biological concepts. Adv Physiol Educ 39:205–208.

Fernandez R, Dror IE, Smith C. 2011. Spatial abilities of expert clinical anatomists: Comparison of abilities between novices, intermediates, and experts in anatomy. Anat Sci Educ 4:1–8.

Foo JL, Martinez-Escobar M, Juhnke B, Cassidy K, Hisley K, Lobe T, Winer E. 2013. Evaluating mental workload of two-dimensional and three-dimensional visualization for anatomical structure localization. J Laparoendosc Adv Surg Tech A 23:65–70.

Garg A, Norman GR, Spero L, Maheshwari P. 1999. Do virtual computer models hinder anatomy learning? Acad Med 74:S87–S89.

Garg AX, Norman G, Sperotable L. 2001. How medical students learn spatial anatomy. Lancet 357:363–364.

Garg AX, Norman GR, Eva KW, Spero L, Sharan S. 2002. Is there any real virtue of virtual reality?: The minor role of multiple orientations in learning anatomy from computers. Acad Med 77:S97–S99.

GMC. 1993. General Medical Council. Tomorrow's Doctors: Recommendations on Undergraduate Medical Education. 1st Ed. London, UK: General Medical Council. 28 p.

GMC. 2009. General Medical Council. Tomorrow's doctors: Outcomes and standards, for undergraduate medical education. In: Regulating Doctors, Ensuring Good Medical Practice. 3rd Ed. London, UK: General Medical Council. 104 p.

Guillot A, Champely S, Batier C, Thiriet P, Collet C. 2006. Relationship between spatial abilities, mental rotation and functional anatomy learning. Adv Health Sci Educ Theory Pract 12:491–507.

Held RT, Hui TT. 2011. A guide to stereoscopic 3D displays in medicine. Acad Radiol 18:1035–1048.

Hilbelink AJ. 2009. A measure of the effectiveness of incorporating 3D human anatomy into an online undergraduate laboratory. Br J Educ Technol 40:664–672.

Hopkins R, Regehr G, Wilson TD. 2011. Exploring the changing learning environment of the gross anatomy laboratory. Acad Med 86:883–888.

Hoyek N, Collet C, Di Rienzo F. 2014. Effectiveness of three-dimensional digital animation in teaching human anatomy in an authentic classroom context. Anat Sci Educ 7:430–437.

Khot Z, Quinlan K, Norman GR, Wainman B. 2013. The relative effectiveness of computer-based and traditional resources for education in anatomy. Anat Sci Educ 6:211–215.

Kockro RA, Amaxopoulou C, Killeen T, Wagner W, Reisch R, Schwandt E, Gutenberg A, Giese A, Stofft E, Stadie AT. 2015. Stereoscopic neuroanatomy lectures using a three-dimensional virtual reality environment. Ann Anat 201: 91–98.

Likert R, Quasha WH. 1995. The Revised Minnesota Paper Form Board Test. 2nd Ed. San Antonio, TX: Pearson Assessment, Inc.

Lufler RS, Zumwalt AC, Romney CA, Hoagland TM. 2012. Effect of visual-spatial ability on medical students' performance in a gross anatomy course. Anat Sci Educ 5:3–9.

Luursema JM, Verwey WB, Kommers PAM, Geelkerken RH, Vos HJ. 2006. Optimizing conditions for computer-assisted anatomical learning. Interact Comput 18:1123–1138.

Luursema JM, Verwey WB, Kommers PA, Annema JH. 2008. The role of stereopsis in virtual anatomical learning. Interact Comput 20:455–460.

Martin CM, Roach VA, Nguyen N, Rice CL, Wilson TD. 2013. Comparison of 3D reconstructive technologies used for morphometric research and the translation of knowledge using a decision matrix. Anat Sci Educ 6:393–403.

McLachlan JC, Patten D. 2006. Anatomy teaching: Ghosts of the past, present and future. Med Educ 40:243–253.

McLachlan JC, Bligh J, Bradley P, Searle J. 2004. Teaching anatomy without cadavers. Med Educ 38:418–424.

Moxham BJ, Plaisant O. 2007. Perception of medical students towards the clinical relevance of anatomy. Clin Anat 20:560–564.

Nguyen N, Wilson TD. 2009. A head in virtual anatomy: Development of a dynamic head and neck model. Anat Sci Educ 2:294–301.

Nguyen N, Nelson AJ, Wilson TD. 2012. Computer visualizations: Factors that influence spatial anatomy comprehension. Anat Sci Educ 5:98–108.

Nguyen N, Mulla A, Nelson AJ, Wilson TD. 2014. Visuospatial anatomy comprehension: The role of spatial visualization ability and problem-solving strategies. Anat Sci Educ 7:280–288.

Nicholson DT, Chalk C, Funnell WR, Daniel SJ. 2006. Can virtual reality improve anatomy education? A randomized controlled study of a computer-generated three-dimensional anatomical ear model. Med Educ 40:1081–1087.

Peters M, Laeng B, Latham K, Jackson M, Zaiyouna R, Richardson C. 1995. A redrawn Vandenberg and Kuse mental rotations test: Different versions and factors that affect performance. Brain Cogn 28:39–58.

Petersson H, Sinkvist D, Wang C, Smedby O. 2009. Web-based interactive 3D visualization as a tool for improved anatomy learning. Anat Sci Educ 2:61–68.

Poggio GF, Poggio T. 1984. The analysis of stereopsis. Ann Rev Neurosci 7: 379–412.

Qayumi AK, Kurihara Y, Imai M, Pachev G, Seo H, Hoshino Y, Cheifetz R, Matsuura K, Momoi M, Saleem M, Lara-Guerra H, Miki Y, Kariya Y. 2004. Comparison of computer-assisted instruction (CAI) versus traditional textbook methods for training in abdominal examination (Japanese experience). Med Educ 38:1080–1088.

Risucci DA. 2002. Visual spatial perception and surgical competence. Am J Surg 184:291–295.

Roach VA, Mistry MR, Wilson TD. 2014. Spatial visualization ability and laparoscopic skills in novice learners: Evaluating stereoscopic versus monoscopic visualizations. Anat Sci Educ 7:295–301.

Rochford K. 1985. Spatial learning disabilities and underachievement among university anatomy students. Med Educ 19:13–26.

Schueneman AL, Pickleman J, Hesslein R, Freeark RJ. 1984. Neuropsychologic predictors of operative skill among general surgery residents. Surgery 96:288–293.

Schwartz RK, Reilly MA. 1980. Learning tools use: Visual proprioceptive recalibration and the development of hand skill. Int J Rehabil Res 3:369–371.

Sergovich A, Johnson M, Wilson TD. 2010. Explorable three-dimensional digital model of the female pelvis, pelvic contents, and perineum for anatomical education. Anat Sci Educ 3:127–133.

Shaffer K. 2004. Teaching anatomy in the digital word. N Engl J Med 351: 1279–1281.

Shepard RN, Metzler J. 1971. Mental rotation of three-dimensional objects. Science 171:701–703.

Silén C, Wirell S, Kvist J, Nylander E, Smedby O. 2008. Advanced 3D visualization in student-centred medical education. Med Teach 30:e115–e124.

Spitzer V, Ackerman MJ, Scherzinger AL, Whitlock D. 1996. The visible human male: A technical report. J Am Med Inform Assoc 3:118–130.

Tam MD. 2010. Building virtual models by postprocessing radiology images: A guide for anatomy faculty. Anat Sci Educ 3:261–266.

Tam MD, Hart AR, Williams S, Heylings D, Leinster S. 2009. Is learning anatomy facilitated by computer-aided learning? A review of the literature. Med Teach 31:e393–e396.

Temkin B, Acosta E, Malvankar A, Vaidyanath S. 2006. An interactive three-dimensional virtual body structures system for anatomical training over the internet. Clin Anat 19:267–274.

Vandenberg SG, Kuse AR. 1978. Mental rotations, a group test of three-dimensional spatial visualization. Percept Mot Skills 47:599–604.

Venail F, Deveze A, Lallemant B, Guevara N, Mondain M. 2010. Enhancement of temporal bone anatomy learning with computer 3D rendered imaging software. Med Teach 32:e282–e288.

Verhoeven BH, Verwijnen GM, Scherpbier AJ, van der Vleuten CP. 2002. Growth of medical knowledge. Med Educ 36:711–717.

Vernon T, Peckham D. 2002. The benefits of 3D modelling and animation in medical teaching. J Audiov Media Med 25:142–148.

Vorstenbosch MA, Klaassen TP, Kooloos JG, Bolhuis SM, Laan RF. 2013. Do images influence assessment in anatomy? Exploring the effect of images on item difficulty and item discrimination. Anat Sci Educ 6:29–41.

Wanzel KR, Hamstra SJ, Anastakis DJ, Matsumoto ED, Cusimano MD. 2002. Effect of visual-spatial ability on learning of spatially-complex surgical skills. Lancet 359:230–231.

Wilson TW. 2015. Role of image and cognitive load in anatomical multimedia. In: Chan KL, Pawlina W (Editors). Teaching Anatomy. A Practical Guide. 1st Ed. Cham, Switzerland: Springer International Publishing. p 237–245.

Yeung JC, Fung K, Wilson TD. 2011. Development of a computer-assisted cranial nerve simulation from the visible human dataset. Anat Sci Educ 4:92–97.

Yeung JC, Fung K, Wlson TD. 2012. Prospective evaluation of a web-based three-dimensional cranial nerve simulation. J Otolaryngol Head Neck Surg 41: 426–436.