Published in final edited form as:
Anat Sci Educ. 2010 ; 3(6): 309–317. doi:10.1002/ase.186.

A Novel Three-Dimensional Tool for Teaching Human Neuroanatomy

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Abstract

Three-dimensional (3-D) visualization of neuroanatomy can be challenging for medical students. This knowledge is essential in order for students to correlate cross-sectional neuroanatomy and whole brain specimens within neuroscience curricula and to interpret clinical and radiological information as clinicians or researchers. This study implemented and evaluated a new tool for teaching 3-D neuroanatomy to first-year medical students at Boston University School of Medicine. Students were randomized into experimental and control classrooms. All students were taught neuroanatomy according to traditional 2-D methods. Then, during laboratory review, the experimental group constructed 3-D color-coded physical models of the periventricular structures, while the control group re-examined 2-D brain cross-sections. At the end of the course, 2-D and 3-D spatial relationships of the brain and preferred learning styles were assessed in both groups. The overall quiz scores for the experimental group were significantly higher than the control group ($t(85) = 2.02$, $P < 0.05$). However, when the questions were divided into those requiring either 2-D or 3-D visualization, only the scores for the 3-D questions were significantly higher in the experimental group ($F_{1,85} = 5.48$, $P = 0.02$). When surveyed, 84% of students recommended repeating the 3-D activity for future laboratories, and this preference was equally distributed across preferred learning styles ($\chi^2 = 0.14$, n.s.). Our results suggest that our 3-D physical modeling activity is an effective method for teaching spatial relationships of brain anatomy and will better prepare students for visualization of 3-D neuroanatomy, a skill essential for higher education in neuroscience, neurology, and neurosurgery.

Keywords

anatomical sciences; medical education; gross anatomy; neurosciences; anatomy teaching; neuroscience/neuroanatomy teaching; three-dimensional visualization

Introduction

Three-dimensional (3-D) information has become increasingly important in medical education and health care (Marks, 2000). However, understanding 3-D information can be challenging, particularly in the medical neurosciences. In addition to traditional localization skills in clinical neurology, technologies such as 3-D magnetic resonance imaging, computed tomography, and computer-assisted surgery require physicians to appreciate complex spatial data for diagnosis and/or treatment of disease. The safe and effective

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Authors have no conflicts of interests and no commercial or financial relationships to disclose.

utilization of 3-D technologies relies upon foundational understanding of anatomy. Unfortunately, the growing consensus among studies in the United States (Cottam, 1999), United Kingdom (Older, 2004; Waterston and Stewart, 2005), and Western Europe (Pabst and Rothkotter, 1997; Prince et al., 2005) is that the standards of anatomy knowledge among medical graduates is deficient and often below the standards for safe medical practice. For instance, in a survey of more than 1,000 residency programs in multiple specialties across the United States, Cottom (1999) reported that 86% of residency directors described anatomy as extremely or very important to mastery of their respective discipline. However, more than half of the surveyed residency directors stated that new residents needed a refresher in anatomy upon arrival (57%) and a substantial number (14%) expressed concerns that adequate anatomical knowledge was seriously lacking. This concern has emerged during an extended time period where there has been relentless pressure to add more conceptual information to the medical curriculum, often at the cost of time spent at the bedside, behind the microscope, at the autopsy table, and in the teaching laboratory (Drake et al., 2009).

Recently, current educational trends have advocated for reduced didactic lecture and increased active learning (Drake, 1999; Irby and Wilkerson, 2003; Drake et al., 2009). Physicians have implored medical educators to integrate newer teaching modalities that encourage interest, understanding, and retention of anatomical knowledge (Turney, 2007; Bergman et al., 2008; Sugand et al., 2010). The call for less theoretical-passive learning and more active-authentic pedagogical experiences is a reprise of recommendations from nearly a century ago from the Flexner Report (Flexner, 1910; Cooke et al., 2006). The modern day call is looking for new pedagogical techniques that accomplish anatomical understanding in less time, but the challenge still remains for students to build and operate within internal mental models of complex biological structures (Sugand et al., 2010). This is particularly important in the neurosciences. Because the nervous system is one of the most spatially complex systems of the human body, innovative tools for assisting in 3-D neuroanatomical visualization are especially valuable to enhance learning.

Classical medical neuroscience curricula teach neuroanatomy through 2-D cross-sections of brain, brainstem, and spinal cord (Nolte and Angevine, 2007). These techniques were sufficient when adequate time to internalize and transform this information into 3-D understanding was coupled with multiple exposures to patient and laboratory materials in the clinical years. Under the time constraints and restricted opportunities for clinico-anatomical experience today, the traditional approach of classical medical neuroscience curricula often falls short in representing the complex 3-D relationships of various brain structures, such as intricate internal morphology of the ventricular system, diencephalon, and basal ganglia. Hence, today's students must integrate the 2-D images into a mental model and extract the relevant 3-D relationships without the benefit of the traditional time and actual hands-on experience with the nervous system to help guide this knowledge acquisition. The success of this task often depends, now to perhaps a greater degree, upon the innate spatial abilities of the student (Rochford, 1985; Guillot et al., 2007; Hegarty et al., 2007) or prior training in mental rotation tasks (Hoyek et al., 2009). Although new teaching technologies, such as computer graphics and virtual reality programs, allow for 3-D representation of the brain, these activities have the potential to increase the cognitive load and hinder a student with poor spatial skills (Garg et al., 1999; Huk, 2006; Levinson et al., 2007). Furthermore, although computer-assisted learning is extremely valuable in many situations, computer graphic representations are limited by their inability to be tangibly manipulated, a feature which may play a very important role in successful 3-D learning.

In this work, we hypothesize that a positive relationship exists between the manipulation of a physical 3-D space and the formation of internal mental models of that 3-D space.

Therefore we predicted that a learning intervention designed to render a complex 3-D neural structure by physical manipulation of (clay or plasticine) modeling materials would show improved access to and understanding of those relationships as tested by traditional forms of assessment of internal mental models in medical education. Support for this hypothesis and design of an intervention using physical models, is found in the literature where computer graphic tools for teaching visuospatial relationships in biomedical science (see for example, Oh et al., 2009) can be a powerful complement to traditional teaching methods. Tactile manipulation of a physical model could help a low spatial learner overcome the high cognitive load of mental rotations. Indeed, research studies exploring visuospatial learning in chemistry have reported that physical models, such as ball-and-stick molecule kits, help students comprehend spatial relationships among atoms, solve chemistry problems, and understand abstract concepts (Wu and Shah, 2004). Consistent with this, some educators suggest that manipulation of 3-D objects facilitates general spatial knowledge development (Dalgarno et al., 2002) and that differences in the performance of spatial ability tasks between genders can be eliminated with 3-D teaching interventions (Piburn et al., 2005). Beyond the classroom, clinicians have initiated powerful applications of physical models for the diagnosis and treatment of disease with the emergence of rapid prototyping, a technology in which 3-D computed tomography images are transformed into plastic or ceramic physical models (Webb, 2000).

The study presented here implemented and evaluated the effectiveness of a relatively simple physical modeling activity for teaching 3-D brain anatomy to first-year medical students enrolled in the Medical Neurosciences course at Boston University School of Medicine (BUSM). The objective of the modeling activity was to reconcile the disconnect between 2-D learning and 3-D understanding of neuroanatomy by directing students to construct color-coded ‘clay’ models of the periventricular brain structures. The study was designed to assess whether our neuroanatomy teaching intervention was effective for improving 3-dimensional understanding of brain anatomy, Furthermore we probed students' impressions and opinions of the modeling activity and examined whether they would recommend the activity as a supplement to the undergraduate medical neuranatomy curriculum.

Methods

Study Population

The study was conducted in the laboratory sections of the first-year Medical Neurosciences course at BUSM during the January 2006 term. A total of 101 first-year medical students participated in this study. Students were randomized into laboratory classrooms for experimental (n=51 students) and control (n=50 students) interventions using a systematic random sampling procedure based on last name spelling and numerically ordered rooms. Groups were comparable in size, age, gender and distribution of VARK preferred learning styles (Fleming, 1995, 2010, Table 1). After the study, the activity was formally implemented into the course curriculum, and students were surveyed for three consecutive years as part of normal course evaluations. All procedures were approved by the Institutional Review Board at Boston University Medical Campus and Boston Medical Center (protocol H-25184). All research personnel completed the Human Participants Protection Education for Research Teams online course by the National Institutes of Health before the commencement of the study.

Study Design

At the time of the study, the first-year Medical Neurosciences course at BUSM consisted of fifty one-hour lectures, five two-hour neurophysiology discussion sessions and seven two-hour neuroanatomy laboratory sessions (entitled Laboratory I-VII) over the course of five weeks. Our study was conducted in the neuroanatomy laboratory sessions during the course. Primary teaching of the neuroanatomy curriculum for all participants (*n* = 101) proceeded according to customary teaching methods throughout Laboratories I-V, in which students divided into small groups of four to five students each and inspected preserved brain tissue, studied plastic embedded sets of coronally and horizontally sectioned brain slabs, and viewed slideshows of 2-D images of coronally and horizontally sectioned brains. Also, each laboratory session in all classrooms included an instructor-led presentation and discussion in which important anatomical relationships and pathways were highlighted. In addition, all students received access to diagrams and photographs from their atlas (Nolte and Angevine, 2007), the online *Interactive Brain Atlas* (Sundsten, 1994) and the Brainstorm (Tancred and Coppa, 1991) program. Secondary teaching or review of the neuroanatomy curriculum (in the form of an in-laboratory review session during Laboratory VI) varied across groups. During laboratory review, students in the experimental group constructed 3-D color-coded physical models of the periventricular structures in small groups of four to five students each, while students in the control group re-examined 2-D cross-sections in similar small groups of four to five students each (see Figure 1).

Procedures for Modeling Activity in Experimental Classrooms

Each small group in the experimental group received one cast model of the ventricular system (Human Brain Ventricles #566786, Carolina Biological Supply Co., Burlington, NC) and an assortment of colored Crayola® Model Magic (Crayola, Easton, PA). Crayola® Model Magic is a non-toxic, safe, soft, foam-like material that can be molded into 3-D shapes and air-dries into a light-weight solid structure. Each cast ventricular model served as a template on which students built periventricular structures according to a prescribed color-coding system shown in Figure 2. Students were left free to build the model on their own within their small group, and a pre-made example model was passed around the room as a learning aid. Students were encouraged to use “Chapter 4 - Building a Brain: Three-Dimensional Reconstructions” from their atlas (Nolte and Angevine, 2007) as well as the *Interactive Brain Atlas* (Sundsten, 1994) as resources for building the models. After the models were constructed, the laboratory instructor walked around the room and appraised each model for appropriate content, size and shape while suggesting corrections or changes if necessary. In addition, a discussion session followed the modeling activity in which various spatial relationships between structures were highlighted on the model. Note that a discussion session was also included in the control classrooms in which spatial relationships were discussed using a slideshow of 2-D images of coronally and horizontally sectioned brains.

Assessment

The course evaluation period, generally reserved for the end of Laboratory VII, was extended in the control and experimental classrooms in order to give an assessment quiz and a survey. Students were informed that participation in the assessment would be anonymous, voluntary, and would have no impact on their grade in the course or their academic reputation in medical school.

Quiz—The assessment quiz consisted of two parts. The first part probed student understanding of anatomical relationships between structures on a 2-D plane (i.e. rostral/caudal, superior/inferior, medial/lateral), and included questions such as, “What structure is located immediately medial to the putamen?” and “What structure follows the lateral borders of the third ventricle?” (left panel, Figure 3). The second part of the quiz measured student understanding of 3-D neuroanatomy. These questions asked students to identify and label structures from photographs of dissected brains to which the students had not previously been exposed. The photographs showed unique and unusual brain dissections in which various periventricular structures such as the caudate, putamen, amygdala, and hippocampus were exposed to show their 3-D structure and relationship to one another (see right panel of Figure 3 for examples). These dissections did not include key views or cues, such as those from familiar 2-D textbook images, but instead required students to use 3-D cues and spatial relationships between structures to correctly answer each question. The photographed dissections used for the 3-D portion of the quiz were adapted with permission from the University of Washington Digital Anatomist and can be viewed online (Sundsten, 1994). The appropriateness of the assessment quiz as an experimental measure was evaluated using LXR Test version 6.0 software (Logic eXtension Resources, Georgetown, SC). The validity was measured by point-biserial correlation and ranged between +0.06 and 0.72, with two questions scoring -0.02. To address this, all analyses were run with and without the low validity questions. The Cronbach's Coefficient Alpha measure of reliability was 0.71.

Survey—After completing the assessment quiz, students were given a survey consisting of two parts. The first part investigated the student's preferred learning style - visual, auditory, read/write or kinesthetic - by asking questions adopted with permission from the *VARK, A Guide to Learning Styles*, available online (Fleming, 1995, 2010). The second part of the survey solicited students' opinions of the 3-D activity (see Table 3).

Statistical Analysis

The discrete variables of the study are medical students, gender, learning styles, and number of students who answered each question reported as frequency (*n*) and percent (%). Continuous variables are age reported as mean ± standard deviation (SD, years), assessment quiz scores and final course grades reported as score (%) ± standard deviation (SD). Assessment quiz scores, final course grades and age were examined using parametric analyses. Within and between group differences in performance on 2-D and 3-D questions of the assessment quiz were examined using a mixed MANOVA with group type (experimental versus control) as the between-subjects factor and question type (2-D versus 3-D) as the within-subjects factor. Post-hoc comparisons of significant effects were made using Tukey-Kramer HSD with adjustments for multiple comparisons within the model. Group differences in total quiz score, final neuroanatomy laboratory practical examination, and final course grades were examined using two-tailed Student's t-tests. Non-paramentric analysis was used to examine the survey data, as well as gender. For the analysis of the VARK survey, a Pearson chi-square analysis was used to examine if there were different distributions of learning styles between experimental and control classrooms. A Pearson chi-square analysis was also used to examine whether the distribution of the students answering “yes” or “no” to the statement, “I would recommend using the ‘clay’ modeling activity for future laboratories” varied based on learning styles (visual - kinesthetic or auditory - read/write on the VARK). Analyses of student assessment scores were performed using JMP statistical software (SAS Institute, Cary, NC). We compared the results of our chi-square analysis performed in JMP with the Fisher Exact Probability test (Lowry, 2010) and found that the P values were essentially the same. We present only the JMP analyses in our results because this provides a unified software approach to the data analysis.

Results

Students successfully completed the modeling activity within 30-45 minutes during laboratory. An example of a student-made model is shown in Figure 2. Forty-two experimental and 45 control students completed the assessment quiz portion of this study, and the scores are summarized in Table 2. The overall quiz score for the experimental group was significantly higher than that of the control group [t (85) = 2.02, $P < 0.05$]. When the questions were divided into those requiring either 2-D or 3-D understanding and analyzed using a mixed MANOVA, three main trends emerged. First, overall the experimental group scored significantly higher than the control group ($F_{1,85} = 5.14$, $P = 0.03$). Second, when collapsed across both groups, students performed better on 2-D questions than 3-D questions ($F_{1,85} = 40.23$, $P < 0.0001$). Third, and most notably, there was a significant group by question type interaction indicating that while the control and experimental groups performed similarly on the 2-D questions, the experimental group scored significantly higher on the 3-D questions ($F_{1,85} = 5.48$, $P = 0.02$). The results for all analyses were the same after removing scores from the two low validity questions. Of note, there were no group differences in final course grades [$t(99) = 0.88$, $P = 0.38$] or in the final laboratory practical examination scores [$t(99) = 0.55$, $P = 0.58$], see Table 2.

Overall distributions of VARK learning styles were 21.4% visual, 19.1% auditory, 9.5% read/write, and 40.5% kinesthetic for the experimental group ($n = 42$) and 23.7% visual, 11.4% auditory, 13.6% read/write, and 43.2% kinesthetic for the control group ($n = 44$). A chi-square analysis revealed that there was no significant difference in the distribution of VARK learning styles across groups ($\chi^2 = 1.21$, $P = 0.75$). Students who scored as multimodal learners (scoring equally on two or more learning styles) were excluded from this analysis (4 experimental groups and 4 control groups), see Table 1.

Survey results for the experimental group are summarized in Table 3. Eighty-four percent of students from the experimental group who responded to the survey question ($n = 40$) described the modeling exercise as either “very helpful” or “helpful”, and this response was equally distributed across learning styles ($\chi^2 = 0.67$, $P = 0.41$). Similarly, 84% of students from the experimental group who answered the question ($n = 38$) recommended repeating the 3-D activity for future laboratories, and this preference was also equally distributed across learning styles ($\chi^2 = 0.14$, $P = 0.70$).

Discussion

This study evaluated the effectiveness of a new activity for teaching human neuroanatomy to first-year medical students through the construction of 3-D color-coded physical models of the internal brain. Our assessment quiz indicated that students who built 3-D models performed significantly better on questions that required 3-D understanding of periventricular structures (Table 2). Our survey results indicated that this tool was perceived as effective and recommended by medical students for use in future years as a supplement to the undergraduate medical neuroanatomy curriculum (Table 3). The results of our study are similar to those reported by Oh and colleagues (2009) who used clay modeling of the brain and other organs to help students understand cross-sectional anatomy and perform in CT scan interpretation. This and our study together support the hypothesis that a direct relationship between building a physical model and the development of accessible internal models of 3-dimensional space can be enhanced with the proper design of instructional interventions that serve as an effective tool to bridge 2-D learning and 3-D understanding of brain anatomy.

We expected that visual or kinesthetic learners would be more likely than auditory or read/write learners to recommend the modeling activity for future years. However, our results demonstrated that this was not the case. The high helpfulness rating and recommendation to use the modeling activity was equally distributed across all VARK learning styles. We speculate that perhaps the visual and kinesthetic learners, who may have a high cognitive capacity for mental model construction, recommended the 3-D activity because it enhanced their already preferred learning style, in a way similar to the “ability-as-enhancer” hypothesis proposed by Mayer (Huk, 2006). Similarly, we conjecture that the auditory and read/write learners equally recommended the 3-D activity because it compensated for or strengthened a deficient or unfamiliar learning style, in a way similar to the “ability-as-compensator” hypothesis of Hegarty and Sims (1994).

Interestingly, we found that the 3-D modeling activity had no effect on final laboratory practical examinations or final grades in the course. This may suggest that the activity was unsuccessful or unbeneficial. However, we assert that the present structure of course examinations do not assess student understanding of 3-D neuroanatomical relationships as is required by current medical practice in neurology. Indeed, students in control classrooms scored a mean 55% (below a passing level) on quiz questions requiring complex 3-D understanding of brain anatomy, yet scored a mean 80% (well above a passing level) in final course grades (see Table 2). Thus, our study suggests that medical students can perform satisfactorily in traditional neuroscience coursework and examinations without acquiring an adequate understanding of spatial relationships, a skill particularly valuable for anatomy-based specialties. This finding is consonant with the recent charge of Stern and colleagues for the need to “rigorously study the neurologic education of medical students, neurology residents, and neurologists to determine the effectiveness of our educational efforts” (Stern et al., 2008).

Accordingly, departments of neurosurgery and radiology have been the first to explore more effective training tools and technologies for 3-D visualization of human anatomy. For example, neurosurgeons have developed advanced stereoscopic (Shimizu et al., 2006; Nowinski et al., 2009) and holographic (Ko and Webster, 1995) imaging applications as well as virtual reality (Kockro et al., 2007; Lemole et al., 2007) and stereolithic biomodeling (Wurm et al., 2004) techniques to teach 3-D neuroanatomical relationships for the planning and simulation of neurosurgical procedures. Moreover, the success of the Visual Human Project of the National Library of Medicine has caused an explosion in the availability and diversity of novel computer programs for studying all regions of human anatomy (see Jastrow and Vollrath, 2003 for review). With these advancing computer technologies and their increased availability, medical educators must ask if the classical medical curriculum should integrate more 3-D spatial learning activities and if so, whether they are empirically more effective than traditional textbook teaching methods and whether they translate to better patient care.

There is some debate over the effectiveness of 3-D graphics to teach anatomy. Some medical educators suggest no learning advantage in using 3-D graphics or virtual reality to teach anatomy, while others report the contrary arguing that differences in the complexity of the anatomical region, the interactivity of the computer program, and the type of post-test questions explain the discrepancy (Nicholson et al., 2008). This debate is particularly important regarding the use of cadavers and the timing of their use in teaching gross anatomy (reviewed in Winkelmann, 2007). Our study supports the notion that the type of post-test question used explains discrepancies in results of 3-D teaching interventions. Indeed, students in our study performed equally well on quiz questions that required only 2-D understanding regardless of the teaching intervention used. However, when the quiz questions required a more sophisticated 3-D understanding of the spatial relationships from views to which they had not previously been exposed, students who had engaged in the 3-D modeling exercise had a significant advantage over those who had not. Similarly, in a study of the effectiveness of a virtual chemistry laboratory, Dalgarno and Harper, (2003) concluded that manipulating objects in a 3-D computer model environment can lead to greater spatial learning, but only if the learning tasks require an understanding of spatial relationships.

How might our “hands-on” physical modeling tool compare in effectiveness to a similar computer-generated program? It is surely plausible that the tactile process of creating a physical modeling is helpful for learning the complex over-under-around qualities of 3-D problems (Jones et al., 2005). However, this comparison was not directly tested in our study, and would be worth pursuing in future studies with particular consideration to variables such as user-control, interaction, key views, object manipulation (Garg et al., 1999, 2001; Dalgarno et al., 2002; Nowinski et al., 2009) and/or haptic feedback (Van der Meijden and Schijven, 2009). Another limitation of our study is that the effect of innate spatial ability on a spatial task (Hegarty et al., 2007) and gender differences in spatial abilities (McGee, 1979; Voyer et al.,1995; Peters et al., 2007) were not measured and should be considered for future studies. Assessments for such future studies ought to consider the differentiation between questions that require an understanding of 2-D versus 3-D spatial relationships. Assessment questions that probe anatomical relationships on a 2-D plane (“Is structure A superior or inferior to structure B?”) are quite different from questions that require students to identify structures from complex or unusual dissections or to mentally rotate an anatomical structure (Rochford, 1985; Guillot et al., 2006; Hoyek et al.,2009; Hegarty, 2009). Finally, although the clay models were superficially evaluated by the laboratory instructor for appropriate content, size, and shape, the aesthetic quality and realistic accuracy of the clay models were not rigorously assessed in our study, as these factors may be a function of artistic talent and not directly related to 3-D learning.

Since the time of this study, we have repeated the 3-D modeling activity for three consecutive years in the neuroanatomy laboratories of the first-year Medical Neuroscience course at BUSM. Each year, more than 80% of the students have recommended repeating the activity for future years (data not shown). On the basis of these student recommendations and the results of this study, we have now integrated the 3-D activity into the formal laboratory curriculum for the course with two modifications. First, we created an instructions guide with a recommended step-by-step sequence for building the model. We found that this instructions guide reduced the time students needed to complete this activity from approximately 45 minutes to 20 minutes. Second, we increased our inventory of cast ventricle models and thereby reduced the group size from four to five students to two to three students in order to encourage individual interaction with the model. It remains to be evaluated whether these two modifications - reduced time and increased participation – add or detract from the overall educational experience of the activity and are important considerations for future studies.

Our results show that this type of “hands-on” physical intervention can be effective in improving the learning of complex three-dimensional relationships and that the experience also has the advantage of being perceived as “helpful” and relatively enjoyable by the learner. As an intervention these findings make the tool both psychologically and pedagogically attractive. Further important research questions remain to be assessed in terms of the frequency of the application of the intervention and its extensibility to other forms of expert medical learning. It will also be crucial to establish the durability of effect in further studies. These questions as well as a more formal evaluation of the mechanisms underlying spatial naïve-to-expert learning are currently being evaluated in our research program.

Acknowledgments

The authors would like to thank Erita Ikonomi at the Educational Media Center at Boston University School of Medicine for assistance with the reliability and validity statistics for the assessment quizzes. The authors would also like to thank the faculty in the Department of Anatomy and Neurobiology at Boston University School of Medicine for their valuable ideas and insight for the smooth execution of the modeling activity in the classrooms: Drs. J. Luebke, D. Rosene, J. Sandell, J-J. Soghomonian, A. Valero-Cabre, I. Zhdanova, and C. Zucker.

Sources of Funding: Grant Sponsors: NIH, grant number: EY01157 (minority supplement for MEE to M. Carter Cornwall – P. I.); NINDS, grant number: F30-NS055511 (to Kristen A. Lindgren); and NIH, grant number: R13DK69541 (to Peter R. Bergethon).

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Biographies

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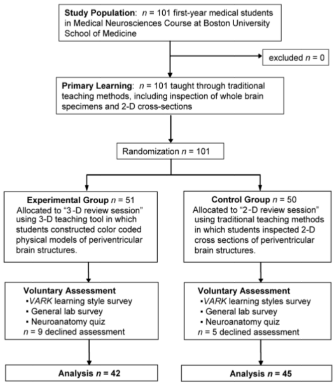
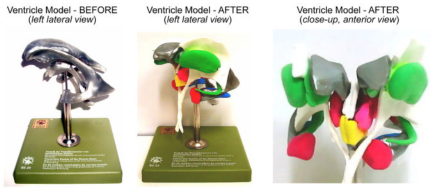


Figure 1.

Flow chart of study design.



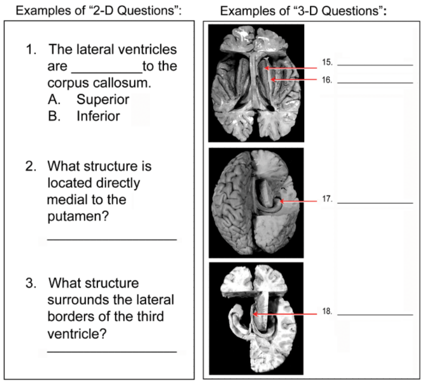
Ventricle Model - BEFORE (*left lateral view*)

Ventricle Model - AFTER (*left lateral view*)

Ventricle Model - AFTER (*close-up, anterior view*)

Figure 2.

Photographic images of a student-made 3-D model of periventricular brain structures. Students were divided into small groups of 4-5 students each. Each group was given a cast ventricular model (left panel, see also Methods) and an assortment of Crayola® Model Magic. Students were instructed to study the parts of the ventricle model first and then identify, build, and place the following structures according the color scheme: thalamus - pink, hypothalamus – yellow, caudate and putamen - green, globus pallidus – light green, hippocampus – blue, amygdala – red, internal capsule and fornix - white. An example student-built model is shown in the middle panel (left lateral view) and right panel (enlarged anterior view).



Examples of "2-D Questions":

1. The lateral ventricles are __________to the corpus callosum.
   A. Superior
   B. Inferior
2. What structure is located directly medial to the putamen?
   ____
3. What structure surrounds the lateral borders of the third ventricle?
   ____

Examples of "3-D Questions":

Figure 3.

Examples of 2-D and 3-D questions included in the assessment quiz. The left panel shows examples of questions that measured student understanding of 2-D neuroanatomical relationships. The right panel shows examples of questions requiring students to use 3-D cues and spatial relationships to label structures from photographs of unusual brain dissections. Photographs used in the study were reprinted with permission from The University of Washington, Digital Anatomist Project: The Interactive Brain Atlas (Sundsten, 1994).

Table 1

Study Demographics.

	Experimental Group	**Control Group**	***t* or χ^2**	***P* value**
Total Participants in Study	***n* = 51**	***n* = 50**		
Mean Age ± SD (years)	24.7 ± 4.13	23.9 ± 2.26	$t(99) = 1.15$	0.25
Gender (M/F)	19/32	21/29	$\chi^2 = 0.24$	0.63
***VARK* Learning Styles Survey %**	***n* = 42**	***n* = 44**		
V	21.4	23.7	$\chi^2 = 1.21$	0.75
A	19.1	11.4		
R	9.5	13.6		
K	40.5	43.2		
Multimodal	9.5	9.1		

Groups were comparable in size, age, gender and distribution of VARK preferred learning styles (Fleming, 1995, 2010), where t is resulting t-value from student t-test analysis, χ^2 is resulting Chi-squared distribution from Pearson Chi-Squared analysis, and SD is standard deviation. Standard deviation of mean age is higher for the experimental group compared to the control group because there was one outlier student in the experimental group of 46 years of age. The age of all other participants ranged from 20-31 years. Results of t-test including and excluding this student were the same. Students who scored equally on two or more learning styles for the VARK survey are indicated in the “Multimodal” row and were excluded from the Chi-Squared analysis (four experimental scoring VR, VA, RK and AR and four control scoring VK, VK, VK and AR). V, visual; A, auditory; R, read/write; K, kinesthetic; VR, visual read/write; VA, visual auditory; RK, read/write kinesthetic; AR, auditory read/write; VK, visual kinesthetic.

Table 2

Assessment Quiz Results and Final Course Grades.

Scores	**Experimental Group (%** ***correct*** **±** ***SD***	**Control Group (%** ***correct*** **±** ***SD*****)**	***F*** **or** ***t***	***P*** **value**
Assessment Quiz	***n = 42***	***n = 45***		
Overall Score[a]	76.8 ± 15.2	70.2 ± 15.1	$t(85) = 2.02$	< 0.05
3-D type questions[a]	69.7 ± 29.8	54.9 ± 25.1	Group: $F_{1,85}= 5.14$	0.03
			Question type: $F_{1,85} = 40.23$	< 0.0001
2-D type questions	80.6 ± 12.0	78.5 ± 14.0	Question type[a]: Group: $F_{1,85} = 5.48$	0.02
Course Grades	***n = 51***	***n = 50***		
Final Neuroanatomy Laboratory Practical Grade	85.5 ± 10.2	84.4 ± 9.6	$t(99) = 0.55$	0.60
Final Overall Course Grade	81.4 ± 8.3	80.0 ± 8.2	$t(99) = 0.88$	0.38

[a] statistically significant difference between experimental versus control groups scores, where *t* is resulting t value from student t-test analysis, *F* is resulting F-ratio from ANOVA analysis, and ± SD is standard deviation.

Table 3
Survey results from students in the experimental group

Items for Survey	**Very helpful or helpful (%)**	**Not helpful or unhelpful/confused me (%)**	***n***
Studying diagram and photographs from text, atlas, or syllabus	97.6	2.4	42
Viewing computer graphic 3-D images and/or interactive MRIs	95.0	5.0	40
Thoroughly reading the syllabus	83.3	16.7	42
Thoroughly reading the textbook	50.0	50.0	34
Actively listening to instructor's mini-lectures or having group discussions (aural interaction in laboratory)	83.3	16.7	42
Listening to instructor go through slides on projector	81.0	19.0	42
Going through slides on my own	95.2	4.8	42
Manipulating/handling the wet brain tissue in buckets	64.3	35.7	42
Studying brainstem rubber models and/or ventricle models	67.5	32.5	40
Studying pre-cut plastic embedded brain slices	73.0	27.0	37
Making a “clay” model of periventricular brain structures in laboratory	82.5	17.5	40
	YES (%)	**NO (%)**	***n***
I would recommend the “clay” modeling activity for future laboratories.	84.2	15.8	38

The survey instructions asked students to rate each item “according to its helpfulness for learning and understanding neuroanatomy”; *n* indicates the number of students who answered each question.