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Learning with Interactive Computer Graphics in the Undergraduate Neuroscience Classroom

John R. Pani,

Department of Psychological and Brain Sciences, University of Louisville

Julia H. Chariker,

Department of Psychological and Brain Sciences, University of Louisville

Farah Naaz,

Department of Psychological and Brain Sciences, University of Louisville

William Mattingly,

Computer Engineering and Computer Science, University of Louisville

Joshua Roberts, and

Department of Psychological and Brain Sciences, University of Louisville

Sandra E. Sephton

Department of Psychological and Brain Sciences, University of Louisville

Abstract

Instruction of neuroanatomy depends on graphical representation and extended self-study. As a consequence, computer-based learning environments that incorporate interactive graphics should facilitate instruction in this area. The present study evaluated such a system in the undergraduate neuroscience classroom. The system used the method of *adaptive exploration*, in which exploration in a high fidelity graphical environment is integrated with immediate testing and feedback in repeated cycles of learning. The results of this study were that students considered the graphical learning environment to be superior to typical classroom materials used for learning neuroanatomy. Students managed the frequency and duration of study, test, and feedback in an efficient and adaptive manner. For example, the number of tests taken before reaching a minimum test performance of 90% correct closely approximated the values seen in more regimented experimental studies. There was a wide range of student opinion regarding the choice between a simpler and a more graphically compelling program for learning sectional anatomy. Course outcomes were predicted by individual differences in the use of the software that reflected general work habits of the students, such as the amount of time committed to testing. The results of this introduction into the classroom are highly encouraging for development of computer-based instruction in biomedical disciplines.

The spatial character of neuronanatomy leads to a method of instruction that makes consistent use of depiction and illustration (as in Felten & Shetty, 2010; Mai et al., 2008;

Nolte & Angevine, 2007; Standring, 2008). In addition, neuroanatomy presents a large and complex curriculum that requires extensive self-study if students are to obtain mastery. Many neuroscience texts, for example, are well over 1,000 pages long (Mai & Paxinos, 2012; Parent, 1996; Squire et al., 2008). The combination of these properties suggests that computers are a technology platform that will provide valuable resources for neuroanatomy instruction. Recent generations of computer systems display graphical material particularly well (LONI, 2013; Surgical Planning Laboratory, 2013), and the capabilities of computers for information management should provide good support for self-study (Saadawi et al., 2008; Koedinger & Corbett, 2006). Despite this promise, most reviews of computer-based instructional applications in the biomedical sciences are not enthusiastic about the progress that has been made (J. Collins, 2008; Cook, 2005; Cook et al., 2010; Issenberg et al., 2005; Ruiz et al., 2009; Tam et al., 2009).

The present paper is part of a project to develop new methods of neuroanatomy instruction that benefit from the capabilities of modern interactive computer graphical systems. A considerable amount of experimental work already has been reported (Chariker et al., 2011, 2012; Naaz et al., 2013; Pani et al., 2013; see also Pani et al., 2005). This work was conducted with paid volunteers recruited from a university community. One reason for that was that the work concerned an untried learning environment, and it could not be required in relevant courses. Asking students to volunteer as subjects would have provided smaller samples than were needed, and most participants would not have served for as long as the research required.

Although valuable information was gathered in these studies, experiments conducted with paid volunteers have important weaknesses. It is the classroom where a learning environment ultimately must be successful, and generalization from experimental studies to the classroom cannot be taken for granted. Students have different perspectives from experimental subjects, and students may use instructional resources differently. Moreover, adaptation of instructional methods to the classroom generally leads to procedures that are modified from those tested in experiments (Barab, 2006; Brown, 1992; A. Collins, 1992; Lagemann, 2002).

The present paper reports an evaluation of a computer-based learning environment for neuroanatomy in the undergraduate neuroscience classroom. The opportunity for this work came from a request by an instructor of neuroscience to integrate experimentally tested versions of the environment into her courses. In the remainder of this introduction, we outline the rationale behind development of the learning environment and briefly review primary experimental findings. We then describe issues that were particularly important in the introduction of the learning environment into the classroom.

Design of a Learning Environment for Basic Neuroanatomy

Graphics controlled by a computer are merely an abstract set of capabilities unless there is theory to guide design of a system. Our group has been pursuing design based on three ideas. The first is that instruction of the spatial characteristics of a complex three-dimensional structure is more effective when people can explore the structure perceptually.

This means that if computer graphics will be used in instruction, they should be high fidelity graphics, relative to what is to be learned. Perception of target structures should not be impaired by incompleteness of the representation, lack of clarity, or difficulty in accessing the information. To enable clear perception of neural structures, an accurate three-dimensional (3D) model of the human brain (Figure 1) was developed from source material in the Visible Human cryosections (version 2.0; Ackerman, 1995; Ratiu et al., 2003).

The second idea for system design comes from decades of work in the psychology of learning. People are relatively poor at learning sets of items that are perceived to be arbitrary collections. People are relatively good at learning items that are integrated (or *organized*) according to a set of familiar relations (Ambrose et al., 2010; Bower et al., 1969; Bransford et al., 2000; Craik & Tulving, 1975; Norman, 2009; Woods et al., 2007). This has led us, for example, to teach whole anatomy and cross-sectional (*sectional*) anatomy together, so that the global information in whole anatomy can be used to integrate the variety of samples in sectional anatomy. When teaching whole anatomy, we have enabled learners to successively remove neural structures in order to reveal what is behind them. This virtual dissection was intended to encourage a cognitive organization of the anatomy in terms of the spatial ordering of structures.

The third idea guiding this effort is that instruction must include testing and feedback to be effective. In a method called *adaptive exploration*, the learner has available high quality graphics that permit intuitive exploration of the domain. This capability is included in a system that tests knowledge of target information and provides detailed feedback on test performance. Repeated cycles of this sequence show the learner what they need to know, what they have learned, and what is left to learn. Further exploration can then be directed to information that will be useful for learning (see Ambrose et al., 2010; Koedinger & Corbett, 2006). In addition, repeated testing improves long term retention (Cepeda et al., 2006; Karpicke & Roediger, 2008).

Synopsis of Research Findings

The primary goal of the experimental studies has been evaluation and comparison of methods for teaching sectional neuroanatomy. The results of these studies have been encouraging. In cases where a learning trial might consist of a few minutes of study (e.g., four), a self-timed test, and a few minutes of feedback (e.g., two), participants learn to recognize 19 structures in whole neuroanatomy in three trials. Learning of whole anatomy then transfers well to learning sectional anatomy. In one recent study, for example, test performance after one trial of sectional anatomy learning was 79% correct (Naaz et al., 2013).

Retention of neuroanatomy in these studies is high after several weeks (e.g., 88.5% retention of sectional neuroanatomy across the three standard views after an interval of 2.5 weeks; Chariker et al., 2011). Generalization to interpreting new biomedical images also is quite good in many instances. For example, when neuroanatomical structures were indicated by arrows on Visible Human images of the brain, participants could name 80% of them despite never having seen such images before (Chariker et al., 2011).

Finally, the spatial ability of experimental participants was measured and related to performance in all of the experimental studies. Across several studies, participants with low spatial ability performed worse in the early trials of learning. However, they learned at a comparable rate to the other participants and completed learning in just a few more trials.

Questions for Introduction of the Learning Environment into the Classroom

To assess the value of this learning environment in the classroom, four basic questions were addressed. The first concerned the level of student satisfaction with the computer-based system. With many sources of information about neuroanatomy available to students, their opinions about the value of a particular source probably will determine how much it is used. A questionnaire was administered at the end of neuroanatomy learning to gather this information.

A second question pertained to student control of the frequency and duration of study, test, and feedback. In the experimental work, the study period in each trial was constrained to constant periods, the test was self-timed, and the feedback period again was constrained. Although this method provided experimental control, it was inflexible, and it seemed likely to be perceived negatively by students engaged in study for college courses. In the classroom setting, the durations of study, test, and feedback were controlled by the students, and one purpose of the study was to examine how students would manage this capability. In particular, we asked three issues about timing. Would permitting students to study for long periods before taking a test lead the students to test themselves less often than occurred in the experimental studies? Taking fewer tests might reduce levels of long term retention. Would students use time adaptively, with more time taken earlier in learning? Finally, the examination of student control of timing would permit gathering benchmark information. What would the relative durations of study, test, and feedback be when they were controlled by the students?

A third basic concern was to assess student preference among two software systems for learning sectional neuroanatomy. One program for learning sectional anatomy presented only the sectional imagery, as in Figure 2. A second program was more compelling in its graphical representation of the brain. The 3D model could be sliced in order to expose the 2D cross-sections as a cut through the whole brain (Figure 3). Experimental work has suggested that this more complex program has an advantage for long-term retention of sectional neuroanatomy (Naaz et al., 2013). We were interested in whether, because it is more graphically impressive, this program would have a particular appeal to undergraduates who were learning neuroanatomy for the first time. Finally, our fourth question concerned whether individual differences among the students in the use of the computer programs would correlate with exam or course grades.

The integration of the existing learning environment into courses was tried first with a graduate course that enrolled 17 students. A focus group was held at the completion of neuroanatomy learning to discuss the effectiveness of the learning programs. A questionnaire that took account of the focus group discussion was administered toward the end of the semester. The software was then introduced the following year into an

undergraduate course. In that class, the frequency and duration of study, test, and feedback were recorded, and the questionnaire was administered immediately after the completion of neuroanatomy learning. We report here the data from the undergraduate course.

Method

Students

Participants were students in an undergraduate introduction to neuroscience that was offered as an elective by the Department of Psychological and Brain Sciences at the University of Louisville. The course enrolled 40 students. All students used the same materials and procedures for neuroanatomy instruction. Twenty-seven students gave informed consent to have their data used for research. Four of these students did not complete neuroanatomy learning to the criterion set by the instructor, and the data from these students were not included in analyses.

Materials

Traditional resources—In addition to the computer programs, to be described below, students in the course had available for their use several resources for learning neuroanatomy. The course required every student to have their own copy of a modern neuroscience textbook with end-of-chapter quizzes and excellent color illustrations of the human brain. A DVD came with the textbook and provided supplementary instruction of neuroanatomy (this material is now online). The students also had available a plastic model of the human brain manufactured for the purpose of neuroanatomy instruction (purchased in 2009 for \$1,000). This model was approximately life size and could be disassembled for study of individual structures and their relations to each other. Re-assembling the model was much like solving a three-dimensional puzzle. There also was a modern atlas of neuroanatomy (in large book format) that was recommended by the instructor. It included several illustrations of whole structures and serial sets of sectional illustrations from throughout the human brain. Finally, the research team made available a second authoritative atlas of neuroanatomy and a classical atlas of neuroanatomy that was composed of high quality medical illustrations.

Computer graphical model—The computer graphical model included 19 neural structures that could be individually selected and which were the targets of testing and feedback. These were amygdala, brainstem, caudate nucleus, cerebellum, cortex, fornix, globus pallidus, hippocampus, hypothalamus, mammillary body, nucleus accumbens, optic tract, pituitary, putamen, red nucleus, substantia nigra, subthalamic nucleus, thalamus, and ventricles.

In the program for learning whole anatomy, these structures were presented as whole 3D structures (Figure 1). In programs for learning sectional anatomy, the structures could be presented in thin cross-sections in the three standard planes (coronal, sagittal, or axial; Figure 2) There were 60 coronal sections, 50 sagittal sections, and 46 axial sections, all at equal intervals. One instructional program for sectional anatomy presented the brain as

whole structures that were truncated at single planes in either the coronal, sagittal, or axial views (Figure 3).

Instructional programs—Five computer workstations were made available to the students in a set of four rooms that were part of a laboratory suite. The computer graphics were displayed on 24-inch color LCD monitors at a resolution of 1920 by 1200 pixels.

A total of five instructional programs were made available to the students on the workstations. Three primary programs came from the research studies which explored neuroanatomy learning. One program was for learning whole anatomy and the other two were for learning sectional anatomy. Two 3D computer graphical atlases were constructed to provide additional coverage of neuroanatomical structures that the instructor wished to be included.

Primary instructional programs: basic program operation: The basic operation of the three primary programs was the same (for more detail, see Chariker et al., 2011). During study, students could freely explore the brain model using graphical tools available for that program. Clicking on a structure with a computer mouse highlighted the structure, and its name appeared prominently at the bottom of the screen.

A single run of the program also included a test phase. Students named the structures they had learned by clicking on each structure and selecting its name from a button panel that represented all 19 structures. Students could omit naming structures if they wished, and a name could be used more than once. After a structure was named, it turned blue to indicate that.

A feedback phase consisted of two parts: a numerical feedback screen and graphical feedback. The numerical screen was presented first. It indicated the number of structures that were named correctly, the number of structures named incorrectly, and the number of structures omitted. The graphical feedback consisted of a color coding of the brain model: structures named correctly appeared in green, structures named incorrectly appeared in red, and structures that were omitted appeared in their original colors (typically a single standard gray). During the feedback stage, students could interact with the color-coded structures using the same tools that were available in study. Students could click on structures, highlight them, and see their correct names. The feedback stage ended with the appearance of an exit screen that displayed the student's test score in terms of a percentage correct.

Primary instructional programs: whole anatomy program: The program for learning whole anatomy featured the 3D model of the brain. During study, the students could explore the model with the help of tools provided for rotation, zooming, and virtual dissection. Virtual dissection was conducted by selecting structures and removing them, using buttons on the panel at the right side of the screen (Figure 1). Students also could restore removed structures.

Interaction during the test of whole anatomy was similar to the interaction during study. Tools for rotating, zooming, and removing and restoring structures were available. Students

were asked to name as many structures as they could by selecting structures, selecting their names in the button panel, and clicking a “Submit Answer” button. The students received numeric feedback and then proceeded to graphical feedback by clicking on a button. With 19 structures in the 3D model of the brain, the test of knowledge of whole anatomy consisted of 19 items.

In the whole anatomy program, the initial orientation of the brain was a view from the front, side, or top. Students were then free to rotate the brain in any amount. The test phase of a trial, however, restricted rotation of the model to plus or minus 45 degrees from the front, side, or top, consistent with the initial orientation in study. This was done to improve generalization of learning with whole anatomy to the three standard views of sectional anatomy.

Primary instructional programs: sections only program: One program for learning sectional anatomy permitted exploring series of 2D sectional samples from the model of the brain (called the sections only program). Students saw thin parallel sections of the brain in a single view (coronal, sagittal, or axial; Figure 2). Students could move from one section to another by using a slider provided at the bottom of the screen. In the coronal view, for example, moving the slider allowed students to see all the sections of the brain from front to back. Students could go to individual sections of the brain and click on structures to learn their names.

The test of sectional anatomy knowledge was slightly different from the test for whole anatomy. In sectional anatomy testing, between 12 and 15 sections of the model were selected for each test. Only a few structures were tested in each of the sections. This procedure was adopted because testing all structures in multiple sections would create a test that was too long.

The structures that were tested were indicated by arrows. The students were to name each structure that was indicated by selecting it, selecting its name from the button panel, and clicking a “Submit Answer” button. Students could move from one test section to the next by clicking on a “Next Section” button, but they could not go back to a previous test section. Longer structures were sampled twice in tests of sectional anatomy (i.e., in two sections). Thus, there were 29 test items for the coronal and sagittal views of sectional anatomy and 27 test items for the axial view.

After completing the test stage of a trial, students received numeric feedback followed by graphical feedback. The graphical feedback phase was similar to the study phase and included all of the sections of the brain. The test sections were marked. The arrows indicating the test items remained, and the test items again were color coded to reflect the performance on the test. The feedback phase allowed students to go through all of the sections and to see where the test sections were taken from the series. They could select structures and see their correct names.

Primary instructional programs: 2D-3D program: A second program for learning sectional anatomy, called 2D-3D, permitted exploring the 3D model using all of the tools

used earlier in the whole anatomy program (Naaz et al., 2013). In addition, the 3D model could be sliced to view sectional anatomy with the help of a slider tool. On moving the slider from left to right, a virtual cutting plane appeared to move through the brain and to remove the part of the brain in front of the plane. This exposed the 2D cross-sections of the 3D structures from one end of the brain to the other (Figure 3). Behind the cutting plane, the 3D structures remained visible, allowing the students to see the relations between 3D and 2D representations. The test and feedback phases were identical to the test and feedback phases of the sections only program (i.e., test and feedback included only the 2D sections).

Additional instructional programs: computer graphical atlases—Two computer graphical atlases were added to the three primary programs (Figure 4). One presented a single cortical hemisphere with labels for the cortical lobes and the major gyri and sulci. Students could rotate and zoom the model, remove the superior or posterior halves of the cortical hemisphere at a plane through its center, and could toggle the labels on and off. However, test and feedback could not be made available at that time. The second atlas labeled a variety of structures associated with the brainstem and midbrain and added several that had not been present in the original model of the brain. Students could rotate and zoom the model and toggle the labels.

Questionnaire—Development of a six-item questionnaire was based on the focus group discussion held a year earlier. The instructions for the questionnaire said that the research team was interested in the individual student's personal opinion about each item. They were invited to skip items if they did not have enough information to provide an opinion. They were assured that their opinions would be anonymous.

Procedure

A two-week segment of the course early in the semester was devoted to learning neuroanatomy. Lecture meetings were not held during those weeks in order to give the students more time to use the learning materials. The students were asked by the instructor to read the appropriate textbook chapters and to take the chapter quizzes. They were asked to study the plastic model of the brain and to learn its parts.

A copy of the neuroscience text, the plastic model of the brain, and the atlases of neuroanatomy were placed on a convenient desk, centrally located, in a main room of the laboratory suite that housed the instructional software. Students were free to use these materials at any time. The students were asked to schedule visits to the lab, but they were free to come as often, and stay as long, as they wished. Students worked both individually and in groups and they tended to move around the lab looking for a comfortable place to study.

Each student was required to use the computer workstations to learn neuroanatomy to at least 90% test performance for whole and sectional anatomy. In particular, they were required to learn whole anatomy from the front, side, and top and to learn sectional anatomy in the coronal, sagittal, and axial views, in that order. Student test performance was saved to files and was checked by the research team.

The operation of the computer programs was demonstrated to the students in a lecture meeting prior to the period for learning neuroanatomy. Written instructions also were available beside each workstation, and a member of the lab was available to answer questions. The students were informed by the instructor that there would be an exam specifically on neuroanatomy and that it would draw from all resources that were available for instruction.

After the students had completed using the instructional programs for whole anatomy, half of them were shown the sections only program and half were shown the 2D-3D program. There was one trial of study, test, and feedback with the initial program. The student was then shown the other program and completed one trial of study, test, and feedback. After the two introductory trials with the sectional anatomy programs were completed, the students chose which program they wished to use to complete their learning of sectional anatomy. They were free to switch to the other program at any time.

Immediately after the introductory trials with the two sectional anatomy programs were completed, an initial two-item subset of the questionnaire was given to the students. The full questionnaire was presented immediately after all of neuroanatomy learning was completed, but before the neuroanatomy exam was taken.

Results

Questionnaire Data

The first two items from the six item questionnaire were most important for assessing student satisfaction with the graphical learning environment. These items, and the responses to them collected at the close of neuroanatomy learning, are presented in Table 1. It is clear that the computer-based graphical software was generally considered a superior way to learn the assigned material (see also Brewer et al., 2012; Hariri et al., 2004; Keedy et al., 2011). In addition, the ability to interact with the brain model was deemed very important to the value of the software.

Performance Data

The students did not always use the learning programs with measurable effort in study, test, and feedback. For example, a student might study for several minutes and then close the program. They might then leave to attend a class, return the same day and study again, and then take the test and examine the feedback. For this reason, a breakdown of the data into learning trials is based on the number of tests taken. A single trial is considered to be the total study, test, and feedback durations associated with a single test.

Test performance over trials—Test performance for whole and sectional anatomy, broken down by the three anatomical views, is shown in Figure 5. Test performance in whole anatomy began above 80% correct and quickly approached 100% correct. Performance in the first test of sectional anatomy was 69.7% correct (SD = 23.77%) and moved upward until the next anatomical view was started, $F(1.19, 26.07) = 17.006$, $p < 0.001$, $\eta_p^2 = 0.436$. There was a decrease in performance at the start of a new sectional view,

but performance in the first trial of an anatomical view improved over trials, $F(1.31, 28.90) = 10.173$, $p = 0.002$, $n_p^2 = 0.316$.

Number of trials to learn—The typical student took 3.96 trials (SD = 1.27) to complete learning of the 19 neural structures in the whole anatomy program, and 8.22 trials (SD = 3.87) to complete learning of sectional anatomy (totaled over both of the sectional programs and all three anatomical views). Clearly, even though sectional anatomy was learned second, it still required more trials to learn, $F(1, 22) = 36.977$, $p < 0.001$, $n_p^2 = 0.627$. Overall, there were 12.17 trials (SD = 4.70) taken to learn both representations of neuroanatomy.

Within both whole and sectional anatomy, the number of trials to reach criterion decreased as the students progressed over the three anatomical views (for whole anatomy, $F(1.43, 31.52) = 8.729$, $p = 0.003$, $n_p^2 = 0.284$; for sectional anatomy, $F(2, 44) = 6.343$, $p = 0.004$, $n_p^2 = 0.224$). For whole anatomy, the students required 1.7 trials to complete learning from the front view (SD = 0.822) and 1.09 trials to complete each of the remaining views (SD = 0.288 for testing from the side view; SD = 0.417 for testing from the top view). For sectional anatomy, the students took 3.35 trials to complete learning for the first (coronal) view (SD = 1.613), 2.61 trials to complete testing for the second (sagittal) view (SD = 1.751), and 2.26 trials to complete testing for the third (axial) view (SD = 1.251).

Total time to learn—The typical student took a total of 2 hours and 20 minutes (SD = 43.97 minutes) with the programs running to complete all of neuroanatomy learning. This consisted of 50.32 minutes (SD = 16.86) to learn whole anatomy (tested from three directions), followed by 1 hour and 29.7 minutes (SD = 31.24) to learn sectional anatomy in the three anatomical views. The data for duration exclude one outlier who took more than twice as long as the next slowest learner.

The total time to learn was broken down statistically into a 2 by 3 repeated measures ANOVA according to type of anatomy representation (whole or sectional anatomy) and trial phase (study, test, or feedback). Mean time to learn when broken down in this fashion is presented in Figure 6. Far more time was spent in learning sectional anatomy than in learning whole anatomy, $F(1, 22) = 20.76$, $p < 0.001$, $n_p^2 = 0.485$. The main effect of trial phase also was significant, along with the interaction between anatomy representation and trial phase (trial phase: $F(1.30, 28.64) = 48.347$, $p < 0.001$, $n_p^2 = 0.687$; interaction of representation and trial phase: $F(1.33, 29.29) = 9.57$, $p = 0.002$, $n_p^2 = 0.303$). In learning whole anatomy, there was a clear decrease in time over the successive phases of a trial. Most time was spent in study (M = 30.4 min., SD = 12.9), next most in testing (M = 19.3 min., SD = 8.05), and relatively little time was spent in feedback (M = 2.76 min., SD = 2.75), $F(1.47, 32.32) = 19.982$, $p < 0.001$, $n_p^2 = 0.463$. All pairwise comparisons for trial phase within whole anatomy were statistically significant after Bonferroni correction, $p < .002$.

In sectional anatomy learning, the most time was spent in testing (testing M = 49.5 min., SD = 29.9; study M = 41.1 min., SD = 27.5; feedback M = 12.5 min., SD = 21.3). There again were statistical differences across study, test, and feedback, $F(1.74, 38.26) = 43.458$, $p < 0.001$, $n_p^2 = 0.664$. In pairwise comparisons (Bonferroni), time in study and test were not

statistically different. Far less time was spent in feedback than in either study or test ($p < .001$).

There was large variation in how long students took to complete learning. The range was 2 hours and 29 minutes. The mean time for the fastest three students to learn both whole and sectional anatomy was 1 hour and 26 minutes. The mean time for the slowest three students (excluding the outlier) was 3 hours and 27 minutes.

Time per trial in study, test, and feedback—The mean time per trial spent in study, test, and feedback, broken down by individual trials and the type of anatomy representation, is presented in Figure 7. In whole anatomy, and within each of the three sectional views, study time dropped rapidly over learning trials. This was tested for whole anatomy by comparing study time for the first trial in each of the three directions of view (for many students, there was not a second trial within a view), $F(1.32, 29.10) = 66.84$, $p < 0.001$, $n_p^2 = 0.752$.

Reduction in time per trial to study sectional anatomy was tested in a 2 by 3 repeated measures ANOVA, where one factor was study time in the first and the last trial of an anatomical view, and the second factor was the anatomical view. Study time per trial dropped from the first to the last trial within a view, $F(1, 22) = 5.612$, $p = 0.027$, $n_p^2 = 0.203$. Change in study time per trial over the three successive anatomical views was not statistically significant ($p > 0.2$).

Time per trial spent in testing and in feedback also dropped over trials (whole anatomy: $F(2, 44) = 68.019$, $p < 0.001$, $n_p^2 = 0.756$). For sectional anatomy, time spent in testing and feedback dropped both for trials within each anatomical view and across the successive anatomical views (trial within view: $F(1, 22) = 18.630$, $p < 0.001$, $n_p^2 = 0.459$; anatomical view: $F(1.47, 32.32) = 19.982$, $p < 0.001$, $n_p^2 = 0.463$).

Comparison to earlier experimental data—In comparing these data to the experimental data, the primary question was whether the opportunity to study for long periods led to substantially fewer tests taken than had been observed in experimental studies. An experimental condition from Pani et al. (2013) was very similar to the method used in this study. In that study, each learning trial included 4 minutes of study, a self-timed test, and two minutes of feedback. As with the classroom students, a participant had to reach test performance of at least 90% correct before moving from whole to sectional anatomy or from one anatomical view to the next. A comparison between the classroom data and the data from Pani et al. for the number of trials required to learn neuroanatomy is presented in Figure 8 for whole anatomy and the three views of sectional anatomy. Overall, the classroom students took 12.12 trials to learn neuroanatomy, and the experimental participants took 13.20 trials, an increase of just 1.08 trials, or 8.22%. Thus, having control over the timing of study, test, and feedback did not in general lead to less testing.

A comparison between the two groups in the time taken to learn is presented in Table 2. The only part of a trial that was self-paced for the experimental participants was the test. As

indicated in the table, the time taken per test was very similar between the classroom and experimental groups in both whole and sectional anatomy learning.

The students spent more time per trial in study and feedback than did the experimental participants. This was true both for whole and sectional anatomy learning. In regard to the total time to learn, the classroom students took about the same amount of time to learn neuroanatomy as did the experimental participants (Table 2).

Comparison of the sections only and 2D-3D programs for sectional neuroanatomy

The questionnaire item comparing the two sectional anatomy programs is presented in Table 3, along with the student responses. These responses suggest that there was no clear preference for one program over the other. The frequency of use of the two programs was fairly even also, although there was a small numerical advantage in favor of the sections only program (Sections only: 52.91% of total trials, 60.87% of students used it more often; 2D-3D: 47.09% of total trials, 34.78% of students used it more often; statistical comparisons were not significant).

There was one statistically significant difference between the sections only and 2D-3D programs in how they were used. When students used the 2D-3D program, they took nearly 2 minutes longer in each trial to test themselves than when they used the sections only program (sections only, $M = 5.44$ min., $SD = 1.07$ min.; 2D-3D $M = 7.36$ min, $SD = 0.667$ min; $t(22) = 3.257$, $p = .004$. This difference was not due to a bias in when during the sequence of learning the two programs were used.

Individual differences

A correlation matrix revealed many intercorrelations among the various measures of time to learn, trials to learn, performance on the neuroanatomy exam, and course grade. Two variables emerged as consistently associated with other measures: mean time per trial spent in study, and mean time per trial spent in testing. For both whole anatomy and sectional anatomy, these two variables were correlated with each other (whole anatomy: $r = .434$, $p = 0.44$; sectional anatomy: $r = .452$, $p = .035$).

Time per trial in study correlated negatively with the number of tests taken (whole anatomy: $r = -.526$, $p = .012$; sectional anatomy: $r = -.562$, $p = .006$). That is, students who spent more time studying in individual trials finished learning in fewer trials. Thus, although student control of timing within a trial did not lead to an overall reduction in the numbers of tests taken, relative to experimental benchmarks, it did permit individual differences where those students who spent more time in study took fewer tests (see later discussion).

Students who completed learning of sectional neuroanatomy in fewer trials generally performed better on the neuroanatomy exam, $r = -.432$, $p = .044$. Completing sectional neuroanatomy in fewer trials also had a marginal relation to course grade, $r = -.387$, $p = .075$ (2-tailed). Overall, course performance was better for those students who learned faster (see later discussion). No other variable or combination of variables predicted exam performance.

Students who received an A in the course (56.5% of the students) had spent more time per test (1.40 minutes) than did the other students, $t(20) = 3.361$, $p = 0.003$. A relationship with time per test and scores on the neuroanatomy exam was much weaker. For example, when students were divided by a median split on exam score, the difference in time per test was relatively small (0.69 minutes) and not statistically significant, $p = .188$.

A further finding of interest concerned the total time spent in testing over the course of neuroanatomy learning. First of all, students who took longer to complete testing for whole anatomy also tended to take longer for sectional anatomy, $r = .485$, $p = .022$. In addition, those students who spent more total time taking tests spent more time per trial in feedback (whole anatomy: $r = .623$, $p = .022$; sectional anatomy: $r = .500$, $p = .018$). That is, with more difficulty in completing learning, students spent more time per trial in feedback.

Discussion

This study examined an introduction into the undergraduate neuroscience classroom of a learning environment for basic neuroanatomy. The system was designed to take advantage of the capabilities of modern interactive computer graphics, to promote integration and organization of the material, and to incorporate multiple cycles of study, test, and feedback.

Student Ratings of the Value of the Graphical Learning Environment

The results of a questionnaire administered immediately after the learning of neuroanatomy suggested that the students considered the computer-based learning programs to be superior in the context of the alternative classroom resources. These included textbook illustrations in book form and on DVD, photographs, diagrams, and illustrations in atlases, and a plastic model of the brain.

There could be several reasons for the students' high levels of satisfaction with the computer-based materials. To begin with, we believe that the ability to explore modern computer graphics provided more effective display of information about anatomical structures than did the static diagrams and illustrations. Part of this advantage was the display of information that suited the momentary concerns of the learner. Rather than seeing a page with 20 labels and 20 arrows pointing to neural structures, or 20 acronyms to be looked up in tables, the user could individually highlight structures and see just the relevant names. In addition, the ability to remove structures to see what was behind them, to change the viewing angle, or to move through serial sections, provided valuable information about spatial relations. The interactive capabilities of the learning environment were rated by the students as being very helpful.

Given the large research literature on the use of animation in instruction (Levinson et al., 2007; Mayer et al., 2005; Tversky et al., 2002), it is important to note that the inclusion of rotation and zooming in the graphics was not intended to provide animation as a continuous event or an intrinsic property of the scene. These were intended to be tools available to the learner for placing neuroanatomy at a view that was most informative. In other words, we did not present a rotating brain; we gave the learner an opportunity to reorient the brain if they wished (see Wang & Simons, 1999). In addition, rotational motion of a 3D object is an

excellent depth cue that does not depend on special equipment or the learner's stereoacuity (Palmer, 2002).

In regard to the plastic model, although it was an actual rather than a virtual 3D object, it was in many ways less realistic than the computer graphics. The parts disassembled into arbitrary piles, they were obviously plastic, and it was our impression that fitting them together was more like working a puzzle than studying the brain (e.g., with the necessity to bend structures and to fit tabs into holes). Physical models are not always the superior form of spatial representation.

Finally, we believe that two closely related properties of the learning environment were important to its positive reception. In the first place, study, test, and feedback were integrated into single learning episodes. Second, testing and feedback took place in continuous cycles, so that students could approach learning as a gradual mastery of the tests, much as popular computer games encourage mastery of different "levels". Of course, such methods can be applied to almost any medium. However, they are more efficiently implemented in a computer-based system. In fact, we think that the comparisons in the present study are representative of how material such as neuroanatomy is generally taught in classroom settings. For traditional materials, students are warned what will be on a test, they are provided resources to use for study, and they are urged to take time and prepare well. The test comes later, and feedback on the test performance constitutes an exam grade and marks the end of instruction for that material.

Student Management of Time in Study, Test, and Feedback

The present data suggest that student management of the frequency and duration of study, test, and feedback is superior to the more rigid schedule used in the earlier experimental studies. The students managed their time adaptively. The time invested in learning generally decreased as learning progressed, except when new challenges were presented. Students who had more difficulty getting through the testing spent more time exploring the feedback.

Student control of the time in study, test, and feedback did not lead to an appreciable decrease in the number of trials required to complete learning. The numbers of tests taken closely approximated the numbers seen in comparable experimental work, where study and feedback periods were constrained to relatively short periods. One reason for this consistency was the requirement that demanding performance criteria be met across a variety of types of test. Thus, whole anatomy was studied over four trials in part because the students had to identify structures from the front, the side, and the top in separate tests. In sectional anatomy, which was more difficult to learn, the requirement to reach at least 90% test performance resulted in most students taking many more than the minimum number of trials to learn.

A comparison of the total time taken to learn between the students and the experimental participants revealed a striking similarity. This is particularly interesting given the very different distributions of times over the course of learning. We believe this to be an important finding, because there are clear advantages of student control of durations. In each

episode of learning, students will feel that they had enough time to learn and that time had not been wasted.

Student Preference Among Alternative Programs for Learning Sectional Anatomy

There was a wide range of opinion as to which of the two programs for learning sectional anatomy was superior. Certainly there was not a preference for the graphically more impressive 2D-3D program. In fact, there was a slight numerical advantage in favor of the sections only program, both in the frequency of use and in the statement of preference in the questionnaire. The advantages of the sections only program are that it is simpler, and the presentation in study is the same as the presentation during test.

It also was found that the students took longer to test themselves when using the 2D-3D program than when using the sections only program. Again, it is important to remember that for the sections only program, the study and test materials were identical. In 2D-3D, the sectional test materials were a highly selective sample of what was seen during study. The additional effort during testing may be one reason that experimental comparisons show an advantage for 2D-3D in long-term retention of sectional neuroanatomy (Naaz et al., 2013; consider Bjork, 1999).

Individual Differences and Use of the Learning Software

The attempt to relate individual differences in the use of the learning software to exam and course grades revealed general differences among the students. First of all, those students who completed learning in fewer trials did better on the neuroanatomy exam. On the face of it, this finding appears inconsistent with the test effect, in which *more* testing leads to better retention of learned material (after one week; Karpicke & Roediger, 2008). However, it is clear from the experimental work that there are two factors involved in the relation between the number of tests taken and retention. One is an individual differences factor that is evident when the number of tests is a reflection only of the rate of learning of the individual. The other is a treatment effect that appears when individual differences are controlled, and the number of tests is varied by an external factor (e.g., an experimental procedure varied between groups). In our experience, even when there is no treatment effect, there are individual differences in the rate of learning, and those students who learn in *fewer* trials retain more of the material. To put it in simple terms, those students are more efficient learners on all measures.

It also was found that students who spent more time on each test were more likely to receive the highest grade in the course. This result must reflect such general factors as motivation, learning strategy, and work habits. Why this relationship was not better reflected in performance on the neuroanatomy exam is not clear. It is probably important that there was a strict performance criterion for completing neuroanatomy learning. The students were required to learn the material, and the resulting exam scores one week later were generally high.

Weaknesses of this Study

There are several weaknesses of this work. Even including the two 3D atlases that were included for use by the class, the students were taught to recognize fewer than fifty neural structures. Ultimately, a learning environment such as this will have to be scaled up to include hundreds of structures (or more). This will require development of new techniques for introducing and moving through a large and complex domain.

A weakness of a different kind is related to the fact that study of real tissue will always be an important part of biomedical education. As computer-based systems become more capable, it will be important to explore how they can best be combined with study of real tissue. This was not attempted in this work. Our hypothesis is that mastery of the graphical material will provide a good preparation for durable learning with real tissue (consider Norman, 2009).

Summation

The biomedical sciences present a large volume of factual material to be learned. Much of this material consists of complex spatial structures and systems. A moderate understanding of the human skull, for example, presents a serious challenge for spatial learning. In such disciplines, appropriately designed learning environments that take advantage of modern capabilities for computer graphics will be especially helpful. Computers excel at presenting graphical material, and they can support the extended self-study required in these disciplines.

The present study examined classroom use of a computer-based learning environment for basic neuroanatomy that used high fidelity interactive graphics. The system began by teaching 3D whole anatomy, and it used the method of adaptive exploration, in which testing and feedback are an integral part of learning. In a questionnaire given at the completion of learning, students expressed a belief that the computer-based system was superior to the typical classroom materials available to facilitate self-study. It was found that students used the system to learn whole and sectional neuroanatomy in about the same number of trials as did participants in closely controlled experimental studies. This learning was efficient, with 2 hours and 20 minutes taken on average to learn to identify 19 neural structures in whole and in sectional form. Time was invested by the students across study, test, and feedback in an adaptive and generally sensible manner. The overall pattern of results suggests that development of interactive computer graphical systems can lead to significant benefits for instruction in biomedical disciplines.

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APPENDIX

Questionnaire Items not Presented Earlier in this Paper

3. In the programs that illustrated sectional anatomy, please rate the importance, in your opinion, of being able to select a structure and to use the slider to move continuously through the sections. Use a scale from 1 to 5, with 1 being “not important” and 5 being “very important”.

Mean = 4.1, SD = 0.81

4. You learned whole anatomy first and then sectional anatomy. In the future, how should whole and sectional anatomy instruction be ordered (circle the letter in front of the statement that best characterizes your opinion)

	Frequency
a) Definitely start with <i>sectional</i> anatomy. Move to whole anatomy afterward.	0
b) Probably should start with <i>sectional</i> anatomy, although it may not matter.	0
c) The order would not matter.	0
d) Probably should start with <i>whole</i> anatomy, although it may not matter.	6
e) Definitely start with <i>whole</i> anatomy. Move to sectional anatomy afterward.	17

5. Please rate the difficulty in moving from whole anatomy to sectional anatomy. In other words, once you know whole anatomy, how challenging is it to learn sectional anatomy with these programs? Please circle the letter in front of the statement that best characterizes your opinion:

	Frequency
a) Whole and sectional anatomy are independent. Knowing one <i>does not help</i> to learn the other.	0
b) Even if you know whole anatomy, sectional anatomy is still <i>very challenging</i> .	8
c) Even if you know whole anatomy, learning sectional anatomy is <i>challenging</i> .	6
d) If you know whole anatomy, learning sectional anatomy is <i>not too bad</i> .	8
e) If you know whole anatomy, learning sectional anatomy is <i>easy</i> .	1

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Figure 1.

Screen image from the instructional program for whole neuroanatomy. The learner has removed the left hemisphere, rotated the brain, and selected the left putamen.

Figure 2.

Screen image from the instructional program for learning sectional anatomy. The brain is represented in the axial (top) view. The learner has moved the slider to a section near the middle of the brain and has selected the left putamen.

Figure 3.

Screen image from the 2D-3D instructional program. The sectioned brain is represented from the coronal view. The learner has used the slider to move the cutting plane to a section near the middle of the brain and has selected the left putamen.

Figure 4.

Screen images from the two 3D atlases used to supplement the primary instructional programs.

Figure 5.

Proportion correct test performance over trials. Students first learned whole anatomy from three directions and then moved to learning the three standard views of sectional anatomy.

Figure 6.

The mean total time per student spent in study, test, and feedback for whole and sectional neuroanatomy learning.

Figure 7.

Mean time per learning trial, broken down by time in study, test, and feedback, as a function of trial. Students first learned whole anatomy from three directions and then moved to learning the three standard views of sectional anatomy.

Figure 8.

The number of trials to complete learning in whole anatomy and the three standard views of sectional anatomy for the classroom students and the experimental participants in Pani et al., 2013.

Table 1

Data from Two Questionnaire Items Aimed at Assessing the Value of the Computer-Based Exploration of Neuroanatomy

1. In this course, you had available several sources of information for learning neuroanatomy. In this context, would you say that the interactive software used in the Visual Cognition Lab was (please circle the letter in front of the statement that best characterizes your opinion):	
	Frequency
a) not helpful for learning neuroanatomy.	0
b) occasionally helpful for learning neuroanatomy.	0
c) helpful for learning neuroanatomy.	0
d) very helpful for learning neuroanatomy.	7
e) superior for learning neuroanatomy.	16
2. If you found the interactive software for 3D whole anatomy helpful in some way, please rate each of the following properties of the software as to how helpful that property was in using the program for whole anatomy. Use a scale from 1 to 5, with 1 being “ <i>not</i> helpful” and 5 being “ <i>very</i> helpful”.	
	Mean
The ability to rotate the 3D model	4.5
The ability to zoom in on the 3D model	3.5
Selection/highlighting of structures	4.9
The ability to remove and replace structures in the 3D model	4.8
The ability, overall, to control your interaction with the 3D model	4.7

A Comparison of Classroom and Experimental Data for Time per Trial and Total Time to Learn for Testing and for Study and Feedback in both Whole and Sectional Anatomy Learning

Table 2

	Time Per trial (min:sec)				Total Time (hr:min)
	Whole Anatomy		Sectional Anatomy		All Anatomy
	Test	Study/Feedback	Test	Study/Feedback	
Classroom	4:42	9:32	6:00	7:47	2:20
Experiment	4:28	6:00 *	5:56	6:00 *	2:23
Difference	0:14	3:32	0:04	1:47	-0:03

* Data were constrained to this value by the experimental design.

Table 3

Data from a Questionnaire Item Comparing the Sections Alone and 2D-3D Programs for Learning Sectional Anatomy.

6. You were introduced to two different methods for learning sectional anatomy. One method, called “sections”, only showed the sectioned anatomy directly facing the user. The other method, called “2D3D”, showed sectional anatomy moving through the whole anatomy model. Which of these programs do you think would work best for future neuroanatomy instruction? Please circle the letter in front of the statement that best characterizes your opinion:	
	Frequency
a) The sections only program is much better.	4
b) The sections only program is somewhat better.	7
c) They’re both about equally good.	4
d) The 2D3D method is somewhat better.	1
e) The 2D3D program is much better.	7