

Using stereoscopy to teach complex biological concepts

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Ferdig R, Blank J, Kratcoski A, Clements R. Using stereoscopy to teach complex biological concepts. *Adv Physiol Educ* 39: 205–208, 2015; doi:10.1152/advan.00034.2014.—Used effectively, stereoscopic three-dimensional (3D) technologies can engage students with complex disciplinary content as they are presented with informative representations of abstract concepts. In addition, preliminary evidence suggests that stereoscopy may enhance learning and retention in some educational settings. Biological concepts particularly benefit from this type of presentation since complex spatially oriented structures frequently define function within these systems. Viewing biological phenomena in 3D as they are in real life allows the user to relate these spatial relationships and easily grasp concepts making the key connection between structure and function. In addition, viewing these concepts interactively in 3D and in a manner that leads to increased engagement for young prospective scientists can further increase the impact. We conducted two studies evaluating the use of this technology as an instructional tool to teach high school students complex biological concepts. The first study tested the use of stereoscopic materials for teaching brain function and human anatomy to four classes. The second study evaluated stereoscopic images to support the learning of cell structure and DNA in four different high school classes. Most important, students who used stereoscopic 3D had significantly higher test scores than those who did not. In addition, students reported enjoying 3D presentations, and it was among their top choices for learning about these complex concepts. In summary, our evidence adds further support for the benefits of 3D images to students' learning of science concepts.

stereoscopic; neuroanatomy; three dimensional; case studies

THERE HAS BEEN a tremendous amount of interest related to student learning in Science, Technology, Engineering, and Math (STEM) content in the United States. For instance, President Obama's current school reform plans are grounded in a 4.34 billion dollar focus on the growth of math and science education (11). To promote student success in these areas, the learning science community agrees that purposeful and engaging activity is important to deep and effective learning (7, 8). However, science textbooks are often filled with facts; tests then follow, asking students to reproduce those biology, chemistry, and anatomy facts (4). This doesn't fit learning in the real world. For example, people who are knowledgeable about neurons and glial cells know more than just the definitions; they also understand why neurons and glial cells have particular properties. Since they understand the relationships between the structure and function of neurons, they are more likely to use what they have to solve novel problems. For instance, learning organ relationships in a traditional environment usually entails the study of line drawings and anatomic atlases plus the memorization of relationship lists from lectures

and texts and supplemented by a laboratory experience dissecting a cadaver (10). In reality, line drawings can differ significantly from author to author, memorized lists are soon forgotten, and laboratory sessions can be less than optimal for the inexperienced student. In these cases, many students are not constructing appropriate understandings of fundamental chemical concepts from the very beginning of their studies. Therefore, they cannot fully understand the more advanced concepts that build upon the fundamentals. One possible solution to help students visualize dynamic interactions is to present critical concepts using three-dimensional (3D) stereoscopy, which is the focus of the present study given that prior research has established its promise for improving student STEM learning.

3D studies have been shown to help students acquire knowledge in many different contexts, such as geometry (16), physics (9), computer science programming (14), geology and geography (20), pathology (15), and anatomy (19). 3D visualizations of science content is known to increase student interest, involvement, and motivation (1, 17). In summary, research has provided initial evidence that 3D learning environments promote understanding of content and skill growth within and outside of STEM content. In addition to greatly facilitating the description and understanding of complex 3D structures and structure-based biology and biochemistry concepts, we believe that the use of stereoscopic display also will excite the interest of students in the subject. The previous studies outlined above have indicated that stereoscopic 3D shows great potential for improving students' learning of biological function. Importantly, domains like biology may benefit most by 3D presentations because biological structures are inherently spatial and structure frequently dictates function.

In science instruction, visual representations have been found to be helpful to communicate phenomena that learners cannot directly observe or experience (5, 12). A common theme among these studies is that visual representations make abstract concepts more concrete for students and also help to display processes and relationships among concepts that would be difficult to describe with text alone (18). Stereoscopic images of physiological data also provide a more realistic spatial representation of macro- and microscopic structures. Numerous imaging modalities produce data consisting of sequential images making up a volume of data. When displayed interactively, far more information can be conveyed, both qualitatively and quantitatively, and this can expose complex structures and interactions found in neural tissues. The importance of viewing biological phenomena in their natural form, as a spatially oriented and interrelated system rather than as a discontinuous set of independent components, is striking. Stereo-images provide details and features regarding spatial anatomy not apparent in two-dimensional (2D) images. For example, branching patterns and 3D structures of the neurons can be clearly appreciated as well as the spatial location of both

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intracellular (nucleus) and extracellular objects (cell bodies of non-neuronal cells) are immediately apparent.

METHODS

To evaluate the efficacy of using stereoscopic images to teach biological concepts, we tested the use of 3D lessons in two high schools. The first stereoscopic lessons included using the Volume Rendered Brain Atlas [VRBA (6)] and human anatomy images. The VRBA uses coregistered MRI (T1) and brain atlas data that are rendered in real time. The VRBA contains 116 segmented anatomic structures and uses a combination of 2D volume rendering to display the anatomic regions and 3D volume rendering to display the T1 data. The brain atlas allows users to interact with, remove data, rotate, zoom, and add neural structures to the visualization. Color and opacity transfer functions are used to display different portions of the data, allowing the user to remove and add anatomic regions and modify the T1 data. In addition, stereoscopic images of human anatomy consisting of 3D computed tomography and MRI data sets highlighting anatomic structures were developed. Using different opacity and color settings, 3D computed tomography/MRI data were displayed interactively to the students covering existing material and augmenting the existing curriculum.

Stereoscopic materials were incorporated to the curriculum of *school alpha*, and students were divided into the following two groups: 3D and NO3D. The 3D group ($n = 44$ students) received images of the brain in stereoscopic 3D, whereas the NO3D group ($n = 45$ students) received images of the brain in traditional, 2D format. Students were then tested on their knowledge of the structure and function of the brain. Students were then rearranged into different 3D and NO3D groups. The 3D group ($n = 43$) received stereoscopic images of anatomy, and the NO3D group ($n = 45$) received non-3D images of anatomy. Students were tested on their knowledge of anatomic concepts by a series of multiple-choice questions after the lessons. Students then received more anatomic images. We rearranged students once again into 3D and NO3D groups to ensure all students had equal access to both learning strategies. Students were again tested on their learning after each of the period-long lessons. All assessments were in the form of multiple-choice questions.

The second stereoscopic study used 3D images to support learning of cell structure and DNA. The Protein Data Bank (2) holds atomic coordinate data of many proteins, chemicals, and biological structures. Stereoscopic images were rendered of DNA and a cell membrane with the Virtual Molecular Dynamics program developed at Beckman Institute at the University of Illinois (13). Virtual Molecular Dynamics has a powerful graphical user interface and has facilities for producing animations and displaying atoms and simplified representations of protein features. These representations can be mixed in the same view so that different levels of detail can be displayed at once. Different components can be colored so that more complex assemblies can be readily identified and the interactions between components clearly defined.

In *school beta*, students across four separate classes received access to 3D images. In addition to the 3D images to support learning of cell structure and DNA, students also received textbook diagrams, access to Brain Pop (an online tool), and the teachers' notes/diagrams. For DNA, students had online access to the Strawberry Lab; for cell structure, they had access to a face-to-face microscope laboratory. The purpose of this study was to determine whether students were more engaged by one medium more than the others and whether one medium would be useful for a given content area. Students were asked eight multiple-choice questions, four questions about DNA and four questions about cell structure. They were asked to select their first and second choice to a number of questions relating to their enjoyment, benefit, and use of viewing the 3D content.

Students in all studies saw 3D and 2D content of some kind and used all types of teaching materials for the same amount of time while

supervised or taught by the instructor. Students were not given any 2D/3D content to study outside the classroom or instructed to use any outside materials during the study. All studies and protocols were approved by the Institutional Review Board of Kent State University before data acquisition.

RESULTS

In *school alpha*, beneficial outcomes were evident for both the stereoscopic brain material as well as 3D anatomy images. In the study using images of the brain in stereoscopic 3D, student exam scores differed significantly ($P < 0.05$), with students in the 3D group outperforming their classmates (80% vs. 73.6%). This provides early evidence that stereoscopic 3D images can be useful in teaching about the brain. The 3D images of anatomy also provided a beneficial effect on learning. There were two main findings. First, after the first anatomy exam, the group that received 3D images scored higher than their counterparts. The 3D group had an average final exam score of 76.85 compared with 63.55 for the NO3D group. These data provide strong evidence that the use of 3D (stereoscopic) images significantly improves learning of this particular subject (human anatomy). Second, when the groups switched and had a second anatomy exam, the 3D group finished with 77.25, showing a marked improvement in learning about anatomy. The NO3D group scored higher at 87.15. The findings from the third exam highlight the fact that not all topics are easier to learn when presented in 3D, suggesting that specific content needs to be carefully selected and tested. The data for the three assessments are shown in Table 1. In addition, example questions for the three exams are listed in the APPENDIX below.

School beta provided three key findings. First, the use of 3D images for instruction is enjoyable for students, with 68% and 70% of students choosing 3D as their first or second most enjoyed format for learning about DNA structure and cell membranes, respectively. Second, many students preferred 3D presentations: 70% of the students chose 3D as their first or second choice for visualizing DNA and 48% of the students indicated it was their first or second choice for understanding DNA. Given these findings from *schools alpha* and *beta*, there is direct evidence that the use of stereoscopic 3D can positively impact student learning. However, the selection of these images as well as the explanations surrounding these images must be robust and thoughtful enough to impact teaching and learning. Such findings should play an important part in the design of future stereoscopic learning modules.

Table 1. Average exam scores for the 3D and NO3D groups

	Score, %
<i>Exam 1</i>	
Brain	
3D group	80
NO3D group	73.6
<i>Exam 2</i>	
Anatomy	
3D group	76.85
NO3D group	63.55
<i>Exam 3</i>	
Anatomy	
3D group	77.25
NO3D group	87.15

DISCUSSION

We live in a world in which our visual and tactile senses perceive our environment in a multidimensional framework. Yet, in the classroom, students are presented with visual formats that lack the richness of this framework. New stereoscopic imaging holds extraordinary potential as an educational tool because it engages students with rich disciplinary content in the form of powerful interactive and immersive 3D images of complex neural structures that determine function. Complex neuroanatomic structures are difficult to appreciate when presented as 2D images in a textbook figure or classroom slide show, and the importance of this structure to understanding function is often entirely left to the imagination. With modern imaging capabilities, 3D stereoscopic display technology offers the unique opportunity to overcome this problem, as students can view complex images in an immersive, interactive, and multidimensional environment. Despite its promise as an excellent instructional tool, stereoscopic image projection has not been fully developed for use in the classroom and laboratory. We have begun to fill that void by developing, deploying, and evaluating 3D stereoscopic teaching modules for teaching high school neuroscience that adheres to the National Science Education Standards' mission and fits within current curricula.

Importantly, the results from the first study demonstrate the promise of these 3D models but highlights the fact that these models need to be selected with caution. Our future work is designed to understand the best practices and mechanisms behind the use of 3D content to help identify topics (and presentation strategies) that benefit most from 3D. The results of the second study suggest students enjoy using them. That is another key feature of the use of 3D stereoscopic display technology is its impact on improving student engagement. In one of the only studies of the use of immersive virtual environments in undergraduate classes (computer graphics and building structures), the authors (3) noted that students were more involved and engaged with virtual environments than during normal classroom activities, which may lead to better learning or retention. Only very limited information describing the benefits of the 3D stereoscopic technology for instructional use in teaching neuroanatomy is currently available in the literature and a rigorous, cross-disciplinary evaluation of the impact of 3D stereoscopic display use on student success, retention, and engagement is currently not available. Our educational initiatives will not only move interactive 3D stereoscopic display technology into classrooms and laboratories but will also provide the first comprehensive assessment of the benefits of stereoscopy for biology education.

A few years ago, this project would not be practically possible. 3D displays were too expensive for home and school use and/or development. The created tools support anaglyph (red/blue) and monoscopic projection methods permitting any school or user with a computer to download and use the learning modules. This greatly expands the potential user base and removes the absolute need for expensive hardware, removing monetary barriers to adopting the technology; anaglyph glasses are about 20 cents each and work with any screen. As the cost of equipment declines and due to the availability of inexpensive anaglyph solutions, no financial barriers exist for the great majority of end users of this technology. As a result,

the method is widely implementable across a variety of educational settings. Most computer monitors and televisions support 3D projection and many are already in student homes; moreover, it is likely that new and low-cost 3D projectors, televisions, and blu-ray systems will soon be ubiquitous for both home and school markets. This trend has been clear over the past 5 yr, beginning with <5% of televisions sold supporting 3D to upward of 50% in the current market. Our work creates a strong foundation for development of 3D visualization in the future classroom given that newly developed 3D systems will be both widely available and affordable.

APPENDIX: EXAMPLE MULTIPLE-CHOICE EXAM QUESTIONS FROM *SCHOOL ALPHA**Brain*

1. Which lobe of the cerebrum contains the somatic sensory area?
 - A. Diencephalon
 - B. Occipital
 - C. Frontal
 - D. Parietal
2. What major neural tract connects the right and left sides of the hemisphere?
 - A. Cerebellar tract
 - B. Corpus callosum
 - C. Amygdala
 - D. Olfactory tract
3. This is the outer portion of the brain that deals with higher order brain processing and reasoning.
 - A. Medulla
 - B. Cerebellum
 - C. Corpus callosum
 - D. Cerebrum
4. This area of the brain is part of the limbic system and processes smell-related stimuli.
 - A. Occipital
 - B. Gustatory area
 - C. Olfactory area
 - D. Epithalamus
5. This part of the brain is part of the epithalamus. It makes cerebral spinal fluid.
 - A. Choroid plexus
 - B. Arachnoid layer
 - C. Hypothalamus
 - D. Hippocampus
6. What part of the brain is responsible for controlling swallowing and vomiting?
 - A. Medulla
 - B. Pons
 - C. Amygdala
 - D. Diencephalon
7. Which part of the brain contains the thalamus, hypothalamus, and epithalamus?
 - A. Cerebrum
 - B. Cerebellum
 - C. Brain stem
 - D. Diencephalon
8. You are a doctor, and you determine that your patient has trouble with spatial learning and memory acquisition following traumatic head injury. Which area of the brain is most likely injured?
 - A. Occipital lobe
 - B. Hippocampus
 - C. Amygdala
 - D. Olfactory bulb

Anatomy

1. Which set of bones are part of the axial skeleton?
 - A. Bones of the limbs
 - B. Shoulder bones
 - C. Skull bones
 - D. Pelvic bones
2. Which of the following is not a fused bone?
 - A. Coccyx
 - B. Sacrum
 - C. Sternum
 - D. Rib
3. Which bone is the strongest facial bone?
 - A. Mandible
 - B. Femur
 - C. Frontal
 - D. Nasal
4. The sternum is _____ to the scapulas.
 - A. Dorsal
 - B. Ventral
5. The picture below illustrates what type of section?
 - A. Sagittal
 - B. Frontal
 - C. Transverse
6. The esophagus, stomach, and intestines are part of what system?
 - A. Integumentary
 - B. Skeletal
 - C. Muscular
 - D. Nervous
 - E. Digestive
7. Below is a picture of a vertebra. Number 2 is labeling the _____.
 - A. Body
 - B. Spinous process
 - C. Transverse process
 - D. Vertebral foramen
8. Which of the following vertebrae does not have a body?
 - A. Axis
 - B. Atlas
 - C. Thoracic vertebrae
 - D. Lumbar vertebrae

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AUTHOR CONTRIBUTIONS

Author contributions: R.F., J.B., A.K., and R.C. conception and design of research; R.F., J.B., A.K., and R.C. interpreted results of experiments; R.F., J.B., A.K., and R.C. edited and revised manuscript; R.F., J.B., A.K., and R.C.

approved final version of manuscript; J.B., A.K., and R.C. analyzed data; A.K. performed experiments; R.C. prepared figures; R.C. drafted manuscript.

REFERENCES

1. Alam GM, Oloruntegbe KO, Oluwatelure AT, Alake EM, Ayeni AE. Is 3D just an addition of 1 to 2 or is it more enhancing than 2D visualizations? *Sci Res Essays* 5: 1536–1539, 2010.
2. Berman HM, Westbrook J, Feng Z, Gilliland G, Bhat Weissig TN, H, Shindyalov IN, Bourne PE. The Protein Data Bank. *Nucleic Acids Res* 28: 235–242, 2000.
3. Bowman D, Gracey M, Lucas J, Setareh J, Varadarajan S., *Immersive Virtual Environments for University Education: Views from the Classroom*, edited by Kunz A, Deisinger J. Aalborg, Denmark: Ninth Eurographics Workshop on Virtual Environments, 2003, p. 1–2.
4. Bransford JD, Brown AL, Cocking RR. *How People Learn: Brain, Mind, Experience, and School* (expanded edition). Washington, DC: National Academy, 2000.
5. Buckley BC. Interactive multimedia and model-based learning in biology. *Int J Sci Educ* 22: 895–935, 2000.
6. Clements RJ, Blank JL. A stereoscopic volume rendered brain atlas. *Brains Minds Media* 3: 1–9, 2008.
7. Collins A, Brown JS, Newman SE. Cognitive apprenticeship: teaching the crafts of reading, writing, and mathematics. In: *Knowing, learning, and Instruction: Essays in Honor of Robert Glaser*, edited by Resnick LB. Hillsdale, NJ: Erlbaum, 1989, p. 453–494.
8. Donovan MS, Bransford JD, Pellegrino JW. *How People Learn: Bridging Research and Practice*. Washington, DC: National Academies, 1999.
9. Dunn TL, Wardhani A. *Robot Simulation for Education*. Melbourne: Proceedings of the 1st International Conference on Computer Graphics and Interactive Techniques in Australasia and South East Asia. 2003.
10. Forman HB, Eccles R, Piggins J, Raila W, Estey G, Barnett GO. Using cross-sectional imaging to convey organ relationships: an integrated learning environment for students of gross anatomy. *Proc Annu Symp Comput Appl Med Care*: 450–453, 1990.
11. Hardy L. *American School Board Journal. The Importance of STEM* (online). <http://www.asbj.com/MainMenuCategory/Archive/2009/October/The-Importance-of-STEM.aspx> [29 April 2015].
12. Hegarty M, Carpenter PA, Just MA. Diagrams in the comprehension of scientific text. In: *Handbook of Reading Research*, edited by Barr R, Kamil ML, Mosenthal PB, Pearson PD. New York: Longman, 1991, vol. 2.
13. Humphrey W, Dalke Schulten KA. VMD—visual molecular dynamics. *J Mol Graphics* 14: 33–38, 1996.
14. Ioannidou A, Repenning A, Webb DC. AgentCubes: incremental 3D end-user development. *J Vis Languages Comput* 20: 236–251, 2009.
15. Kalinski T, Zwonitzer R, Jonczyk-Weber T, Hofmann H, Bernarding J, Roessner A. Improvements in education in pathology: virtual 3D specimens. *Pathol Res Pract* 205: 811–814, 2009.
16. Kaufmann H, Schmalstieg D, Wagner M. *Construct3D: a Virtual Reality Application for Mathematics and Geometry Education, Education and Information Technologies*. Dordrecht: Kluwer Academic, 2000, p. 263–276.
17. Korakakis G, Pavlatou EA, Palyvos JA, Spyrellis N. 3D visualization types in multimedia applications for science learning: a case Study for 8th grade students in Greece. *Comput Educ* 52: 390–401, 2009.
18. Patrick MD, Carter G, Wiebe EN. Visual representations of DNA replication: middle grades students' perceptions and interpretations. *J Sci Educ Technol* 14: 353–365, 2005.
19. Petersson H, Sinkvist D, Wang C, Smedby O. Web-based interactive 3D visualization as a tool for improved anatomy learning. *Anat Sci Educ* 2: 61–68, 2009.
20. Yoshino D, Kishira S, Shimizu M, Tsuchida K, Uehara S, Yaku T. Geography learning technology based on 3D CG with geography data archives. *IEEE Comput Soc*: 472–476, 2007.