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The UW Virtual Brain Project: An Immersive Approach to Teaching Functional Neuroanatomy

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Learning functional neuroanatomy requires forming mental representations of 3D structure, but forming such representations from 2D textbook diagrams can be challenging. We address this challenge in the UW Virtual Brain Project by developing 3D narrated diagrams, which are interactive, guided tours through 3D models of perceptual systems. Lessons can be experienced in virtual reality (VR) or on a personal computer monitor (PC). We predicted participants would learn from lessons presented on both VR and PC devices (comparing pretest/posttest scores) but that VR would be more effective for achieving both content-based learning outcomes (i.e., test performance) and experience-based learning outcomes (i.e., reported enjoyment and ease of use). All participants received lessons about the visual system and auditory system, one in VR and one on a PC (order counterbalanced). We assessed content learning using a drawing/labeling task on paper (2D drawing) in Experiment 1 and a Looking Glass autostereoscopic display (3D drawing) in Experiment 2. In both experiments, we found that the UW Virtual Brain Project lessons were effective for teaching functional neuroanatomy, with no difference between devices. However, participants reported VR was more enjoyable and easier to use. We also evaluated the VR lessons in our classroom implementation during an undergraduate course on perception. Students reported that the VR lessons helped them make progress on course learning outcomes, especially for learning system pathways. They suggested lessons could be improved by adding more examples and providing more time to explore in VR.

What is the significance of this article for the general public?
We designed and evaluated interactive 3D narrated diagrams to teach functional neuroanatomy. These lessons can be experienced on desktop PC and in virtual reality (VR) and are helpful for teaching undergraduates about structure and function of perceptual systems in the human brain.

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To learn functional anatomy, such as how sensory information is processed in the human brain, students must form mental representations of 3D anatomical structures. Evidence suggests forming mental representations is easier for learners when they are presented with 3D models (i.e., different views can be rendered by translation and rotation), compared with 2D images (see Yammine and Violato, 2015, for a meta-analysis). This benefit of 3D models, at least in part, is because piecing together multiple views from 2D images incurs a cognitive load that detracts from learning the content, especially for learners with lower visual-spatial ability (Bogomolova et al., 2020; Cui et al., 2016).

Prior studies have suggested physical models are better than computer models for illustrating gross anatomy (Khot et al., 2013; Preece et al., 2013; Wainman et al., 2018, 2020). However, physical models are limited in their potential to illustrate dynamic, functional processes, such as how neural signals are triggered by sensory input and propagate through a perceptual system. Given that our focus was on functional anatomy, we focus our discussion on computer-based models only.

The present study is part of the UW Virtual Brain Project, in which we have developed and assessed a new approach for teaching students about functional anatomy of perceptual pathways. Previous computer-based 3D models of the human brain were geared toward teaching medical students about gross anatomy (Adams & Wilson, 2011; Allen et al., 2016; Cui et al., 2017; Drapkin et al., 2015; Ekstrand et al., 2018; Kockro et al., 2015; Stepan et al., 2017).[1] In contrast, our lessons give learners guided, first-person view tours through "3D narrated diagrams" illustrating the functional anatomy of the human brain. We use the term "3D narrated diagram" to refer to 3D models combined with labels and verbal descriptions, analogous to content found in textbook diagrams with corresponding text. They can also include animations that illustrate dynamic aspects of the system. Thus, 3D models form the basis for the environment used to teach students about sensory input, system pathways, and system purposes, which are key learning outcomes in an undergraduate course on sensation and perception.

Our aim was to develop structured, self-contained lessons for an undergraduate audience that harnessed principles for effective multimedia learning (Mayer, 2009). These principles have previously been shown to facilitate learning in a variety of domains. For example, using visual cues to signal students where to look during a lesson can help them learn about neural structures (signaling principle; Jamet et al., 2008). Learners benefit from having self-paced controls through a lesson, compared with experiencing system-paced continuous animation (segmenting principle; Hasler et al., 2007). Moreover, receiving input from multiple modalities (audio narration plus visual illustration) can be better than receiving visual input alone (modality principle; Harskamp et al., 2007).

The UW Virtual Brain 3D narrated diagrams can be viewed on personal computer monitors (referred to as "PC"; the same image is presented to both eyes) or in virtual reality using a head-mounted display (HMD) with stereoscopic depth (referred to as "VR"; different images are presented to each eye).[2] In the VR version, the brain is room sized, so learners can "immerse" their whole body inside the brain. This study investigated whether students made significant gains in content-based learning outcomes from the Virtual Brain lessons and whether viewing device (VR vs. PC) influenced the degree to which learners achieved content-based and experience-based learning outcomes. Content-based learning outcomes included being able to describe (draw/label) key brain regions and pathways involved in processing visual and auditory input. Experience-based learning outcomes included finding the lessons enjoyable and easy to use.

[1] Studies evaluating the efficacy of these 3D models used a myriad of comparison conditions that differed from the 3D models in multiple dimensions. Thus, it is challenging to form general conclusions from their results (see Wainman et al., 2020, for a discussion of this issue).

[2] We note earlier literature used the term "VR" in reference to viewing 3D models on 2D displays (e.g., computer monitors), rather than immersive head-mounted displays (see Wainman et al., 2020, for a discussion of this issue). In this article, we reserve the term "VR" for head-mounted displays, like an Oculus Rift, Oculus Go, or HTC Vive.

We predicted that learners would make significant gains in content-based learning outcomes from lessons experienced in both VR and PC viewing (compared to a pretest baseline) but that VR viewing would be more effective. We also predicted VR would be more effective for achieving experience-based learning outcomes. Previous work strongly supports our prediction for experience-based learning outcomes, demonstrating that VR facilitates enjoyment, engagement, and motivation, compared with less immersive experiences (Hu-Au & Lee, 2017; Makransky et al., 2020; Pantelidis, 2010; Parong & Mayer, 2018; Stepan et al., 2017). However, prior evidence concerning our prediction that VR would better support content-based learning outcomes is mixed. Research on learning 3D structure and spatial layout suggests VR should facilitate learning, but research on narrated lessons suggests VR may hinder learning, as discussed below.

Research on learning 3D anatomical structure suggests stereoscopic viewing facilitates learning compared to monoscopic viewing of the same models, at least when viewing is interactive. A meta-analysis reported that viewing interactive stereoscopic 3D models provided a significant benefit, compared with viewing interactive monoscopic 3D models (i.e., the same image was presented to both eyes or the image was presented to one eye only; Bogomolova et al., 2020). For example, Wainman et al. (2020) found students learned better when stereoscopically viewing 3D models compared to when one eye was covered while using a VR HMD. The additional depth information provided by stereopsis likely contributes to these enhanced learning outcomes (Bogomolova et al., 2020; Wainman et al., 2020). Evidence suggests that stereoscopic information is especially beneficial for 3D perception under interactive viewing conditions where head-tracking-based motion parallax information and task feedback are available (Fulvio & Rokers, 2017), perhaps because viewers tend to discount stereoscopic information under passive viewing conditions (Fulvio et al., 2020). This may explain why the contribution of stereopsis to achieve learning outcomes was more limited under passive viewing (Al-Khalili & Coppoc, 2014) and fixed viewpoint rendering (Chen et al., 2012; Luursema et al., 2008).

A separate line of studies testing the ability to remember spatial layout in new environments suggests that VR facilitates spatial memory. Comparisons between learning in VR or on a desktop PC suggest participants were better at navigating a virtual building (Ruddle et al., 1999) and recalling the spatial location of objects (Krokos et al., 2019) in VR. These results have been explained by increased presence (feelings of "being there"; Sanchez-Vives & Slater, 2005) in VR, due to greater immersion supported by proprioceptive and vestibular sensory information available during VR experiences (Krokos et al., 2019; Ruddle et al., 1999). Increased presence enables learners to leverage spatial cues in the environment to facilitate memory (i.e., the method of loci or the memory palace technique; Krokos et al., 2019).

Although work on stereopsis and spatial memory suggests VR will help with learning spatial structure in the Virtual Brain lessons, research comparing narrated lessons viewed in VR or on PC suggests VR might hinder learning. Studies on narrated lessons about scientific procedures (e.g., DNA sample preparation) reported no difference (Makransky et al., 2020) or worse performance for VR (Makransky et al., 2019, 2020) compared to PC viewing. One exception in which VR facilitated learning was when it was paired with enactment using physical objects in between the VR lesson and testing (Makransky et al., 2020). The general concern about narrated VR lessons is that presence from immersion in VR can distract learners from the content in the lesson, which impedes learning (Makransky et al., 2019, 2020; Parong & Mayer, 2018). Thus, it is possible that adding additional cognitive load from narration will diminish or even reverse the benefits of learning 3D structure from added stereopsis and increased presence in VR.

In the following sections, we first describe the general method for designing and implementing the UW Virtual Brain Project lessons. We then present the results of two laboratory experiments that assessed learning outcomes of lessons presented in VR versus PC viewing (Experiment 1 and Experiment 2). Finally, we discuss how we implemented the lessons in an undergraduate course on the psychology of perception and present results from student evaluations ("Classroom Implementation").

General Method

We created and evaluated two UW Virtual Brain lessons, the Virtual Visual System and Virtual Auditory System. Learners could travel along a track and stop at information stations to hear narration about key structures and pathways involved in perceptual processing (see Figure 1). The interactive diagrams in our Virtual Brain lessons were adapted from figures in a popular sensation and perception textbook (Wolfe et al., 2014) and constructed from human neuroimaging data.

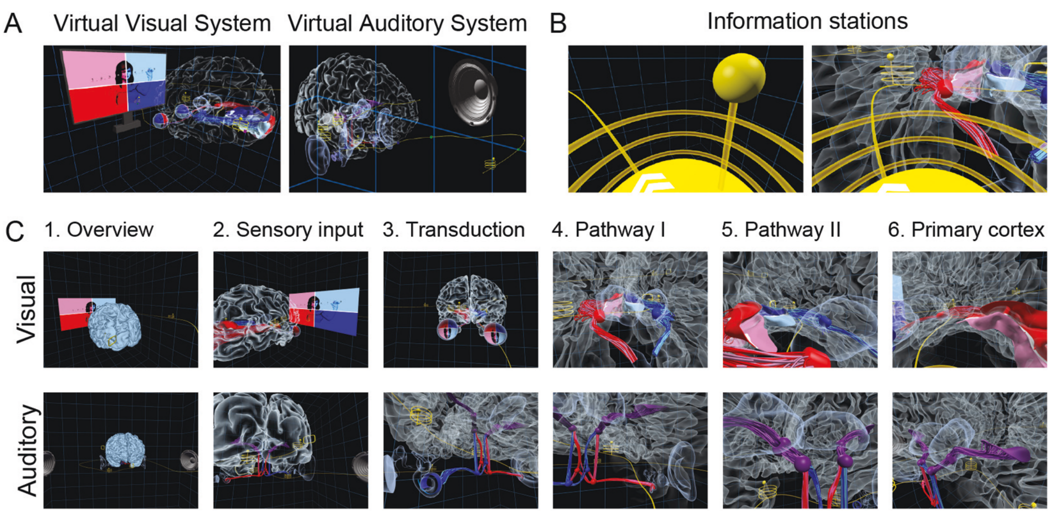
The UW Virtual Brain Project lessons leveraged several principles for creating effective materials for multimedia learning (Mayer, 2009). In our lessons, verbal narration was combined with visual input (multimedia principle) in a way that enabled learners to listen and look at the same time (modality principle). Through the narration, we provided verbal cues about where to look (e.g., "Look to your left, you will see. . .") to help learners align the visual and verbal input (signaling principle). The lessons were self-paced (segmentation principle) as learners controlled their motion and triggered narration by choosing when to enter an information station. We avoided additional elements unrelated to the content (coherence principle) by only including neural structures and labels that were relevant to the perceptual system featured in a given lesson.

For any kind of VR-based visualization, motion sickness can lead to considerable discomfort (Stanney et al., 2020). We employed several design considerations to mitigate motion sickness. First, we optimized our code to maintain the maximum frame rate of the VR headset. Second, the participant was in control of all movement, eliminating the possibility of any drastic and unexpected motion signals. Third, the trajectory along which the participant could move was always visible, allowing the participant to anticipate the visual consequences of any initiated movement. We evaluated the efficacy of these design considerations using the Simulator Sickness Questionnaire (SSQ; Kennedy et al., 1993) and a questionnaire assessing participants' enjoyment and ease of use in the different conditions, which we describe in the "Measures" section of Experiment 1A. The SSQ results are presented in the online supplemental materials.

Figure 2 outlines our pipeline for constructing the virtual environments. We began with a T1-weighted anatomical MRI scan and used FreeSurfer (Fischl, 2012) to extract the pial surface of the brain. This approach was similar to Ekstrand et al. (2018). We generated cortical regions of interest by extracting surfaces from FreeSurfer's default segmentation and cortical surface generation and Glasser's Human Connectome Project Multimodal Parcellation Atlas (Glasser et al., 2016). For some subcortical structures, we estimated their location based on gross anatomy and rendered them manually. We generated major white matter pathways

Figure 1

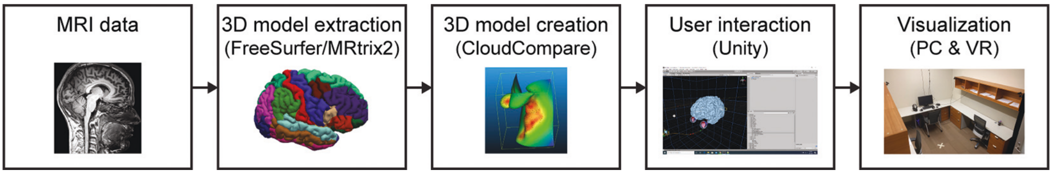
Illustration of the UW Virtual Brain Project



Note. (A) Screenshots of the Virtual Visual System and Virtual Auditory System. (B) Information stations where participants learn about the structures and pathways via audio narration. (C) Each lesson has six stations that learners visit along a track at key points in the perceptual system pathway. See the online article for the color version of this figure.

Figure 2

Pipeline for Creating the UW Virtual Brain Lessons, Beginning With an MRI Scan and Ending With Lessons That Can Be Used on Personal Computer (PC) Desktops or in Virtual Reality (VR)



Note. See the online article for the color version of this figure.

using probabilistic tractography and manually recreated smaller pathways. We then imported all geometry into the Unity game engine and added features including voice-over playback, text rendering, and navigation. Additional details on the history of VR brain rendering can be found in the online supplemental materials.

The Virtual Visual System and Virtual Auditory System (Figure 1A) each have six information stations, which start outside of the brain (Station 1) and follow along a track from sensory input (Station 2), to transduction (Station 3), to midbrain regions and pathways (Stations 4 and 5), to primary cortex (Station 6), as shown in Figure 1C. When learners arrive at a station, glowing yellow rings appear around the perimeter of the station (Figure 1B), and voice-over narration provides information relevant to that location. After the audio finishes, the rings fade away, and learners can continue along the track. The locations and narration for the two perceptual systems were as parallel as possible, and the lessons were equal in length (∼5 min). See the online supplemental materials for descriptions of the lesson experiences and narration scripts. The lessons can be downloaded from https://github.com/SchlossVRL/UW-Virtual-Brain-Project.

In Experiments 1 and 2, the VR and PC setups were powered by a Dell Alienware Aurora workstation with an nVidia GeForce 970 GPU. In the VR version, we used an Oculus Rift CV1 with 360° tracking enabled. Three Oculus camera sensors were placed in the upper corners of a 6-ft × 8-ft tracked space. Participants stood in the middle of the space, and the Oculus cord was suspended from above, enabling full 360° body rotation. Although our participants stood, the VR lessons could be done while seated on a swivel chair. Participants heard narration through built-in speakers in the HMD and interacted with the environment using Oculus Touch controllers. They moved forward/backward along the track by pressing the Oculus Touch joystick and looked around the room by moving their head. The HMD tracked this head movement (6 degrees of freedom head tracking) and updated the image to match the head motion. In the PC version, learners sat in front of a 24-in. Samsung monitor and heard narration through headphones. They used the left/right mouse buttons to move forward/backward along the track and slid the mouse in any direction to "look around" (rotate the view). In the Classroom Implementation, we used wireless Oculus Go HMDs, which support 3 degrees of freedom head tracking (rotation only), and the Oculus Go controller to move along the track.

For each device in the experiments, participants completed a practice lesson that introduced them to the virtual environment and the device controls. The environment included a model of the brain's cortical surface (no structures/pathways). Audio narration instructed participants about how to use the controls for the given device and asked them to practice moving forward/backward and looking around. In the VR practice, participants also used a virtually rendered eye chart to adjust the interpupillary distance of the Oculus lenses to minimize blurriness.

Experiment 1

Experiment 1 compared the effects of PC versus VR viewing on achieving content-based and experienced-based learning outcomes. Assessments of content-based learning outcomes were done by drawing/labeling on paper. Experiments 1A and 1B were the same except Experiment 1B had twice the sample size to increase statistical power.

Experiment 1A

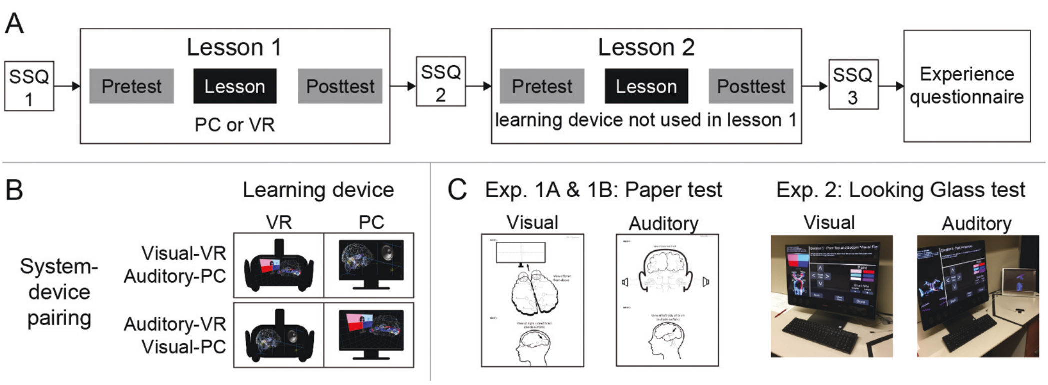
Method

Participants. Sixty undergraduates (30 female, 29 male, one no report; *M* age = 19.1) participated for credit in Introductory Psychology at University of Wisconsin–Madison. Data from three others were excluded due to experimenter error. A power analysis estimating a medium effect ($d = .5$) for a two-tailed paired *t* test comparing PC versus VR ($\alpha = .05$, power of .9) suggested a sample of $n = 44$, but we rounded to $n = 60$ to be more conservative. All participants had typical color vision (screened using H.R.R. Pseudoisochromatic Plates; Hardy et al., 2002) and typical stereo vision (screened using the RANDOT® Stereovision test). For all experiments in this study, all participants gave informed consent, and the University of Wisconsin–Madison Institutional Review Board approved the protocol.

Design and Procedure. Figure 3 shows an overview of the experiment procedure (Figure 3A), the experiment design (Figure 3B), and the testing materials (Figure 3C). The design included 2 devices (VR and PC; within subjects) × 2 device orders (VR first or PC first; between subjects) × 2 perceptual system-device pairings (visual-VR/auditory-PC or auditory-VR/visual-PC; between subjects; $n = 15$/group, randomly assigned).

During the consenting process, we emphasized that participants could end the experiment at any time if they felt unwell. During the experiment, participants first completed the SSQ as a baseline measure for motion sickness symptoms. Second, they completed the first lesson block, which included a paper pretest, a practice experience for the given device, the lesson, and a posttest. Third, participants completed the second SSQ to assess how they were feeling after the first lesson. Fourth, participants completed the second lesson block, which was the same as the first except using a different device (e.g., if VR was used in the first lesson block, PC was used in the second lesson block) and different perceptual system (e.g., if the visual system was used in the first lesson block, the auditory system was used in the second lesson block). Fifth, participants completed another SSQ to assess how they were feeling after the second block. Last, participants completed the experience questionnaire. The procedure lasted approximately 1 hr. The time to complete the VR condition was about 3 min longer than the PC condition due to extra time adjusting the HMD in the practice room before the VR lesson.

Figure 3
Overview of the Experimental Procedure



Note. (A) In both Experiments 1 and 2, each lesson block featured a pretest, the lesson (either desktop personal computer [PC] or virtual reality [VR]), and a posttest. Three Simulator Sickness Questionnaires (SSQs) were administered throughout the course of the experiment, with an experience questionnaire at the end. (B) Illustration of the experimental design. We randomized the 2 Learning Device (within subjects) × 2 Perceptual System-Device Pairings (between subjects). Each row represents the lessons experienced by a participant. Not explicitly represented is device order. If the figure presented represents VR first, the PC-first groups would mirror that (between subjects). (C) Illustration of paper tests (Experiments 1A and 1B) and Looking Glass tests (Experiment 2) used to assess content-based learning outcomes for each perceptual system lesson. See the online supplemental materials for full tests and instructions and for larger images of the Looking Glass display (Figure C10). See the online article for the color version of this figure.

Measures.

Content Learning. We assessed content learning using a pretest/posttest design for each perceptual system with the same test provided at both time points. We used a drawing/labeling task, which aligned with the content-based learning outcomes of describing key regions and pathways of the perceptual systems. We used the same pretest and posttest because it was a controlled way of testing exactly what gains in knowledge were made during the lessons. A limitation of this approach is that learners were primed on the critical information prior to starting the lesson. However, since the design was consistent across the PC and VR conditions, this priming could not account for differences between conditions.

Tests for both perceptual systems were matched in number and types of questions. Tests for each system included two line drawing images of the brain from different perspectives (Figure 3C), which resembled perspectives experienced during the lessons. Participants responded to five questions by coloring/labeling structures and drawing pathways on the two images (Image 1 for Questions 1–4; Image 2 for Question 5), using pens in three hues (red, blue, purple), with two pens per hue (light/dark), and one black pen (seven pens total). The questions built on one another, requiring participants to use the hues/lightness of the pens to indicate how the sensory input from the world travels into and through the perceptual system and projects onto the system's structures. Participants were encouraged to answer all questions, even if guessing. If they made a mistake, they were told to ask for a new blank page. See the online supplemental materials for full tests and instructions (Figures C1–C5).

In the visual system test, the first test image consisted of a TV screen and an axial slice of the brain featuring two eyes and outlines of the optic chiasm, LGNs, and V1 structures. The second test image showed a sagittal slice of the brain, featuring the right hemisphere, with the corresponding eye, LGN, and V1. Participants were told to use the colored pens as follows: "Reds: information processed from the left visual field; Blues: information processed from the right visual field; Black: Labeling structures." The questions are summarized as follows: (a) Use the colored pens to indicate (color in) the four parts of the visual field in the TV screen (i.e., "dark red pen: bottom left visual field"), (b) Color in the quadrants on the eyes, with respect to where the visual field projects (i.e., "dark red pen: quadrant(s) of the eyes where the bottom left visual field projects"), (c) Use the black pen to write the names of the structures on the blank lines, (d) Use the "appropriate colors" (based on previous responses) to draw the path from both the right and left visual field through all relevant structures, and (e) On Image 2, indicate (color) where the bottom and top visual field project on the marked structure (which was V1).

In the auditory system test, the first image featured a coronal slice of a head with ears and a brain, flanked by speakers "producing" sound waves. In the brain, the cochleas, MGNs, and A1 structures were outlined, and circles represented the cochlear nuclei, superior olives, and inferior colliculi. The second test image showed a profile view of the left side of the head and had outlines of MGN and A1. Participants were told to use the colored pens as follows: "Reds: information processed by the ear seen on your right; Blues: information processed by the ear seen on your left; Purples: information processed by both ears; Black: Labeling structures." The questions for the auditory test paralleled the visual except in place of the visual field (TV), participants colored in the sound waves from the speakers and drew the pathways in regard to low and high frequency sounds. Also, instead of the retina and V1, participants colored the parts of the cochlea and A1 in reference to processing lower/higher frequencies.

Experience Questionnaire. We assessed experience-based learning outcomes by having participants rate seven items on a Likert scale from 1 (*not at all*) to 7 (*very much*). The items asked how much participants (a) found the experience awe inspiring, (b) found the experience aesthetically pleasing, (c) enjoyed the experience, (d) would like to use this kind of experience for their own studies about the brain in the future, (e) would recommend the experience to a friend for learning about the brain, (f) would recommend the experience to a friend to do for fun, and (g) found ease with using the control system to move around and see what they wanted to see. This task was done on paper.

Simulator Sickness Questionnaire (SSQ). We assessed a subset of symptoms from the SSQ (Kennedy et al., 1993). For each symptom (headache, nausea, eye strain, and dizziness with eyes open), participants indicated how they felt by circling *none*, *slight*, *moderate*, or *severe* (scored as 1–4). The SSQ results are reported in the online supplemental materials; see Figure D1. For all experiments, mean responses to all four symptoms were between *none* and *slight* at all time points, and no participant reported *severe* symptoms. This task was done on paper.

Results and Discussion

Scoring. Each test was scored by two independent raters using an 18-item rubric with each item worth 1 point (see the online supplemental materials). Prior to collecting and scoring the data, we collected data from five pilot subjects to fine-tune the rubric. The two raters used an initial rubric to independently score the pilot data. They then discussed discrepancies in their scores and updated the rubric to make it more precise. No changes to the rubric were made once testing in Experiment 1A began.

During the experiment, each test page was given a random code that represented subject number and condition. The raters did not have access to these codes, so they could not identify which tests were pretests versus posttests, which were from VR or PC lessons, and which belonged to the same participant. To evaluate interrater reliability, we correlated each of the raters' scores over 240 tests (60 participants × 2 lessons [visual, auditory] × 2 tests [pretest, posttest]). The correlation was high (r = .94), so we averaged the scores across raters for each participant. We then calculated change in performance for each participant as the posttest scores minus pretest scores (ranging from −18 to 18) for each device. Data for all experiments can be found at https://github.com/SchlossVRL/UW-Virtual-Brain-Project.

Content Questions. Figure 4A shows mean change in test performance for the PC and VR devices, averaged over participants, testing order, and perceptual system-device pairing. *T* tests against zero showed that change scores were significantly positive for both PC and VR, $t(59) = 13.05$, $p < .001$, $d = 1.68$, and $t(59) = 11.69$, $p < .001$, $d = 1.51$, respectively, indicating that participants learned from the Virtual Brain lessons on both devices. A paired-samples t test did not reveal a significant difference in learning between devices, $t(59) = 1.59$, $p = .118$, $d = .21$.

In an exploratory analysis to test for effects of device order and perceptual system-device pairing, and their interaction with device (mixed-design analysis of variance [ANOVA]: 2 Devices [VR vs. PC; within subjects] × 2 Device Orders [VR first vs. PC first; between subjects] × 2 Perceptual System-Device Pairing [visual-VR/auditory-PC vs. auditory-VR/visual-PC; between subjects]), there was no effect of device, $F(1, 56) = 2.47$, $p = .122$, $\eta_p^2 = .041$, or system-device pairing, $F < 1$, but there was a main effect of device order, $F(1, 56) = 4.56$, $p = .037$, $\eta_p^2 = .075$, in which the mean change in performance was greater for participants in the VR-first group than the PC-first group. The two- and three-way interactions were not significant (Fs < 1.19).

We also explored whether there was a difference in the pretest performance for the two perceptual systems and found greater performance for the visual system, $t(59) = 7.00$, $p < .001$, $d = .90$. Given the way we coded the counterbalanced factors, an interaction between device and perceptual system-device pairing would indicate differences in change in performance for the visual and auditory systems. We do not see such a difference here, indicating learning was similar across perceptual systems.

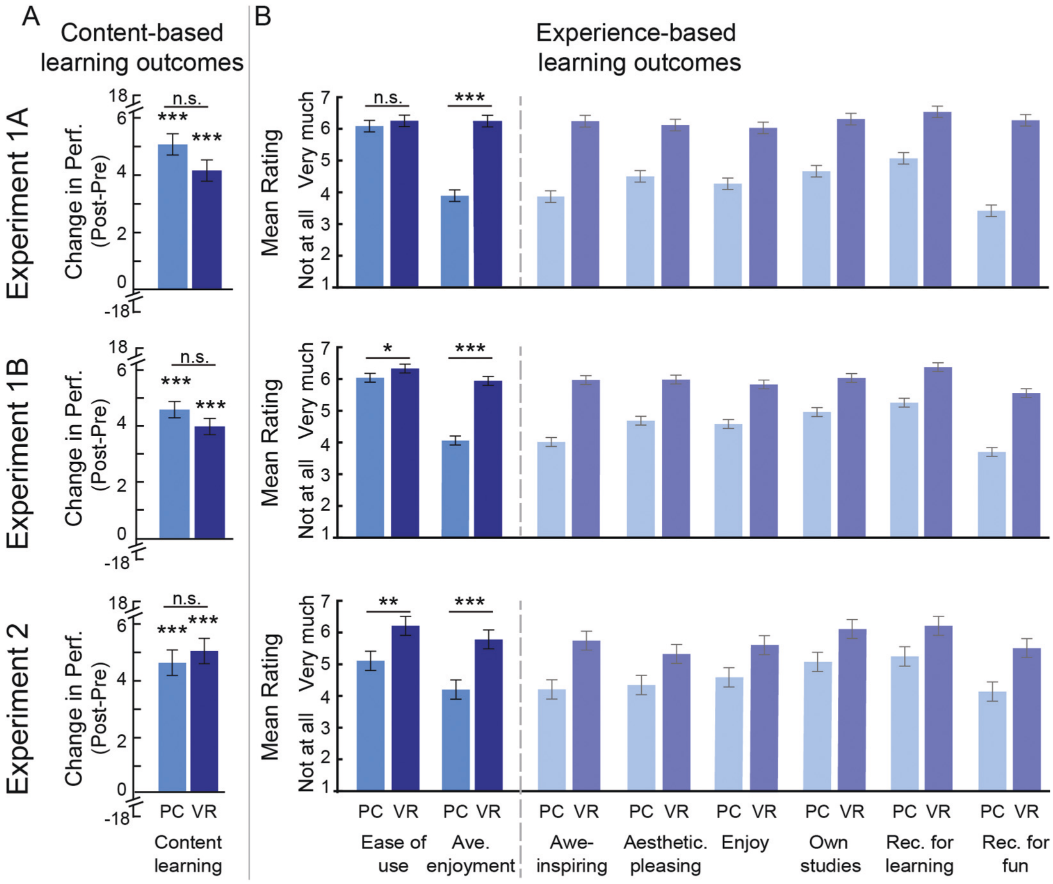
Experience Questionnaire. Figure 4B shows the mean ratings for each of the seven experience questionnaire items. From visual inspection, VR ratings were much higher than PC for every item except ease of use. This suggests participants found the VR experience more awe-inspiring, enjoyable, and aesthetically pleasing and were more likely to use it themselves and recommend it to others for learning or for fun than the PC experience.

Given that many of the items were highly correlated (see Table D1 in the online supplemental materials), we used Principal Component Analysis (PCA; with oblique rotation) to reduce the dimensions before conducting statistical tests to compare across devices.[3] All items except "ease of use" loaded strongly onto the first principal component, which can be summarized as "enjoyment" (capturing 66% of the variance). Thus, we used the mean of these items for subsequent analysis and refer to it as "average enjoyment." Item 7, ease of use, was an outlier in the PCA, so we treated it separately. Paired-samples t tests comparing devices showed that average enjoyment was significantly greater for VR than for PC lessons, $t(59) = 9.50$, $p < .001$, $d = 1.23$, and there was no significant difference for ease of use, $t(59) = .86$, $p = .39$, $d = .11$.

[3] Five of the participants left one item blank, so we inserted the mean of all other participants' responses for that item.

Figure 4

Results of Learning Outcome Assessments as a Function of Device (PC vs. VR)



Note. (A) Mean change in test performance and (B) mean ratings for ease of use and "average enjoyment" for personal computer (PC; light bars) and virtual reality (VR; dark bars) devices, averaged over participants, testing order, and perceptual system in Experiments 1 and 2. The data to the right of the vertical dashed line in (B) correspond to the six individual items used to calculate "average enjoyment." Error bars represent standard errors of the means. * $p < .05$. ** $p < .01$. *** $p < .001$. See the online article for the color version of this figure.

In summary, this experiment demonstrated that participants learned key content such as the brain regions and pathways involved in processing sensory information from the lessons experienced on both devices. There was no significant difference in content learning between devices, but assessments of experience-based learning outcomes showed that participants enjoyed the VR lesson significantly more than the PC lesson. There was no significant difference in ease of use.

In the *a priori* power analysis for this experiment, we estimated a medium effect size comparing VR and PC devices for measures of content learning, but a power analysis using our observed effect size ($\eta_p^2 = .041$, when accounting for device order and perceptual system/device pairing) with power of .80, $\alpha = .05$, suggested we needed a larger sample size (112 participants) to observe an effect. We note that if this effect were significant, it would be in the opposite direction of our prediction (i.e., greater learning for PC than VR). To test this possibility, we conducted Experiment 1B as a direct replication of Experiment 1A with an increased sample size (120 participants to be more conservative).

Experiment 1B

Method

The method was the same as Experiment 1A except we increased the sample size based on the power analysis reported in Experiment 1A. One hundred twenty undergraduates (79 female, 36 male, five no report; *M* age = 18.60, two no report) participated for extra credit in Introductory Psychology at University of Wisconsin–Madison. All had typical color and stereo vision and gave informed consent. Eight additional participants were excluded due to experimenter error or technical difficulties (four participants), atypical color vision (one participant), or atypical stereo vision (three participants).

Results and Discussion

Content Questions. The two raters from Experiment 1A scored the tests (interrater reliability: $r = .91$). As in Experiment 1A, change scores were significantly greater than zero for PC, $t(119) = 15.46$, $p < .001$, $d = 1.41$, and VR, $t(119) = 13.94$, $p < .001$, $d = 1.27$, indicating that participants learned on both devices (Figure 4A). The *t* test comparing devices averaged over all other factors again showed no significant difference between devices, $t(119) = 1.62$, $p = .109$, $d = .15$. Likewise, the full ANOVA (2 Devices [VR vs. PC; within subjects] × Device Orders [VR first vs. PC first; between subjects] × 2 Perceptual System-Device Pairings [visual-VR/auditory-PC vs. auditory-VR/visual-PC; between subjects]) again showed no significant effect of device, even after having increased power, $F(1, 116) = 2.95$, $p = .089$, $\eta_p^2 = .025$. The other main effects were also not significant: device order, $F(1, 116) = 2.01$, $p = .159$, $\eta_p^2 = .017$, system-device pairing, $F < 1$. There was a significant Device × System-Device Pairing effect, $F(1, 116) = 15.93$, $p < .001$, $\eta_p^2 = .121$, which can be reduced to better performance for the visual system than the auditory system. That is because participants with the system-device pairing of visual-VR/auditory-PC had higher scores for VR (visual) compared to PC (auditory), whereas participants with auditory-VR/visual-PC pairings had higher scores for PC (visual) than VR (auditory), indicating overall greater learning for the visual system. This is further supported by a paired-samples *t* test comparing change in performance scores for visual and auditory lessons, $t(119) = 3.95$, $p < .001$, $d = .36$. The other two-way interactions and three-way interaction were not significant: Device × Device Order, $F < 1$; Perceptual System-Device Pairing × Device Order, $F < 1$; three-way interaction, $F(1, 116) = 2.30$, $p = .132$, $\eta_p^2 = .019$. Examining the pretest scores, the visual system scores were again significantly greater than the auditory system scores, $t(119) = 7.66$, $p < .001$, $d = .70$.

Experience Questionnaire. As in Experiment 1A, we conducted statistical tests on mean enjoyment (averaging over six items) and ease of use. This data set includes only 114 out 120 participants because six participants did not complete the survey. Mean enjoyment was significantly greater for VR than for PC, $t(113) = 9.16$, $p < .001$, $d = .86$ (Figure 4B), as in Experiment 1A. Ease of use was also significantly greater for VR than PC, $t(113) = 2.39$, $p = .02$, $d = .22$, which was not significant in Experiment 1A (likely due to the smaller sample size in Experiment 1A).

In summary, Experiment 1B showed that with greater statistical power, there was no difference between VR and PC viewing on achieving content-based learning outcomes (learning occurred on both devices). However, increasing power may be responsible for the finding that participants rated VR as significantly easier to use than PC, which was only marginal in Experiment 1A.

Experiment 2

Experiment 1 showed no differences between PC and VR devices for content learning. However, it is possible that a difference could still exist and our paper test measure was not sufficient to detect it. Although paper assessments (2D drawing) may be the norm in the classroom, they may be limited in their ability to assess students' mental representations of 3D structures. Moreover, paper assessments were better aligned with 2D viewing on the PC than 3D viewing in VR. Thus, in Experiment 2, we examined whether testing under 3D viewing would reveal differences in learning from VR versus PC devices. By comparing these results to Experiment 1, we could test for effects of alignment between learning and testing method (similar to Wainman et al., 2018).

The most straightforward way to implement testing in 3D viewing would have been to test in the same VR device used for learning. However, in Experiment 1, testing was implemented using a different format (paper/pens) from the two devices used for learning (VR and PC), so we also wanted to use a different format for testing in Experiment 2. Thus, we used a Looking Glass 3D autostereoscopic display, which allowed 3D viewing without glasses via parallax barriers and multiple layers of displays. Participants interacted with the Looking Glass using a Leap Motion hand-tracking controller, enabling them to complete analogous tests as in Experiment 1 but using their hands to draw/label in 3D.

Method

Participants

Forty-eight undergraduates (29 female, 18 male, one no report; *M* age = 19.17) participated for extra credit in Introductory Psychology at University of Wisconsin–Madison.[4] All had typical color and stereo vision. Additional participants were excluded due to experimenter error (four participants), not finishing in the allotted time (one participant, reported eye strain), atypical color vision (two participants), or atypical stereo vision (one participant).

Design, Displays, and Procedure

The design, displays, and procedure were the same as in Experiment 1, except we replaced the paper drawing/labeling tests with analogous tests using a 15.6-in. Looking Glass autostereoscopic display system (Dodgson, 2005), see Figure 3C. The overall display resolution was 3,840 × 2,160 pixels, with 45 separate views rendered at 768 × 240 pixels/view. Participants interacted with the Looking Glass using a Leap Motion hand-tracking controller and a 28-in. touch screen PC (A Dell XPS 27–7760 All-in-One Desktop). Due to the novelty of the Looking Glass and the need to train participants on how to use it, the experiment typically lasted 15–30 min longer than Experiment 1 (approximately 1.5 hr).

The Looking Glass displayed the 3D model of the virtual brain from the lessons, except that it was resized to fit on the display. It featured different subsections of the brain, providing views similar to the outlines on the paper drawing/labeling tests (see Figures C8 and C9 in the online supplemental materials for images of the touch screen and corresponding views on the Looking Glass for each test question).

The touch screen contained four main sections: the questions (top), response buttons (right), a screenshot of the previously completed questions (left), and controls for changing the viewpoint of the display (middle). The questions were the same as the paper tests, except we replaced the use of pens with the response buttons (i.e., color swatches, labels). The questions were presented one at a time, with different response buttons activated to match the question (i.e., structure labels would replace the color swatches for labeling questions). Screenshots of completed questions appeared on the left of the touch screen, allowing participants to view their previous answers. Each test had four tasks analogous to the paper test: filling in structures, labeling structures, drawing pathways, and painting on structures (see online supplemental materials for details). For each task, participants used one hand to make selections on the touch screen and the other hand to complete the drawing task. The Leap Motion tracked their drawing hand and replicated its motion using a 3D hand model in the Looking Glass. Because the Looking Glass tasks were novel, participants received training on how to do the tasks prior to completing the first pretest. They learned how to fill, draw, paint, and label parts of a 3D model house. Additional details on this training, including instructions (Figures C6 and C7) and example displays (Figure C10), can be found in the online supplemental materials.

Results and Discussion

Content Questions

Pre- and posttests were automatically scored, except for items requiring painting portions of the system (i.e., painting the halves of V1 to represent where the upper/lower visual field maps onto V1; four questions in the visual system and seven for the auditory system) and one question addressing fiber crossovers in the visual system. These questions were scored by the same two raters from Experiment 1 for all 192 tests (48 participants × 2 tests × 2 experiences) following a rubric adapted from that of Experiment 1. Interrater reliability was

[4] We planned to collect data for 120 participants to match Experiment 1B, but data collection was suspended due to COVID-19. The pattern of results of this experiment parallel those of Experiment 1, suggesting that the change in testing method does not change the main results, even with the reduced sample size.

high ($r = .98$), and scores were averaged over raters for each participant.

As in Experiment 1, change in performance was significantly positive for both PC, $t(47) = 9.55$, $p < .001$, $d = 1.38$, and VR, $t(47) = 12.08$, $p < .001$, $d = 1.74$, indicating participants learned using both devices (Figure 4A). The t test comparing devices averaged over all other factors again showed no significant difference between devices, $t(47) = -.80$, $p = .428$, $d = .12$. Similarly, the full ANOVA (2 Devices [VR vs. PC; within subjects] × Device Orders [VR first vs. PC first; between subjects] × 2 Perceptual System-Device Pairing [visual-VR/auditory-PC vs. auditory-VR/visual-PC; between subjects]) showed no significant effect of device ($F < 1$). None of the other main effects or interactions were significant: device order, $F(1, 44) = 2.87$, $p = .097$, $\eta_p^2 = .061$; system-device pairing, $F < 1$; Device × System-Device Pairing, $F < 1$; Device × Device Order, $F(1, 44) = 2.46$, $p = .124$, $\eta_p^2 = .053$; System-Device Pairing × Device Order, $F < 1$; three-way interaction, $F < 1$. Examining just the pretest scores again indicates that the visual system scores were significantly greater than the auditory system pretests, $t(47) = 5.77$, $p < .001$, $d = .83$.

We next examined whether testing format (2D drawing on paper in Experiment 1 vs. 3D drawing on the Looking Glass in Experiment 2) resulted in different patterns of performance from PC or VR learning. We used a mixed-design ANOVA with 2 Lesson Devices (PC vs. VR; within subjects) × 2 Testing Devices (paper vs. Looking Glass; between subjects). There were no significant effects of lesson device, $F < 1$, or testing device, $F(1, 226) = 1.30$, $p = .254$, $\eta_p^2 = .006$, and no interaction, $F(1, 226) = 2.86$, $p = .092$, $\eta_p^2 = .013$. Thus, we saw no significant effect of whether the testing format (2D vs. 3D drawing) was aligned with the learning format (2D vs. 3D viewing). However, it is noteworthy that the lack of effects related to testing device suggest participants could demonstrate their knowledge similarly using the novel Looking Glass as with familiar paper/pen testing.

Experience Questionnaire

As in Experiment 1, average enjoyment was significantly greater for VR than PC, $t(28) = 4.08$, $p < .001$, $d = .76$ (Figure 4B). As in Experiment 1B, ease of use was also significantly greater for VR lessons than PC lessons, $t(28) = 3.32$, $p = .002$, $d = .62$.[5]

In summary, Experiment 2 replicated Experiment 1, even though testing was conducted in a different format (i.e., drawing in 3D using stereoscopic depth rather than drawing on paper). Thus, aligning the assessment to 2D versus 3D viewing had no significant effect on performance.

Classroom Implementation

Given that we developed these lessons to assist undergraduate students learning functional neuroanatomy of the brain, we implemented and evaluated our lessons in an undergraduate course, Psychology of Perception (University of Wisconsin–Madison, Spring 2019). Our goals were to (a) gather indirect measures of learning, which reflected students' self-perception of the efficacy of the Virtual Brain lessons for learning the material, and (b) obtain feedback on which aspects of the lessons contributed to their learning and what aspects could be more useful.

With 25 Oculus Go VR headsets, approximately 80 students completed each 5-min lesson within 20 min. The lessons were used at different times in the semester when the material in the Virtual Brain lessons was typically covered. The Virtual Visual System was used in Week 2 of the course, in place of slides typically used to cover that material. Students completed the VR lesson at the start of the class period, and the instructor immediately transitioned to lecturing on new material. The instructor observed that starting a class meeting with VR felt abrupt and that transitioning from the VR lesson to new material felt disjointed. Therefore, we revised our approach for the auditory system, implemented in Week 11. We embedded the VR lesson in a pre-VR lecture and post-VR activity, allowing for gradually released instruction (Bransford et al., 2000): I do it, I do it with you, you do it alone). In the "I do it" phase, the instructor first lectured briefly on the material that would be covered in VR. In the "I do it with you phase," students completed the guided tour in VR. In the "you do it alone phase," students worked in pairs to enact the auditory system: One student "held" an imaginary brain, and the other used their fingers to draw the pathways and point out the structures, which were listed on a slide to

[5] The experience questionnaire data set includes 29/48 participants because several participants did not realize the items were split over two screens and thus did not complete the task, and the experimenters unfortunately did not notice until later.

remind students where to "stop" on their imaginary tour. Next, one pair volunteered to demonstrate their imaginary tour, which transitioned focus back to the front of the classroom and fostered peer learning. Finally, the instructor moved on to new material. This approach also leveraged the pre-training principle for effective multimedia learning, by which people learn more deeply from multimedia lessons when they know the names and characteristics of main concepts before beginning the lesson (Mayer, 2009).

At the end of the semester (Week 14), we conducted a voluntary survey in class to evaluate how the VR lessons contributed to achieving course learning outcomes. Students were informed that this study was separate from their course work and the instructor would not know who participated (a different member of the study team administered the survey).

Method

Students were told participation in the evaluation was voluntary and not part of their course work (n = 53 chose to participate). Participants were given a survey that first asked them to circle "yes" or "no" to indicate if they experienced each of the VR lessons used in class several weeks prior. If participants answered "yes," they were asked to rate how much they thought the VR lesson helped advance their progress on three learning outcomes: (a) Describe the key brain regions involved in processing visual/auditory information and the pathways that connect them (system pathways), (b) Explain how sensory input from the world stimulates the visual/auditory system (sensory input), and (c) Describe how the way information that is processed in the visual/auditory system supports the general purposes of the system (system purpose). Although all three learning outcomes were relevant to the material, one was most specific to the VR lesson (systems pathways). We were interested in whether students' progress ratings on this outcome would be greater than the other outcomes.

Participants responded using a 5-point scale by selecting *no apparent progress*, *slight progress*, *moderate progress*, *substantial progress*, or *exceptional progress* (coded as 1–5). There were also two free-response questions: (a) What aspects of the Virtual Brain activities contributed to your learning? and (b) What would make the Virtual Brain activities more useful for your learning?

Results and Discussion

Two coders independently recorded the ratings and transcribed the free-response answers. Discrepancies were resolved by a third coder. The data can be found at https://github.com/SchlossVRL/UW-Virtual-Brain-Project.

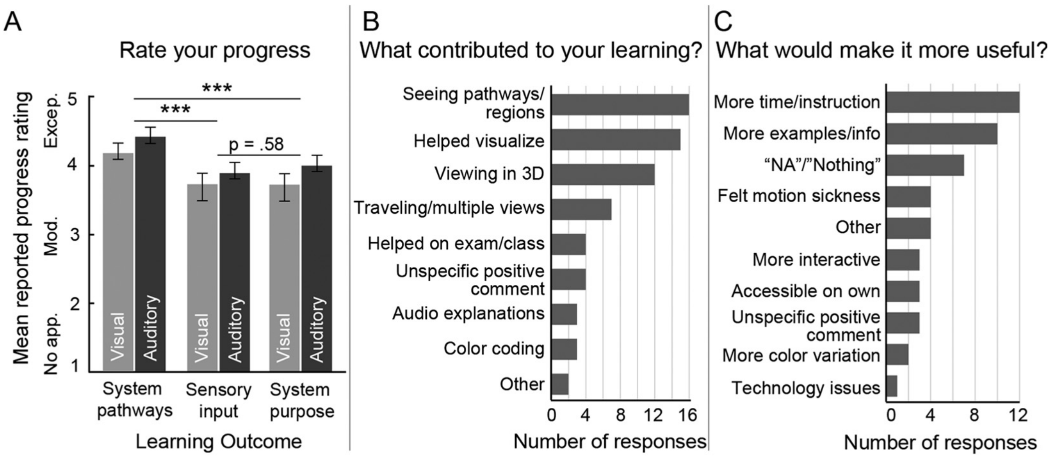
Learning Outcome Ratings

We analyzed data from participants that experienced both lessons (n = 40) so we could directly compare the visual and auditory systems. On average, students reported that VR lessons helped them make moderate to substantial progress on all learning outcomes (Figure 5A). A repeated-measures ANOVA comparing 2 Perceptual Systems (visual vs. auditory) × 3 Learning Outcomes (sensory input vs. system purpose vs. system pathways) revealed main effects of learning outcome, $F(1, 78) = 16.14$, $p < .001$, $\eta_p^2 = .293$, and perceptual system, $F(1, 39) = 10.70$, $p = .002$, $\eta_p^2 = .215$, with no interaction, $F < 1$. The main effect of system indicated students reported more progress from the auditory system lesson than the visual system lesson. This may have been because the auditory lesson was embedded in pre-VR/post-VR activities, using gradual release of instruction (Bransford et al., 2000), whereas the visual system was not. However, given that the auditory system lesson was used later in the semester, we cannot rule out alternative explanations based on timing. By the time students experienced the Virtual Auditory System, they may have developed greater familiarity/comfort with VR and greater general knowledge about perception. Further work is needed to disentangle these possibilities.

We also compared learning outcomes using pairwise t tests (Holm corrected). Ratings were higher for system pathways, the key learning outcome for Virtual Brain lessons, compared with sensory input, $t(78) = 5.05$, $p < .001$, $d = .80$, and system purpose, $t(78) = 4.42$, $p < .001$, $d = .70$. There was no significant difference between sensory input and system purpose, $t(78) = -.57$, $p = .57$, $d = -.09$. Given that the learning outcome factor did not interact with sensory system (reported above), we can conclude that the higher ratings for system pathways carried through both lessons and were not significantly affected by whether the lesson was done earlier or later in the semester.

The results of this assessment are limited in that they are based on indirect student self-reports rather

Figure 5
Student Evaluations of the Virtual Brain Lessons Following the Classroom Implementation



Note. (A) Mean self-report ratings for how the Virtual Visual System (light gray) and Virtual Auditory System (dark gray) affected progress on three learning outcomes, ranging from no apparent progress (no app.) to moderate progress (mod.) to exceptional progress (except.). Error bars represent standard errors of the means. (B) Frequency of free responses sorted into each theme relating to what aspects of the Virtual Brain contributed to learning. (C) Frequency of free responses sorted into each theme relating to what would make the activities more useful for learning. "Other" includes comments not directly related to the Virtual Brain and comments that were unclear. *** $p < .001$.

than external, direct measures of learning gains. It is possible that students' reports could be attributed to the novelty of VR in the classroom rather than the learning per se. However, novelty alone cannot explain the differences seen between perceptual systems and between learning outcomes, especially because the lesson that was rated higher (auditory system) was completed after learners had already experienced VR earlier in the semester and it was therefore less novel.

Free-Response Feedback

To organize the free responses, one coder reviewed the transcribed responses and identified themes for each question based on common repeating or related key words. She and two additional coders then completed a cursory thematic analysis by sorting responses into those themes. In order for a response to be counted for a theme, at least two coders had to be in agreement. Figures 5B and 5C show the frequency of responses across themes for each question. We focus our discussion on themes that emerged among at least one quarter of the responses (the top two themes for each question in Figures 5B–C).

In response to what aspects of the Virtual Brain activities contributed to learning, 50/53 participants responded (two blank, one "NA"). Students (16) reported benefits of seeing the pathways, structures, and their connections. Some elaborated that this helped them visualize the systems later while studying. In another theme, students (15) mentioned that they were visual learners and/or that the lessons helped them visualize the material. In response to what would make the Virtual Brain activities more useful for learning, 37/53 responded (nine blank, seven "NA"/"nothing"). One theme centered on the amount of information with suggestions for more details or examples in and outside the VR lessons (10). Another theme addressed implementation in the classroom, with recommendations for additional time exploring the lessons, more space in the classroom, and greater clarification of the device controls (12).

In summary, student evaluations suggested the Virtual Brain lessons are valuable tools for learning about system pathways in the classroom. Student evaluations also provided useful feedback for improving implementation.

General Discussion

In this study, we developed and evaluated guided tours through 3D narrated diagrams of the human brain. The lessons teach learners about functional anatomy in the visual and auditory systems. These lessons can be experienced on different devices, including a desktop PC or a VR head-mounted display (following guidelines for cross-platform access in Concannon et al., 2019). We tested three hypotheses: (a) participants would learn from lessons presented on both PC and VR devices (pretest vs. posttest scores), (b) VR would be more effective for achieving content-based learning outcomes (i.e., describe key brain regions involved in processing sensory information and the pathways that connect them), and (c) VR would be more effective for achieving experience-based learning outcomes (i.e., enjoyment and ease of use). We assessed content learning using a drawing/labeling task on paper (2D drawing) in Experiment 1 and using a Looking Glass autostereoscopic display (3D drawing) in Experiment 2.

Supporting our first hypothesis, participants showed significant content-based learning for both devices. Against our second hypothesis, we found no significant differences between PC and VR devices for content-based learning outcomes. This result could not be explained by (mis)alignment of teaching and testing methods as results did not differ when testing was done in 2D (Experiment 1) or 3D (Experiment 2). Supporting our third hypothesis, VR far exceeded PC viewing for achieving experience-based learning outcomes in both experiments. Thus, our UW Virtual Brain Project lessons were effective in teaching functional neuroanatomy. Although knowledge about functional neuroanatomy was similarly accessible across devices, VR was more enjoyable and easier to use. In designing our lessons, we also aimed to prevent motion sickness. Responses to the SSQ for all experiments suggest these efforts were effective as mean responses were between *none* and *slight* for all symptoms and were never reported as *severe*.

To consider why we found no difference between devices for content learning, we return to our discussion of prior work in the introduction. Prior evidence suggests that active exploration and stereopsis improve content-based learning outcomes. Yet research investigating students' abilities to learn laboratory procedures in narrated lessons reported no differences or worse performance under 3D VR viewing (Makransky et al., 2019, 2020). They attributed worse performance to distractions from immersion in VR. In our study, it is possible that distractions from increased immersion within the narrated lesson cancels the benefits of VR for learning 3D structures. It is also possible that VR lessons could have disproportionately benefited students with lower visual-spatial ability (Bogomolova et al., 2020; Cui et al., 2017). However, because we did not collect measures of visual-spatial ability, we cannot test that possibility with the present data.

The result that VR and PC viewing are comparable for achieving content-based outcomes may be a positive outcome. It means that learners can have similar access to learning about functional neuroanatomy through multiple platforms. Thus, our Virtual Brain lessons can accommodate learners who do not have VR headsets or who would have difficulty with VR due to factors like motion sickness or lack of stereoscopic depth perception.

In this study, we also conducted a classroom implementation, which incorporated the Virtual Visual System and Virtual Auditory System lessons within a 75-min lecture of an undergraduate course, Psychology of Perception. At the end of the semester, we gathered indirect measures on learning. These measures reflected students' self-report on the efficacy of the Virtual Brain lessons. The measures also provided feedback on which aspects of the lessons contributed to learning and which aspects could be improved. Of the three learning outcomes we evaluated, students' ratings indicated that the lessons were most effective for making progress on the outcome we prioritized while designing the lessons: learning system pathways. In free responses, students reported that the lessons were most helpful for seeing the pathways and regions and for visualizing the material. Students indicated the lessons could be improved by including more examples and more time in VR to explore the lessons. Both of these aspects would be especially beneficial to students with relatively low visual-spatial ability.

With the rise of portable VR headsets and enthusiasm for integrating technology into classrooms, it is important to consider the potential roles of VR in education. In our view, VR provides a lens, similar to a microscope or telescope, for transporting learners to environments they could not otherwise inhabit. But, just as students do not spend entire classes with a microscope attached to their face, they should not spend an entire class in a VR headset isolated from real-world interactions with their peers and instructor. Some display systems, such as CAVEs, can reduce the isolating aspects of HMDs by allowing multiple simultaneous viewers of the content (Cruz-Neira et al., 1993), but these display systems are also less portable. A possible best-case scenario would adopt a multiuser, networked virtual environment where content is viewed collaboratively via multiple HMDs, such as in Fischer et al. (2020). Still, we believe VR should supplement and support conventional classroom teaching techniques, rather than replace them (Mantovani et al., 2003; Markowitz et al., 2018).

Our results suggest students are enthusiastic about learning in VR, as supported by the high ratings for VR on the individual items of the experience questionnaire, including wanting to use these kinds of experiences for future studies and recommending these experiences to friends for learning or for fun. Although we did not assess long-term outcomes, these positive experiences in VR have the potential to spark interest and lead to greater future engagement with the material (Hidi & Renninger, 2006). However, it is also possible that greater situational interest may not lead to greater learning in the future (Renninger & Hidi, 2015). To maintain enthusiasm for VR in the classroom, one challenge will be avoiding "technological obsolescence" that can arise from using the same VR lessons while failing to keep pace with rapid advances in VR technology (Vergara et al., 2020).

The UW Virtual Brain Project is an ongoing effort to create interactive diagrams for teaching sensation and perception. We are developing lessons for additional perceptual systems with greater learner interactivity (i.e., learners activating signals that propagate through the systems) and incorporating text caption options to increase accessibility. Our lessons are freely available online for educational use, and we post new lessons as they become available: https://github.com/SchlossVRL/UW-Virtual-Brain-Project.

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