The UW Virtual Brain Project: An immersive approach to teaching functional neuroanatomy (Supplemental Material)

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This Supplemental Material file includes the following content:

Appendix A

Creating the virtual environments

We created the UW Virtual Brain 3D diagrams using a processing pipeline that converts raw volumetric magnetic resonance imaging (MRI) data into a 3D surface format and then into a Unity game engine format (Figure A1).

Our target audience and learning outcomes are distinct from prior work on VR brain models, which primarily focused on surgical training (Bernardo, 2017; Larsen, Haase, Østergaard, et al., 2001; Sanz Leon et al., 2013). However, we build on prior approaches for constructing VR models out of MRI data. Early approaches to reconstructing and rendering 3D brain data adopted direct volumetric rendering of aligned MRI image stacks (Lawonn, Smit, Bühler, & Preim, 2018) used in neuroanatomy lectures (Kockro et al., 2015). Recent approaches employ game engine technology such as Unity or Unreal, which are free for non-commercial purposes, and contain editing environments for creating content and compiling applications for multiple forms of hardware (e.g., desktop, mobile VR HMDs). Game engine technologies rely on polygonal mesh formats as the primary rendering primitive rather than volumetric image data. For this reason, more recent work has adopted pipelines that convert brain MRI data to mesh formats (Ekstrand et al., 2018; Stepan et al., 2017). Although Stepan et al. (2017) supports the Oculus Rift VR HMD, it relies on PrecisionVR's Surgical Theater, proprietary software aimed at medical professionals. Ekstrand et al. (2018) use Unity for their VR environment creation, but focused solely on anatomical structures.

MRI data

We acquired MRI data at the Waisman Center in Madison, WI using a GE Discovery Medical 3T MRI scanner equipped with a 32-channel head coil (GE Healthcare, Inc., Chicago, IL, USA). First, we acquired a whole-brain structural T1-weighted scan (2.93 ms TE; 6.70 ms TR; 1 mm^3 isotropic voxels). This anatomical scan was followed by a

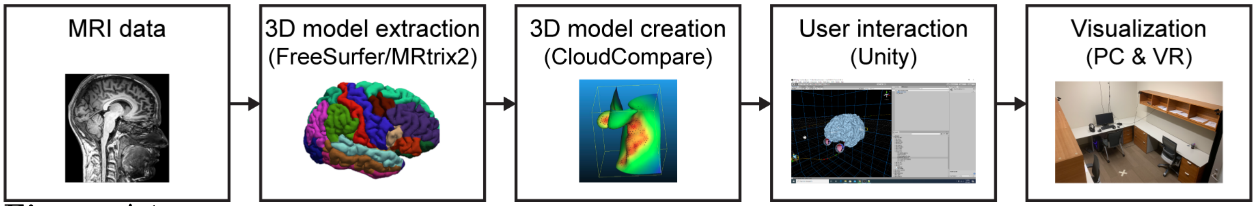

Figure A1

Pipeline for creating the UW Virtual Brain lessons, beginning with an MRI scan and ending with lessons that can be used on PC desktops or in VR.

diffusion-weighted sequence consisting of two opposite phase-encoded 48-direction scans (anterior-posterior [AP] and posterior-anterior [PA] phase-encoding; 6 b0 images per scan; 76.7 ms TE; 8.1 s TR; 2x2x2 mm^3 isotropic voxels; b=2000 s/mm2; reconstruction matrix FOV: LR 212 mm x AP 212 mm x FH 144 mm).

3D model extraction

We began by estimating mesh geometry from a whole-brain structural T1-weighted scan. We imported the anatomical scan into FreeSurfer, an open source software suite for processing and analyzing brain imaging data (Fischl, 2012). Using the input T1 volume, FreeSurfer generates surface-based reconstructions of the brain and identifies and labels various brain structures and regions of interest (ROIs).

3D model creation

In creating the 3D diagrams, we extracted 3D mesh geometry from the source MRI images similar to approaches in (Zhao, 2014). Using CloudCompare, an open-source software for processing point cloud datasets (Girardeau Montaut, 2015), a Poisson surface reconstruction algorithm was used to generate a 3D surface from FreeSurfer's pial surface estimate (Kazhdan, Bolitho, & Hoppe, 2006). This resulted in a polygonal 3D model representing the entire brain surface (excluding the cerebellum). For the visual and auditory systems, we identified ROIs using either FreeSurfer's default parcellations or

Glasser's HCP-MMP1.0 atlas (Glasser et al., 2016). We extracted individual brain regions by segmenting the FreeSurfer or Glasser atlas point data by region, and constructing 3D surface models from the individual regions. Regions were further edited for appearance using mesh smoothing algorithms and additional hand adjustments in Blender ("Blender - a 3D modelling and rendering package," 2020).

White matter pathway creation

We used a combination of probabilistic tractography and manual approaches to create visual and auditory white matter pathway models. Large white matter projections were identified probabilistically using the MRtrix2 package (Basser & Jones, 2002; Behrens et al., 2003; Calamante, Tournier, Jackson, & Connelly, 2010; Conturo et al., 1999; Mori & Van Zijl, 2002; Parker, Haroon, & Wheeler-Kingshott, 2003; Tournier, Calamante, & Connelly, 2007, 2012; Tournier, Calamante, Gadian, & Connelly, 2004). Our diffusion-MRI pre-processing and tractography pipelines have been described previously elsewhere (Allen, Schmitt, Kushner, & Rokers, 2018; Allen, Spiegel, Thompson, Pestilli, & Rokers, 2015; Miller, Liu, Krivochenitser, & Rokers, 2019). We probabilistically identified white matter projections for the optic nerves (optic nerve head to optic chiasm), optic tracts (optic chiasm to lateral geniculate nucleus), optic radiations (lateral geniculate nucleus to V1), and acoustic radiations (medial geniculate nucleus to primary auditory cortex). Spurious fibers were manually removed from each pathway. The cleaned fibers were then smoothed in Blender ("Blender - a 3D modelling and rendering package," 2020) before being imported into Unity where they were aligned to the existing brain model. For several smaller pathways where probabilistic tractography was not feasible, the pathways were manually constructed based on gross anatomy. Those pathways which were manually constructed include the auditory pathways connecting the cochlea and cochlear nucleus (vestibulocochlear nerve; CN VIII), cochlear nucleus and superior olive, superior olive and inferior colliculus, and the inferior colliculus and medial geniculate nucleus. All pathways—including those manually generated or derived from tractography—were rendered as tubes within Unity. The manually drawn pathways were created by stretching and scaling existing pathways until they roughly matched the correct shape. Pathways were also edited slightly in some cases to ensure clear cortical connections at their start and end points.

User interaction

We next imported the 3D region models into Unity ("Unity Real-Time Development Platform," 2020). As the brain surface and brain region models generated from FreeSurfer and CloudCompare were already positioned correctly relative to one another, they could be imported into Unity without requiring any edits to their position or scale. While designing the 3D lessons, we reduced geometric complexity and abstracted elements of the perceptual systems, such as number of fibers depicted, to achieve sufficient frame rates for visually comfortable VR experiences. We carefully considered which elements to reduce or abstract while preserving the overall structure of the perceptual system. For both lessons, the brain is placed floating in the center of a cube shaped room, with blue grid-lines marking the boundaries of the room.

Once the brain region models were in place, the track, stations, and anatomy models were positioned around them. Anatomy models, namely models representing the eyes and ears, were purchased from various 3D asset stores. Using a plugin to view the original MRI volume within the Unity editor, they were scaled and positioned as closely to the eyes and ears in the original MRI scan as possible. We placed information stations at locations where learners would stop to hear the audio narration. We constructed the track manually using three-dimensional splines so that it guides the learners through each information station. We decided to confine motion along a clearly marked yellow track to help viewers anticipate their motion trajectory. Such anticipation can reduce motion sickness symptoms in VR. Learners do not embody an avatar in VR, but a circular yellow platform appears where their feet would be located, with arrows that point forwards along the track. We incorporated the platform after receiving feedback on early prototypes that some learners who were averse to heights felt uncomfortable floating on the track, high above the virtual floor.

The visual properties of the brain are designed to change as the learner experiences the lesson. For example, when learners enter the interior of the brain, the brain surface near the learner fades away so it does not obstruct their view. Certain brain structures also fade as the learner passes through them, as described in the section for each lesson. The text on labels rotates side to side so that it always faces the learner's head position. Some labels also rotate up and down to a certain extent so they remain easy to read. Labels are also visible through other objects, so they are not obscured by the complex geometry inside the brain.

Appendix B

The UW Virtual Brain lessons

In this section we provide the synopsis and script for the *Virtual Visual System* and *Virtual Auditory System*. Each system has six information stations that learners visit as they travel through the virtual brain with audio narration at each station. The numbers 1-6 in the audio scripts refer to each station seen in Figure 1 in the main text. The third script is the narration for the practice experience for both the VR and PC lessons.

Virtual Visual System

Synopsis of the Virtual Visual System.

In the *Virtual Visual System*, learners explore how sensory input, provided by an image on a TV screen, projects onto different parts of the retina and travels along pathways to primary visual cortex (V1). Station 1 is located outside the brain, and the brain is opaque, preventing viewing of the pathways and limiting the number of potentially distracting elements. The narration provides an overview of the functional significance of the visual system and the role it plays in everyday life. As learners move along the track to Station 2, the brain becomes translucent, revealing the pathways and structures inside. Station 2 is located near the sensory stimulus, a TV screen, where the narration describes the nature of the visual input. The spatial arrangement of the visual field is represented by a color coded scene on the TV screen: the left half of the screen is red and the right half is blue, whereas the top half is light and the bottom half is dark. This color coding is maintained on the retinas, within the fibers, and all the way to the end of the pathway, helping learners follow the processing of different parts of the visual field. The track brings learners through the TV screen, in front of the brain, and then in through the left retina, where Station 3 is located. At Station 3, the narration explains that visual information is transduced from the sensory signal into neural signals. Station 4 is located at the optic chiasm. The narration describes the process of crossing over to the opposite (contralateral) side of the brain. The track then crosses the optic chiasm and travels into the right half of the brain, continuing to the lateral geniculate nucleus of the thalamus (LGN). Station 5, near the thalamus, includes narration describing how the signal passes through the LGN and onto the secondary sensory nerve fibers. As learners leave this station, the left (blue) half of the brain structures fade out as they approach the last station. Station 6 ends the track at the right V1 where the red (left) half of the TV image can be seen. The narration describes retinotopic organization and its functional significance. From the final vantage point, the learner can look back and appreciate the full pathway from the TV screen to V1.

The general learning outcome for the lesson is to describe the sensory regions and pathways. This goal includes items such as describing how information crosses from both eyes into separate pathways and listing the key steps/stations of the system. The lesson also briefly touches on outcomes focused on describing sensory input, like identifying the visual field map, and explaining the general purpose of the system.

Script for narration in the Virtual Visual System

Station 1: Start. Welcome to the virtual brain visual pathway demo. In this demo you will fly through the brain stopping at a series of stations. You will learn how a visual scene is projected onto the eyes, and then travels along the visual pathway. Many structures in the visual pathway work together to allow us to perceive the people, objects, and events we encounter on a daily basis. Move along the track. As we approach the brain, the surface will become transparent so we can see the structures and pathways inside.

Station 2: TV over shoulder. Here we are looking at a person's brain, as if we are looking over their shoulder. In front of the brain you can see what that person would be seeing. We have colored the left half of the image on the TV in red, and the right half in blue, so we can show you how different parts of the image travel along different tracts in the brain. Similarly, we shaded the top half of the image lighter, and the bottom half darker.

Station 3: Eyes. Look behind you at the TV and notice how the T V image projects onto each eye. For example, you can see that the red colors project onto the opposite side of each eyeball. Also notice that the image is flipped upside down with the lighter colors from the upper part of the screen projecting onto the bottom of the eyes. This flipping happens because of the way light passes into the eye. Next, we will follow the visual signal into the eyeball. When information reaches the back of the eye, called the “retina”, it is converted to electrical signals. Those signals then travel along the optic nerve and into the brain. The fibres you see are approximations of the real fibres, which are actually bundles containing hundreds of thousands of individual axons. Move along the path to follow the signal along the optic nerve through the right eye.

Station 4: Optic chiasm. Look down and to your right, we have reached a junction known as the Optic Chiasm. Notice that half of the fibers from each eye combine and cross over into only one side of the brain. You can see that the light red and dark red parts of the visual field cross over into the opposite side of the brain. Next, you will follow the fibres of the optic tract. Keep moving yourself along...

Station 5: Thalamus/LGN. The pathway travels through a relay structure called the Lateral Geniculate Nucleus of the thalamus (or LGN). Take a moment to look back at the flow of information from the TV screen, you can see that the colors from the red side of the image project to the opposite side of the eyeball. You can see from the color of the fibers after the optic chiasm, that information from each side of the visual field has crossed over into opposite hemispheres of the brain. Keep following the track, the next destination of the visual pathway is primary visual cortex (or V1).

Station 6: V1. V1, also known as primary visual cortex, contains a complete map of the visual field on the surface of the brain. This is a feature known as “retinotopic” organization. The valley-like structure in front of you, running all the way across the middle of V1 is called the calcarine sulcus, this divides the upper and lower visual field, notice the light red color from the top of the image is seen on the lower bank of V1. From V1 forward higher brain regions enable more complex processing such as catching a ball that is thrown to you, or recognizing a friend's face in a crowd.

Virtual Auditory System

Synopsis of the Virtual Auditory System

In the *Virtual Auditory System*, learners explore how sound waves emitted by audio speakers stimulate and are transduced by the cochlea before traveling along pathways terminating in primary auditory cortex (A1). Station 1 begins with a view outside the opaque brain that features ears and is flanked by speakers on both sides. The narration gives an overview of the functional significance of the auditory system and its role daily life. As learners move along the track to Station 2, the brain becomes translucent. Station 2, located near the speakers, plays narration describing the nature of the input. Graphical depictions of high and low frequency tones appear in the space between the speakers and ears. The sound waves are shown in purple (a mixture of red and blue) to represent information processed by both ears, and are coded as light/dark for high/low frequencies, respectively. The track brings learners through the right ear and into the cochlea. Here, at Station 3, narration explains how sensory information is transduced from sound waves into neural signals. The colors are now mapped based on which side of the brain processes the information: blue on the right, red on the left, until the information is merged, where everything becomes purple again. This color-coding scheme is designed to help the learner track the crossing over and mixing of auditory information from the outside world to opposite sides of the brain. Station 4 is located at the initial nerve pathway from the ear into the brain, near the cochlear nucleus, superior olive, and inferior colliculus. The narration describes the cross-over process to the opposite (contralateral) side of the brain. Station 5 is at the medial geniculate nucleus of the thalamus (MGN). The narration describes how the signal passes through the MGN to secondary sensory nerve fibers. The last station, Station 6 is located at A1. The narration describes tonotopic organization and its functional significance. This region is colored purple to indicate processing of information from both ears, however, the tonotopic arrangement of frequencies in the cochlea is preserved in the lightness gradient projected on the surface of A1. From the final station, the learner can look down to see the entire flow of information from the opposite speaker to the current view of A1.

The learning outcome for the auditory lesson is to describe the sensory regions and pathways. For this lesson, we focus on describing how sounds played independently to the left or right ear combine (i.e. cross-over of information), listing the key steps/stations, and naming the relevant fiber pathways of the system. This lesson also briefly touches on learning outcomes like describing the sensory input and the general purpose of the system.

Script for narration of the Virtual Auditory System

Station 1: Start. Welcome to the virtual brain auditory pathway demo. In this demo you will fly through the brain stopping at a series of stations. You will learn how sounds activate structures in the ears, and then travel along the auditory pathway. Many structures in the auditory pathway work together to allow us to perceive the speech, music, and environmental sounds we encounter on a daily basis. Here we are looking at a person's brain while they listen to sounds coming from speakers. Move along the track. As we approach the brain, the surface will become transparent so we can see the structures and pathways inside.

Station 2: Sounds/speakers. A speaker produces sound through vibrations, which lead to pressure waves in the air. The wave for a guitar chord can be seen next to the speakers. [Complex wave plays]. Everyday sound is a mixture of waves with different frequencies. Complex sounds can be broken down into a combination of simpler waves. [Complex wave splits out into five sinusoids]. At many stages of the auditory system, high and low frequency sounds are processed separately. Look over to the brain... to illustrate this separation of frequencies, dark colored fibres indicate processing low frequency sounds and light colored fibres indicate processing high frequency sounds. Sound from the speakers reaches both ears. Shades of red indicate the signal from one ear and shades of blue indicate the signal from the other ear. Next, we will follow the auditory signal into the ear.

Station 3: Ear/Cochlea. When the signal reaches the spiral structure in the inner ear, called the “cochlea”, it is converted to electrical signals. Different parts of the cochlea respond to different frequencies of sound. Higher frequencies activate the base of the cochlea, shown in light blue, and lower frequencies activate the apex, shown in dark blue. Those signals then travel along the auditory nerve and into the brain stem. The fibers you see are approximations of the real fibers, which are actually bundles containing hundreds of thousands of individual axons. Move along the path to follow the signal into the brain stem.

Station 4: Brainstem structures Look ahead, notice that the signals from each ear partially cross over into the opposite side of the brain. The fibres from the cochlear nucleus remain on the same side. Then the fibres from both cochlea nuclei connect to both superior olives. This comparison of tiny differences in signals from the two ears is used to detect the direction of sounds. The signal arrives at structures called inferior colliculi, by this point, most of the information comes from the opposite ear. The left inferior colliculus responds mostly to signals from the right ear, and vice versa. Next the signal from both ears is combined as indicated by the purple color of the fibres. Light fibers still indicate signals from high frequencies, and dark fibers still indicate signals from low frequencies. Move along the track.

Station 5: MGN/Thalamus. The pathway travels through a relay structure called the Medial Geniculate Nucleus of the thalamus (or MGN). The separated mapping of low and high frequencies is preserved. Keep following the track, the next destination of the auditory pathway, is primary auditory cortex (or A1).

Station 6: A1. A1, also knows and primary auditory cortex continues to maintain the mapping of frequency on the surface of the brain. This is a feature known as tonotopic organization. Notice that light purple color is shown on the front of A1. From A1 forward many of the features of sound important to humans are processed. Higher brain regions enable more complex processing such as the appreciation of music or recognising a friend's voice in a crowded room.

Virtual practice experiences

Script for narration of the VR virtual practice experience

Introduction. Welcome to a visualization of the human Brain. You will have the opportunity to explore the brain and to learn about its structure and function.

Calibration. First, let's make sure you are comfortable with the VR headset.

Look at the two eye charts in front of you. You should be able to clearly distinguish the letters directly above the red line in both the near and far charts. If the image appears blurry, the headset will need adjusting.

You can adjust the position of the headset on your face, and adjust the straps so that it stays in place and is comfortable. You can also adjust the slider on the bottom right of your headset. With your thumb, move the slider back and forth until you feel viewing is most comfortable and the image is clear. Let the experimenter know when you are done.

[The experimenter now makes the brain appear by pressing SPACEBAR]

Start. Let's go over how to use the controller. To move along the track, use the joystick under your thumb. Push it forward to move forwards, and pull it backward to move backwards. You will keep moving as long as you are pushing or pulling the joystick. You can also move your head and body to look around in any direction.

Look straight in front of you, there is the first of a series of information stations. When you arrive at each one, my voice will play to provide information relevant to that station. Please move toward the first station.

Station 1: Outside brain. When you arrive at a station, rails will appear around you while my voice is playing. Once the rails disappear you can continue moving. Please move toward the next station.

Station 2: Outside brain. As you approach the brain, the surface will become transparent so that you can see inside. Follow the track into the brain to activate the next station.

Station 3: Inside brain. Now, take moment to explore the environment. You can practice looking around and moving back and forth along the track. Let the experimenter know when you feel comfortable moving around the space, and we will move on to the lesson plan.

Script for narration of the PC virtual practice experience

Introduction. Welcome to a visualization of the human Brain. You will have the opportunity to explore the brain and to learn about its structure and function.

[The experimenter now makes the brain appear by pressing SPACEBAR]

Start. Let's go over how to use the mouse. To move along the track, use the left and right mouse buttons. Hold down the left mouse button to move forward, and the right mouse button to move backwards. You will keep moving as long as you hold the button down. You can also move the mouse to look around in any direction.

Look straight in front of you, there is the first of a series of information stations. When you arrive at each one, my voice will play to provide information relevant to that station. Please move toward the first station.

Station 1: Outside brain. When you arrive at a station, rails will appear around you while my voice is playing. Once the rails disappear you can continue moving. Please move toward the next station.

Station 2: Outside brain. As you approach the brain, the surface will become transparent so that you can see inside. Follow the track into the brain to activate the next station.

Station 3: Inside brain. Now, take moment to explore the environment. You can practice looking around and moving back and forth along the track. Let the experimenter know when you feel comfortable moving around the space, and we will move on to the lesson plan.

Appendix C

Testing Materials

Paper drawing/labeling test

This section includes the full set of instructions and test materials for the paper tests used in Experiment 1. Figure C1 shows the general instructions, which apply for both the visual and auditory system tests. Figures C2 and C4 are the instructions and questions for the visual and auditory system tests, respectively. Participants respond to these questions by drawing/labeling on Figures C3 and C5 which each feature images of the visual and auditory systems, respectively.

Looking Glass drawing/labeling test

The Looking Glass drawing/labeling tests paralleled those of the paper tests, including the test questions (Figures C1, C2, and C4). In these tests, participants had four main kinds of tasks across the same five questions: filling in structures/regions with solid color, applying labels to structures, drawing pathways between structures, and painting colors onto structures/regions. See Figures C8 and C9 for screenshots of the touchscreen interface and the Looking Glass display for the five questions in the visual and auditory lesson tests, respectively. See Figure C10A for larger example images of the Looking Glass display, including the Leap Motion hand tracking controller.

For filling in structures/regions with solid color, participants selected a swatch of color from the touchscreen with one hand, which would create a sphere of that color on the tip of the index finger of the 3D other hand. Participants would move their hand to align the 3D hand over the desired structure or region they wished to color. When the 3D hand was hovering over the structure, the structure glowed in the color that was selected. Participants could then press the "APPLY" button on the touchscreen, which would apply the color onto the entire structure or selected region. Labeling tasks prompted participants to select a structure label, which would then appear on the 3D hand's index finger.

Participants would apply the label when hovering over the desired line/structure, glowing white to show which structure was selected. To draw pathways, participants first select a color swatch, creating the sphere. Upon applying the sphere to the structure, a 3D line would appear, connecting the selected structured to the 3D hand. Participants move their hand to the desired second structure and press apply, which would drop the end of the line onto the structure, connecting the two. Lastly, for painting questions, rather than applying the color to the entire structure, once participants selected the color swatch, participants could move their index finger across the glowing, paintable structures, creating streaks of paint on that structure.

Participants could also rotate the view of the structures in the Looking Glass, undo previous actions, and restart questions, removing all responses in the current view of the brain.

Looking Glass drawing/labeling training

In Experiment 2, prior to the first pre-test, all participants completed training on how to use the Looking Glass and accompanying touchscreen monitor. Figures C6 and C7 shows the instructions for the Looking Glass training procedure. The entire instructions were read aloud to the participants. Text that appeared on the Touchscreen monitor is colored red. The training used the context of building and decorating a 3D house to teach participants all of the different kinds of interactions (i.e. coloring, labeling, drawing fibers, etc.) that would be needed for testing, as described above. This procedure took approximately 10-15 minutes.

GENERAL INSTRUCTIONS

In this exercise, we will ask you to show where information is processed in the brain.
You will receive further instructions on the next page, but here are some general things to keep in mind.

1. If you make a mistake on any page, please do not cross out or write over any answers. Put an "X" on the top right corner of the page and ask for a new blank page to answer the questions on that page.

2. You will be given 7 colored pens to answer the questions.

Dark red	Light red	Black
Dark blue	Light blue	
Dark purple	Light purple	

For some questions you will be told which colors to use to answer each part of the question.
For other questions you will be asked to "use the appropriate colors", which are consistent with your answer to earlier questions. You can look back at your answers to earlier questions to help select colors for later questions.

Figure C1

General instructions for the paper tests used in Experiment 1.

VISUAL SYSTEM
In this exercise, we will ask you to show where **visual** information is processed in the brain. Do your best to answer the questions, given the knowledge that you have. Even if you feel you are guessing, still provide an answer.

Throughout these questions, please use the colors in the following way:

Reds: information processed from the left visual field
Blues: information processed from the right visual field
Black: Labeling structures

1. **Image 1** is of a person looking at a TV screen. Use the colored pens to color in the dotted lines to indicate the following parts of the visual field on the TV screen:

 1.1 DARK RED pen: bottom left visual field
 1.2 LIGHT RED pen: upper left visual field
 1.3 DARK BLUE pen: bottom right visual field
 1.4 LIGHT BLUE pen: upper right visual field

2. In **image 1,** you see the person's brain and eyes from above and slightly behind. Use the colored pens to color in the dotted quadrants on the eyes to show how the image from each part of the visual field is projected onto the eyes. Be sure to color in <u>both eyes</u>.

 2.1 DARK RED pen: quadrant(s) of the eye(s) where the <u>bottom left visual field</u> projects
 2.2 LIGHT RED pen: quadrant(s) of the eye(s) where the <u>top left visual field</u> projects
 2.3 DARK BLUE pen: quadrant(s) of the eye(s) where the <u>bottom right visual field</u> projects
 2.4 LIGHT BLUE pen: quadrant(s) of the eye(s) where the <u>top right visual field</u> projects

3. In **image 1**, the view of the brain contains structures labeled A through D. Using the BLACK pen, write the names of the following structures on the correct blank line(s) (currently in alphabetical order):
LGN, Optic Chiasm, Retina, V1

4. On **image 1**, draw the following pathways through the brain.

 4.1 Use the appropriate colors to draw the path from the <u>right visual field</u> through all the relevant structures from Structure(s) A to Structure(s) D.

 4.2 Use the appropriate colors to draw the path from the <u>left visual field</u> through all the relevant structures from Structure(s) A to Structure(s) D.

5. On **Image 2**, use the appropriate colors to indicate where the bottom visual field and top visual field project onto the structure marked with an arrow in the RIGHT hemisphere.

Figure C2

Instructions for the visual system paper test used in Experiment 1.

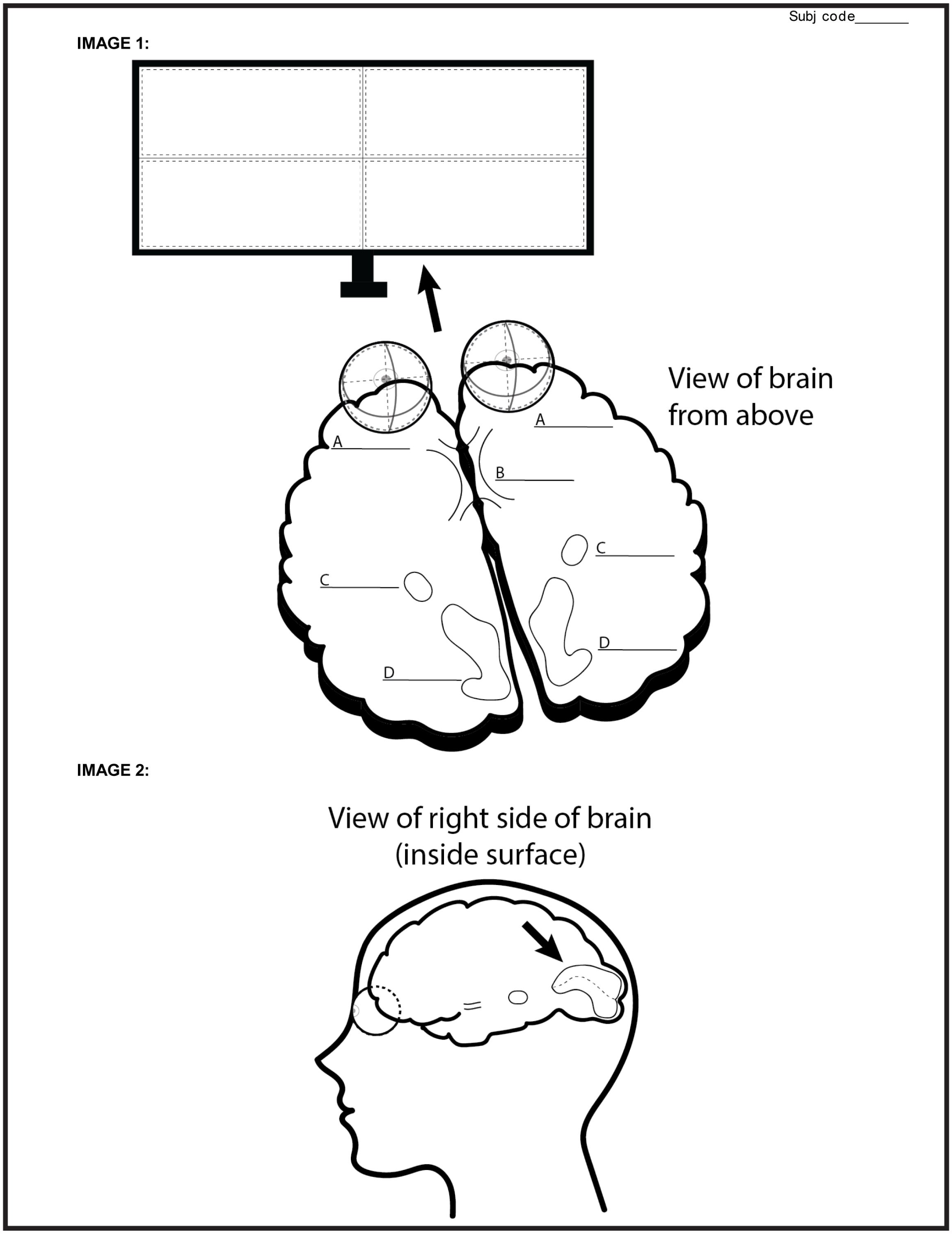

Figure C3

Paper test for the visual system used in Experiment 1.

AUDITORY SYSTEM

In this exercise we will ask you to show where **auditory** information is processed in the brain. Do your best to answer the questions, given the knowledge that you have. Even if you feel you are guessing, still provide an answer.

Throughout these questions, please use the colors in the following way:

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

1. **Image 1** shows the brain and ears from the front. There are speakers on the left and right. Use the appropriate colors to color in sound waves within the dotted lines, traveling from the speakers to the ears:

1.1 Dark pen: low frequency sound waves, left speaker
1.2 Light pen: high frequency sound waves, left speaker
1.3 Dark pen: low frequency sound waves, right speaker
1.4 Light pen: high frequency sound waves, right speaker

2. In **image 1**, you see the inside of the brain. You can see spiral structures on each side. Use the colored pens to color in the dotted parts within each structure that respond to lower frequencies and those that respond to higher frequencies.

2.1 DARK RED pen: right structure, lower frequencies
2.2 LIGHT RED pen: right structure, higher frequencies
2.3 DARK BLUE pen: left structure, lower frequencies
2.4 LIGHT BLUE pen: left structure, higher frequencies

3. In **image 1**, the brain contains structures, labeled A through F. Using the BLACK pen, write the names of each of the following regions on the correct blank line (currently in alphabetical order):

A1, cochlea, cochlear nucleus, inferior colliculus, MGN, superior olive

4. On **image 1**, draw the following pathways through the brain.

4.1 Use the appropriate colors to draw the path of low frequency sounds from each ear through all relevant stations from Station(s) A to Station(s) F.

4.2 Use the appropriate colors to draw the path of high frequency sounds from each ear through all relevant stations from Station(s) A to Station(s) F.

5. On **image 2,** Use the appropriate colors to indicate where the low and high frequencies project onto the structure marked with an arrow in the LEFT hemisphere.

Figure C4

Instructions for the auditory system paper test used in Experiment 1.

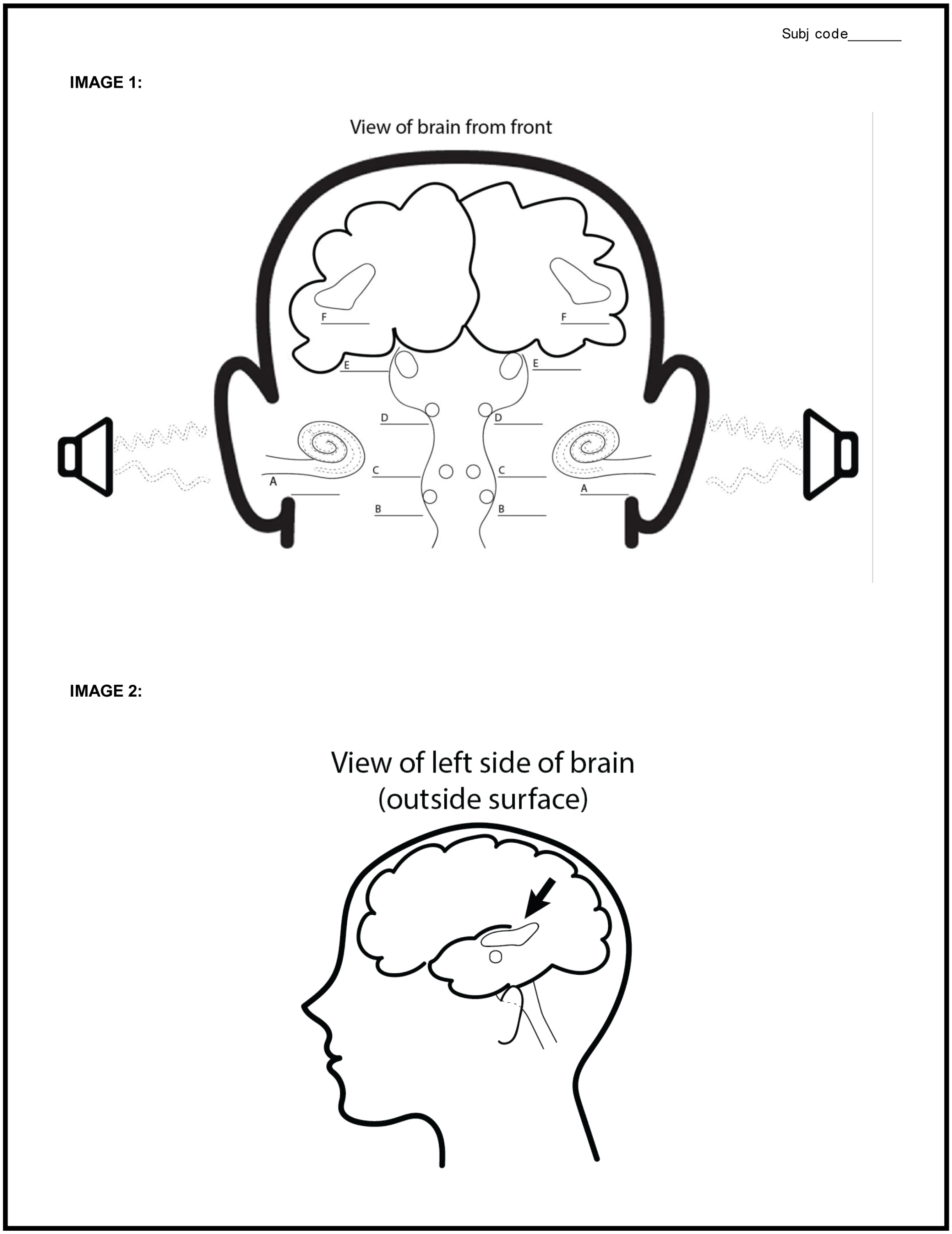

Figure C5

Paper test for the auditory system used in Experiment 1.

Building and decorating a house
A tutorial on using the Looking Glass for the Virtual Brain Experiment

The research assistant will read this entire script to the participant, with a copy of the instructions in front of the participant as well. Text in red will appear on the TouchScreen monitor, indicating a task that must be completed on the LG. Have participants complete that task when instructed.

In this exercise, we will ask you to color, paint, and build parts of a 3D house to help you learn how to navigate the Looking Glass prior to completing the experiment.

The Looking Glass projects a 3D hologram of the house. The motion sensor follows your hand movement, allowing you to interact with the 3D hologram.

On the touchscreen, the location of the text "Color Structures" is where instructions will be displayed for the actual experiment. Information needed to complete each task will be printed on a sheet of paper, so be sure to refer to both as you complete each question.

On the far left of the touchscreen, images of previously completed questions will appear. In the center are the buttons that allow you to interact with the hologram: by rotating the space, coloring, painting, and labeling objects, and drawing fibers. Notice, not all of these buttons I named are currently present, as they will change depending on the current task.

If you make a mistake, press the UNDO button.

Do your best to follow the directions and ask any questions during this practice if anything is unclear.

---- QUESTION 1: COLORING STRUCTURES ----
This is the front of our house. First try waving your **right** hand above the motion sensor in front of the Looking Glass, noticing how the sensor tracks your hand movement.

First, let's color in different parts of the house. With your left hand, touch the DARK GREEN color swatch on the touchscreen monitor and then move your right hand above the motion sensor. Notice the green sphere on your fingertip. Hover your finger above one of the windows until it glows green and then press the APPLY button, coloring the entire window green.
Color all the windows on the front of the house DARK GREEN.

Now, select the DARK ORANGE. The sphere on your fingertip has changed color.
Color the front door DARK ORANGE.

Not all objects can be colored this way, like the walls. Only the objects that glow when you are touching them can be colored.

--ROTATING VIEW --
The side and back of the house also have doors and windows. Use the arrow buttons on the touchscreen to rotate the house in different directions.
Color the side windows LIGHT YELLOW and the side door LIGHT GREEN.
Color the back windows LIGHT YELLOW and the back door LIGHT GREEN.

Recolor the back door LIGHT ORANGE by selecting the color swatch and applying the color to the door, noting that it colors over the previous color.

Figure C6

First page of instructions for the Looking Glass training procedure used in Experiment 2.

Note for these tasks, the instructions do not tell you when to rotate, so keep in mind that you can do this for any task, at any time.

Once you've checked over your work, touch DONE to move to the next task.

------ QUESTION 2: LABELING STRUCTURES ------

Now here are lines next to the different parts of the house. Touch the ***Front door*** label and see that it appears on your fingertip. Move your right hand around and when the structure or the line next to the structure you want to label is glowing, touch APPLY. Notice the label stays on your finger, allowing you to label multiple objects with the same name. Remember, you may need to rotate to get to all of the structures. Place labels on all of the following parts of the house, and touch DONE after they are all labeled.

Front door, Side door, back door, window

------ QUESTION 3: CREATING FIBERS -----

Now we will use FIBERS to connect the four orbs on each corner of the roof to the floating pyramid centered above the house. Build a LIGHT ORANGE roof. To create a fiber, touch on the color swatch you want to use and it will appear on your finger. Then hover above one of the orbs until it glows and touch APPLY. The fiber is now attached to that orb and your finger. Hover over the pyramid and touch APPLY again to drop the end of the fiber and connect the two parts.

Continue using LIGHT ORANGE to connect fibers from each of the four corners to the peak of the roof.

Now use DARK YELLOW to add a second set of fibers from each corner to the peak. Notice that the DARK YELLOW fibers appear next to the previously created LIGHT ORANGE fibers. Touch DONE to move to the last section.

--------- QUESTION 4: PAINTING STRUCTURES ------

Lastly, we will paint the front of the house LIGHT GREEN. To paint, select the desired color, which will again create the sphere on your fingertip. You do not need to press APPLY to paint. Simply move your finger around the surface of the house to paint the wall. The "plus" and "minus" buttons allow you to change the size of the brush.

Note, for some questions you will be told which colors to use. For other questions you will be asked to "use the appropriate colors", which are consistent with your answer to earlier questions. You can look at the images on the left side of the screen to see your previous answers.

Lastly, add the COLOR OF THE SIDE WINDOWS to the front of the house, noting that when you move your finger over previously painted objects, you paint over the previous color.

--------- FINISH ----------

Remember to check your work after each task before clicking the DONE button.

You can return to previous tasks using the BACK button, but will have to re-do all tasks following the one you wish to restart. If you make a mistake within a question, press the UNDO button.

Do you have any questions about how to use the Looking Glass or any of the tasks you just completed?

Figure C7

Second page of instructions for the Looking Glass training procedure used in Experiment 2.

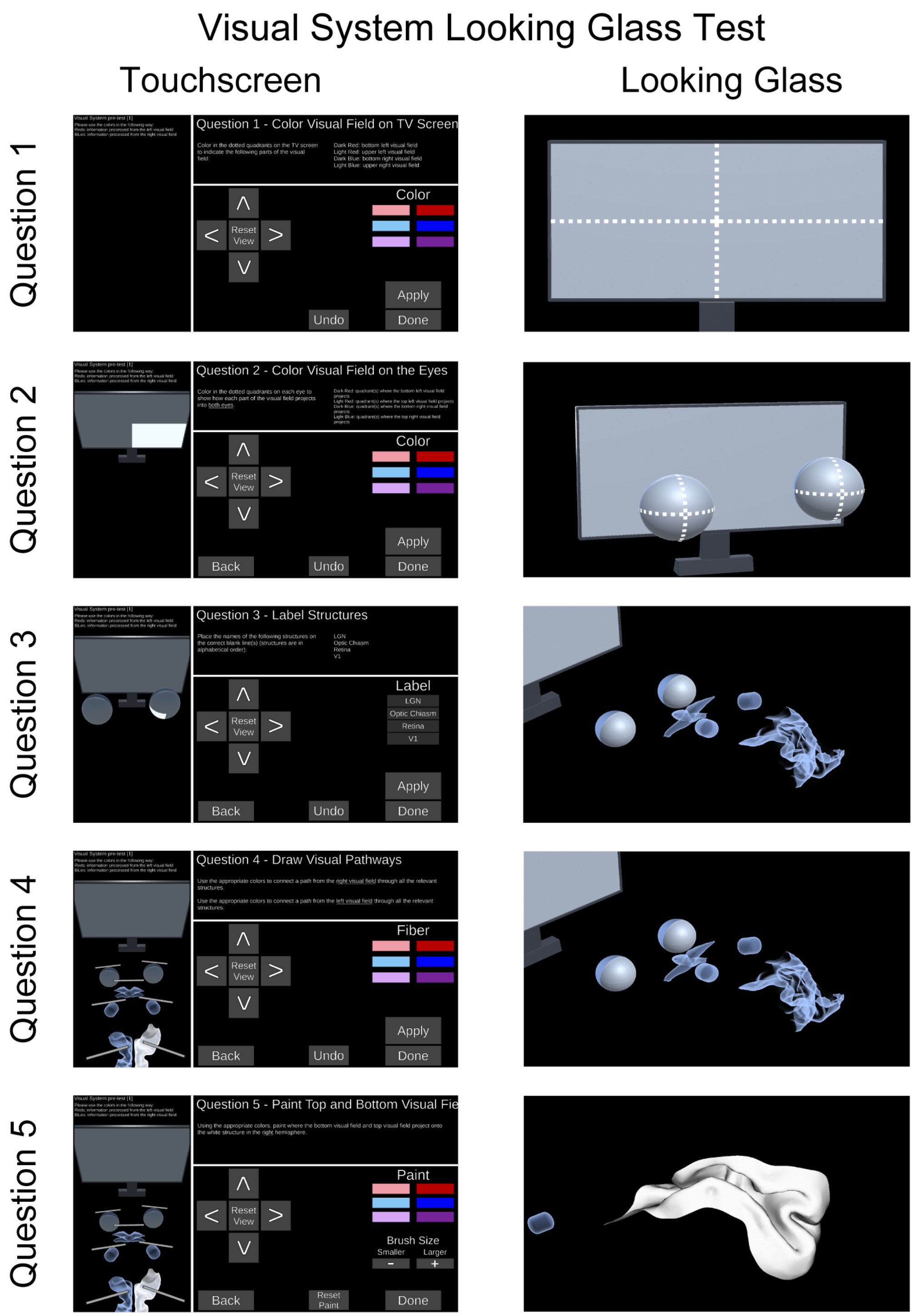

Figure C8

Screenshots of the touchscreen (left) and model views used as input to the Looking Glass (right) for the visual system test in Experiment 2.

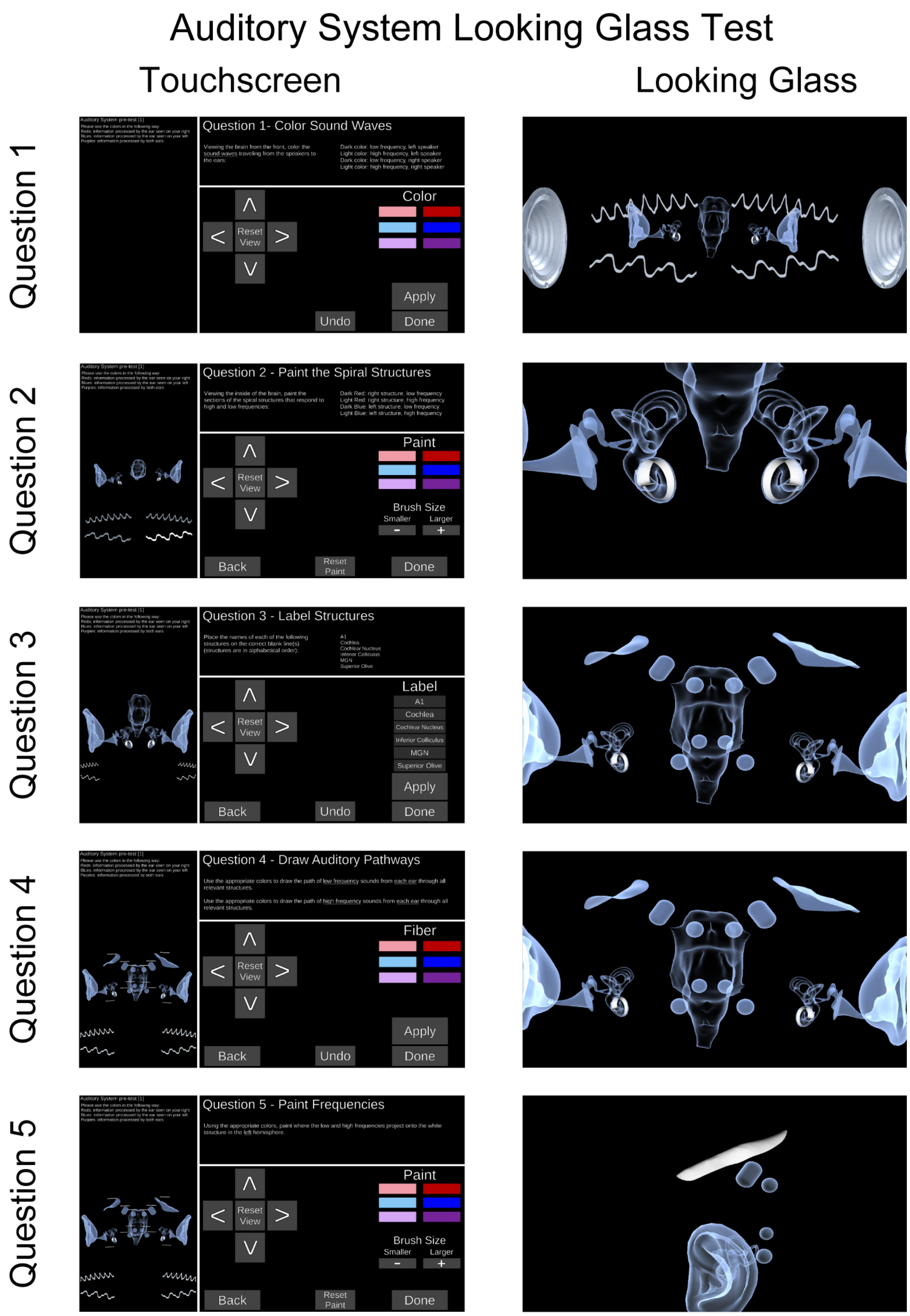

Figure C9

Screenshots of the touchscreen (left) and model views used as input to the Looking Glass (right) for the auditory system test in Experiment 2.

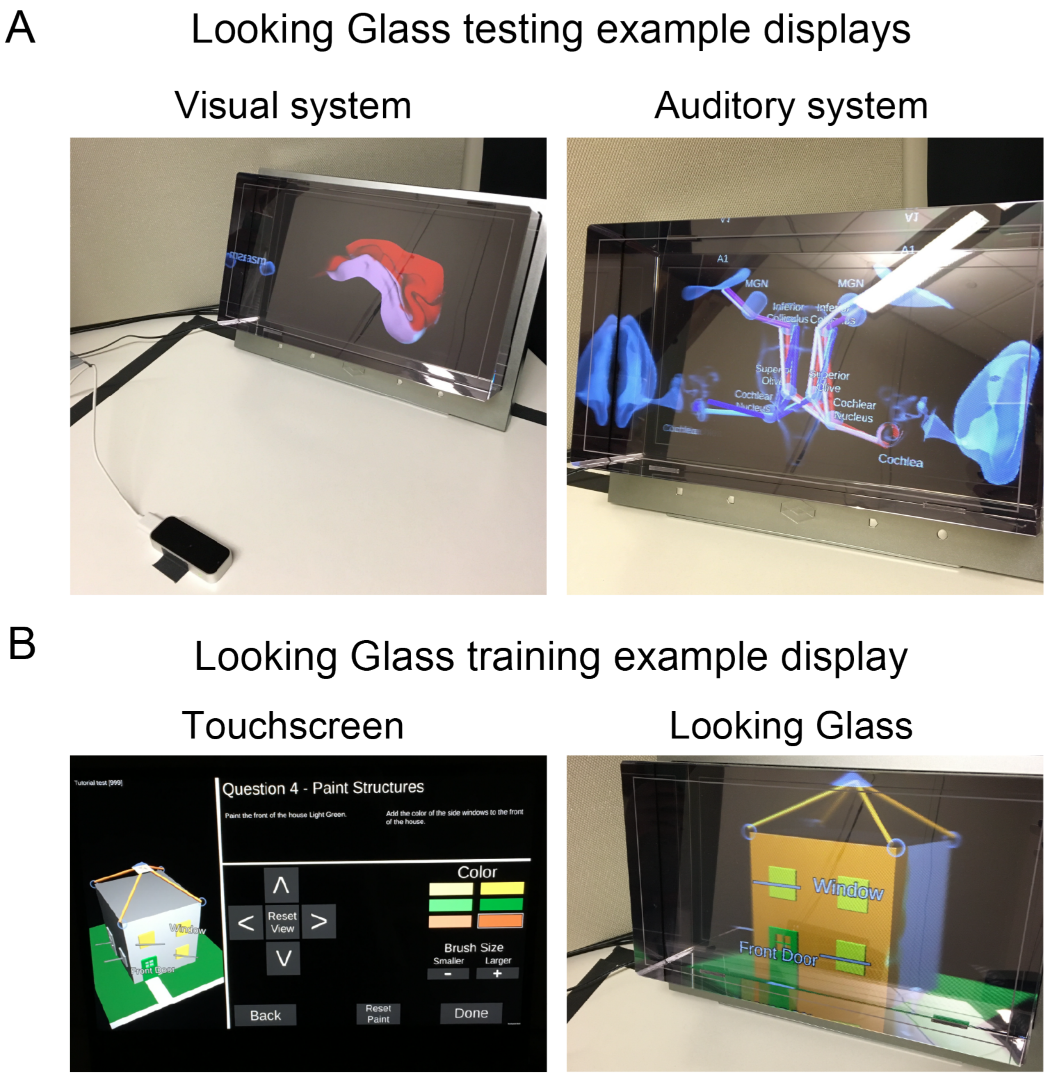

Figure C10

(A) Example Looking Glass displays for the visual system test, in which V1 has been painted, and auditory system test, in which the structures have been labeled and fibers have been drawn. In the lower left of the visual system image, the Leap Motion hand tracking controller is visible. Black tape marked the region the Leap Motion could detect a hand. (B) Example touchscreen and Looking Glass training displays. The 3D house has been painted orange. The doors and windows have been labeled and filled in with green and yellow, respectively and orange fibers connect the four corners to the peak, forming a roof.

Scoring rubrics

The paper and Looking Glass drawing/labeling tests were graded by two coders using an 18-item rubric. Each item was worth one point. Items 1-14 referred to responses to questions 1-4 on image 1. Items 15-18 referred to question 5, on image 2. The rubrics, with additional details on how to score each item, can be found at <Github URL>.

Visual system grading rubric

Items with an asterisk were graded relative to responses to items 1 and 2.

(1) Red on left visual field. Blue on right visual field.

(2) Light on top visual field. Dark on bottom visual field.

(3) Flip left visual field onto right of eye and right onto left*.

(4) Flip top visual field onto bottom and bottom on top*.

(5) Entire field is represented in both eyes (2 hues x 2 lightness).

(6) Left and right structure labels match and are correct (each 1/4 point).

(7) Two hues (pathways) form each eye.

(8) Two lightness levels (pathways) from each eye.

(9) Pathways crossover once and only once.

(10) A crossover occurs at the optic chiasm.

(11) Only one hue per hemisphere at V1.

(12) Two lightness levels per hemisphere at V1.

(13) Hue from left visual field ends on right V1 and hue from right ends on left V1*.

(14) All four stations visited in correct order.

(15) Only used one hue in V1.

(16) Light and Dark both used in V1.

(17) Light and Dark location correct* in V1.

(18) Hue used in V1 is correct* (hue of left visual field).

Auditory system grading rubric

(1) Used purple for frequencies of soundwaves.

(2) High frequency soundwaves are light and low frequency are dark.

(3) Light and dark of SAME hue used within a cochlea.

(4) Light and dark used for inner and outer portions of cochlea.

(5) High frequency is light (outer) and low frequency is dark (inner) in cochlea.

(6) Left and right structure labels match and are correct (each 1/6 point).

(7) Light and dark of SAME hue (pathway) leave matching cochlea.

(8) Cochlear Nucleus to Inferior colliculi is a straight pathway with same hues.

(9) Some hues cross and some go straight at crossover location.

(10) Pathway crossover occurs once and only once.

(11) A crossover occurs between cochlear nuclei and superior olives.

(12) Starting at and everything after inferior colliculus is purple and stays purple.

(13) Light and dark present at A1.

(14) All stations visited in correct order.

(15) Only used one hue in A1.

(16) Light and dark both used in A1.

(17) Light and dark splitting left/right (horizontally) in A1.

(18) Only used purple in A1.

Appendix D

Supplemental data and analyses

Relations between initial test performance and change in performance

Given previous evidence for relations between between initial scores (baseline) and amount of learning in VR (Zinchenko et al., 2020), we correlated pretest performance and change in performance for each device. In Exp. 1A, correlations were negative, but not significant (VR: $r = -.24, p = .06$, PC: $r = -.24, p = .06$). In Exp. 1B, correlations were also negative (VR: $r = -0.065, p = .481$, PC: $r = -.28, p = .002$), but only PC was significant. In Exp. 2 correlations were again negative (VR: $r = -.261, p = .07$; PC: $r = -.257, p = .07$) but not significant. Taken together, these results suggest a weak, and mostly non-significant trend in which learners with poorer performance initially had a slight tendency to benefit more from the lessons.

Results for experience questionnaire items.

As described in the main text, mean ratings for items 1-6 on the experience questionnaire were highly correlated with each other (see Table D1) so we reduced the dimensions using Principle Components Analysis.

	Awe	Aesthetic	Enjoy	OwnStudy	RecLearn	RecFun	EaseUse
1. Awe	1						
2. Aesthetic	.81	1					
3. Enjoy	.84	.83	1				
4. OwnStudy	.72	.70	.80	1			
5. RecLearn	.68	.71	.77	.82	1		
6. RecFun	.82	.71	.77	.72	.69	1	
7. EaseUse	.24	.24	.22	.17	.21	.27	1

Table D1

Correlations of ratings on the 7 items from the Experience questionnaire (Exp. 1A).

Results from Simulator Sickness Questionnaire (SSQ)

Figure D1 shows mean responses to the four simulator sickness symptoms (scored such that “none” = 1, “slight” = 2, “moderate” = 3, “severe = 4). In all experiments, mean responses to all four symptoms fell between none and slight at all time points. No participants ever reported experiencing severe symptoms. This figure omits date from one participant (Exp 1A) who was excluded because two SSQ tests were marked as timepoint 2.

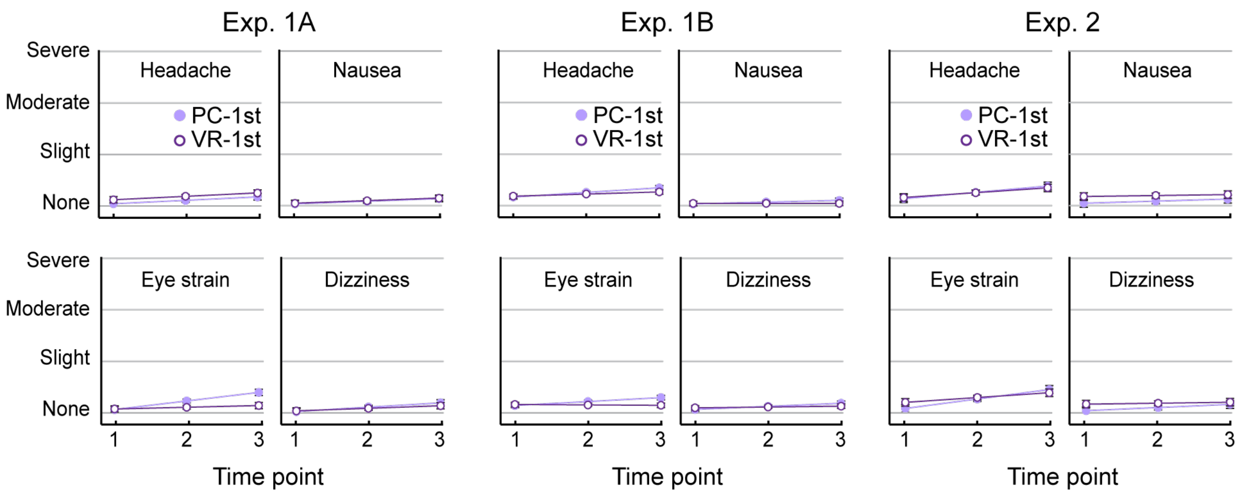

Figure D1

Mean scores on each SSQ symptom for Exp. 1A, Exp. 1B, and Exp. 2 for participants who completed VR-first (dark lines) and PC-first (light lines). Error bars represent SEMs.

Appendix E

*

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