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Immersive and Interactive Virtual Reality Improves Learning and Retention of Neuroanatomy in Medical Students: A Randomized Controlled Study

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Abstract:	Background: Spatial three-dimensional understanding of the brain and its structures is essential to learning neuroanatomy. Studying the anatomy of the brain has been regarded as difficult for medical students (neurophobia) and more efficient and effective methods of study are necessary. Three-dimensional learning techniques have been proposed as tools to enhance neuroanatomy training. In this study we have explored the role of immersive virtual reality (VR) as a novel tool for neuroanatomy learning. Methods: Medical students (N = 64) were randomized into a VR or paper-based study group and studied the spatial relationships between neural structures after performing a neuroanatomy pre-test, with both test and control questions. Immediately following the study period, a post-test was performed. A delayed post-test was administered approximately one week after initial testing. Qualitative measures were also obtained. Results: Both groups performed comparably on the pre-test questions and showed significant performance improvements on the test questions following study. There were no significant differences between groups for the control questions nor for the immediate post-test questions or the delayed retention post-test questions. Interestingly, the VR group showed significantly better retention of the pre-test questions compared to the

	paper-based group, and neurophobia was also decreased. Interpretation: Results from this study provide evidence that training neuroanatomy in an immersive and interactive VR environment leads to knowledge retention that is equivalent, and may even surpass, traditional book learning methods. They also suggest that integration of VR into neuroanatomy training may improve knowledge retention, increase study motivation, and decrease neurophobia.

Immersive and Interactive Virtual Reality Improves Learning and Retention of Neuroanatomy in Medical Students: A Randomized Controlled Study

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Interpretation: Results from this study provide evidence that training neuroanatomy in an immersive and interactive VR environment leads to knowledge retention that is equivalent, and may even surpass, traditional book learning methods. They also suggest that integration of VR into neuroanatomy training may improve knowledge retention, increase study motivation, and decrease neurophobia.

Immersive and Interactive Virtual Reality Improves Learning and Retention of Neuroanatomy in Medical Students: A Randomized Controlled Study

Spatial understanding of neuroanatomy is essential to neurological-based medical and surgical specialties, including neurology, neurosurgery, and psychiatry (1). A comprehensive understanding of neuroanatomy is reliant on thorough knowledge of the intricate relationships between multiple three-dimensional (3D) structures (2). Traditionally, methods of learning neuroanatomy include extended teaching time and supplementation through anatomical dissection and histological slides to examine the spatial 3D relationships between structures (3). Time constraints and a desire for cost effectiveness have prompted medical schools to reduce anatomy and laboratory teaching time with human cadaveric specimens (3-6), the main supplementation material being textbooks and two-dimensional (2D) images (3, 7). These restrictions may influence an individual's ability to translate 2D to 3D spatial relationships, as it requires the student to perform complex cognitive reconstructions (8, 9), potentially impairing neuroanatomical learning.

A previous study showed a dramatic decrease in neuroanatomy recall for graduating medical students (10), and a number of studies have reported that medical graduates' overall anatomic competence did not meet safe practicing level (11-14). One potential factor contributing to this is a phenomenon coined 'neurophobia', a perceived reluctance of medical students to learn or relearn neuroanatomy (15-19). In an effort to diminish neurophobia and improve spatial and 3D neuroanatomy learning, 3D strategies have been proposed (3, 20-22). Several studies have shown that 3D neuroanatomical learning is an effective strategy for increasing neuroanatomical knowledge, motivation, and retention of neuroanatomy material (2, 22-26). Studies have shown that participants improve in their knowledge of spatial relationships

when they were exposed to both physical (11) and virtual (25-27) 3D brain models.

Virtual reality technology (VR) may be a logical next step for enhanced 3D and interactive learning. At present, there are few studies that have investigated the efficacy of immersive VR environments on neuroanatomy training. Kockro et al. (26) found significantly better performance at test for a VR study group compared to a 2D powerpoint group, however, this study did not include a pre-test or retention test. Armstrong and colleagues (28) developed an immersive, interactive VR environment and found that this system was qualitatively effective and user friendly, however they did not quantitatively examine participants' performance. In this study, we sought to explore the efficacy and limitations of immersive and interactive VR on neuroanatomy learning. Furthermore, we aimed to examine neuroanatomical knowledge retention after VR learning.

Methods

Participants

A randomized, controlled design was used to compare VR to traditional paper-based learning. Using an independent sample 2-tailed *t* test (5% significance level), a sample size of 64 participants (32 in each group) was calculated to provide a statistical power of 0.90. A 10% higher score (SD = 12%) on the postintervention quiz for the VR group was the primary end point. Participants consisted solely of 66 first or second year medical students from the University of Saskatchewan who were randomly assigned to either the VR or paper-based group (33 in each group) in blocks of four using an online randomization tool. One participant was excluded from analysis due to a methodological error in administering the tests, and one participant dropped out of the study, resulting in 64 participants in the final analysis (see Tables

1 and 2 for demographic information), 31 in the VR group and 33 in the paper-based group. This study was approved by the Research Ethics Board at the University of Saskatchewan.

Materials

Both the VR and paper-based study materials contained the following labelled brain structures: the caudate, putamen, globus pallidus, thalamus, ventricles, amygdala, hippocampus, lateral corticospinal tract, and spinothalamic tract. For the VR brain, these structures were created from T1-weighted images of a healthy individual's brain using Freesurfer software (http://surfer.nmr.mgh.harvard.edu/) and DSI Studio (http://dsi-studio.labsolver.org) for the white matter tracts, and compiled for the VR environment in Blender (https://www.blender.org). In the VR environment, visualization of the different structures and their labels was controlled by the participant, which allowed them to navigate the VR environment and examine the 3D relationships between the structures (see Appendix A for an example of the VR environment and user interface). HTC Vive™ was used as the VR system and the VR neuroanatomy interface was developed by Sprockety Ventures Inc. The book learning group was provided with a booklet containing 15 colour figures adapted to display labels for the relevant structures to be studied (the same structures as the ones rendered in the VR environment) from various views and orientations from Blumenfeld's 'Neuroanatomy through clinical cases: Second Edition' (29), a commonly used textbook to teach neuroanatomy.

Twenty-three pre- and twenty-three post-test multiple-choice questions designed to assess the participants' ability to visualize the relationships of the structures in 3D were developed. Both the pre- and post-test contained 14 test questions (i.e., related to the study materials) and nine control questions (containing neuroanatomy content not available from the study materials),

resulting in a total of 23 questions. Control questions were included in order to ensure that the two groups did not differ in prior neuroanatomy knowledge.

Procedure

Participants were randomized to the VR or paper group. Both groups were then given 10 minutes to complete the pre-test to assess their baseline knowledge of neuroanatomy. After the pre-test, participants randomized to the VR group were given a tutorial to help them navigate the VR system. The tutorial contained a simple, unlabelled model of a human brain, consisting of an outer shell and two inner shells to simulate the cortex and putamen, respectively, whereby they were instructed on how to turn on and off the brain structures to ensure sufficient proficiency in VR navigation. Following training, participants were presented with the labelled study brain and given 12 minutes to memorize the spatial relationships between the different structures. Participants randomized to the paper-based group were provided with the booklet of adapted figures and were also given 12 minutes of study time.

Following the completion of the intervention, participants were given 10 minutes to complete a post-test to assess immediate information retention. They then filled out a thirty-question questionnaire containing three demographic information questions (age, sex, neuroanatomy experience) and 27 questions assessing satisfaction with either the VR or paper-based interventions. A second questionnaire assessed self-reported study strategies, which asked the participant to check off as many study strategies that they utilize as applicable from: Textbook, Lectures, Drawing, Flashcards, Models, and Youtube. A delayed retention test was administered 5-9 days after the original intervention for both the pre- and post-test questions (46 in total), during which the participants had 20 minutes to respond. Prior to analysis, a researcher blind to participant responses assessed the test questions to ensure that each question could be

answered from the study material. Two questions were identified as problematic because they could not be clearly answered from the study material and were removed, thus resulting in 12 test questions for both the pre- and post-tests.

Analysis

Participant scores for each condition were converted to Percent Error by a researcher who was blind to participant experimental group. IBM SPSS Statistics© version 24 was used to manage, aggregate, and analyze the data.

As this study employed both within- and between-subjects factors, the primary analysis conducted was a 4 (Test; Pre-test, Immediate post-test, Pre-test question Retention, Post-test question Retention) x 2 (Question Type; Test, Control) x 2(Group; VR, paper-based) mixed-measures ANOVA on Percent Error, with Test and Question as within-subject factors, and group as a between-subject factor (Table 3).

Further, two 4 (Test; Pre-test, Post-test, Retention pre-test, Retention post-test) x 2 (Group; VR, Paper-based) mixed-measures ANOVAs were conducted for the Test and Control Questions (Table 4). Independent samples t-tests were used to further examine these effects (Table 5).

To examine within-group differences, two general-linear model repeated-measures one-way ANOVAs were performed for each group and question type (Table 6). Paired-sample t-tests were performed for each group and time point (Table 7).

Results

The demographic characteristics of the participants are described in Tables 1 and 2. The two groups did not significantly differ in age or number of semesters of neuroanatomy based on

independent t-tests (Table 1). Chi-squared tests between groups found no differences in medical school year, gender, previous neuroanatomy experience, or study strategy (Table 2).

	VR	Paper	*t*	*p*
Age (years)	24.3	24.4	-.173	.864
Semesters of Neuroanatomy	18	17	-.779	.439

Table 1. Independent t-tests of demographic information for each group (age and semesters of neuroanatomy).

	VR	Paper	χ^2	*p*
Medical school year ($1^{st}/2^{nd}$)	19/12	22/11	.201	.654
Gender (male/female)	13/18	15/18	.080	.777
Previous neuroanatomy experience (yes/no)	19/12	17/16	.621	.431
Textbook (yes/no)	16/15	20/13	.525	.469
Lectures (yes/no)	22/9	21/12	.390	.532
Drawing (yes/no)	19/12	17/16	.621	.431
Flashcards (yes/no)	11/22	12/19	.201	.654
Models (yes/no)	17/14	16/17	.258	.611
Youtube (yes/no)	15/16	18/15	.243	.622

Table 2. Chi-squared tests of demographic information for each group (gender, previous neuroanatomy experience, and study strategies).

For the primary analysis, we found significant main effects of Test and Question Type. The main effect for Group was not significant, nor the Test x Group and Question Type x Group or Test x Question Type x Group interactions.

	F	dof	*MSE*	Sig. (two-tailed)
Test	18.03	3, 186	246.18	< .001
Question Type	160.03	1, 62	258.88	< .001
Group	2.33	1, 62	568.70	.132
Test x Group	.820	3, 186	246.18	.484
Question Type x Group	.469	1, 62	258.88	.496
Test x Question Type x Group	1.81	3, 186	234.33	.147

Table 3. Results of omnibus ANOVA.

The results for the mixed-model ANOVAs as a function of question type are as follows. For the Test Questions, we found significant main effects of Test and Group. The Test x Group

interaction was not significant. Independent samples t-tests found no significant difference between groups for Pre-test questions, immediate Post-test questions, or retention post-test questions (Table 5). The difference between groups with retention pre-test questions was significant (see Figure 1 for means and 95% confidence intervals, Loftus & Masson (30)).

		F	**dof**	***MSE***	**Sig. (two-tailed)**
Test Questions	Test	37.35	3, 186	201.48	<.001
	Group	4.58	1, 62	245.56	.036
	Test x Group	1.99	3, 186	201.48	.117
Control Questions	Test	.412	3, 186	279.03	.744
	Group	.554	1, 62	582.02	.460
	Test x Group	.809	3, 186	279.03	.490

Table 4. Results of the mixed-measure ANOVAs as a function of question type.

	Independent samples t-test	***t***	**dof**	**Sig. (two-tailed)**
Test Questions	Pre-test	.344	62	.732
	Post-test	.378	62	.707
	Retention Pre-test	3.20	62	.002
	Retention Post-test	.703	62	.484
Control Questions	Pre-test	1.824	62	.073
	Post-test	-.272	62	.786
	Retention Pre-test	.036	62	.971
	Retention Post-test	.606	62	.547

Table 5. Results of independent samples t-tests as a function of question type for the VR group.

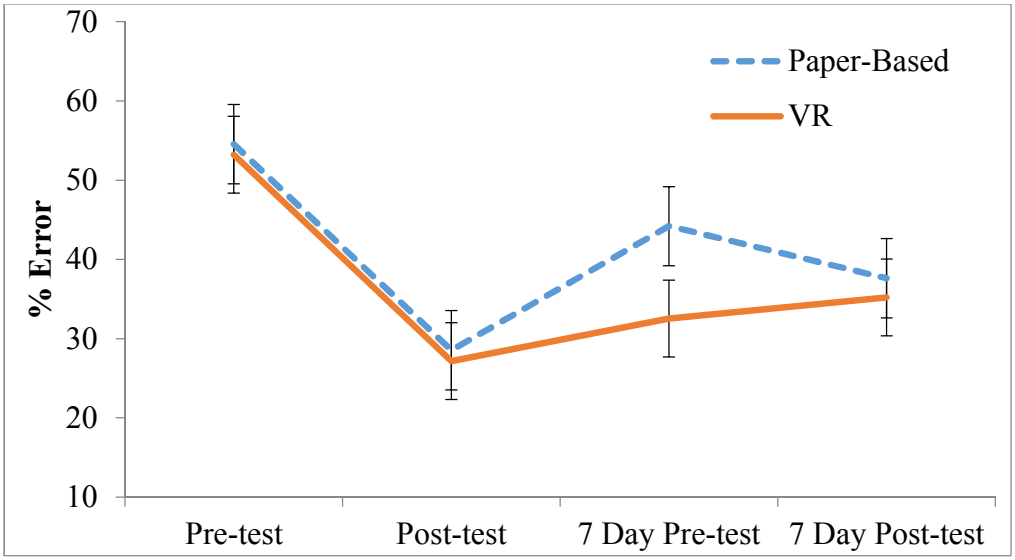

Figure 1. Test question percent error for the paper-based and VR groups at each testing point.

For the Control questions, there were no significant main effects of Test or Group, suggesting that participants performed equally well (Table 4), The Test x Group interaction was not significant. Independent samples t-tests found no significant differences between groups for any condition (Table 5, Figure 2).

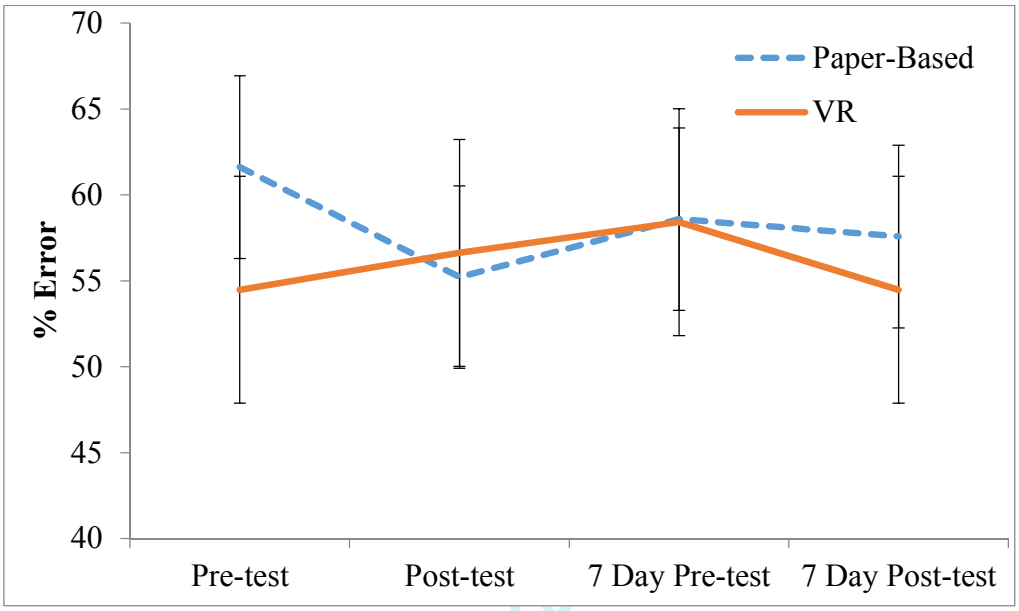

Figure 2. Control question percent error for the paper-based and VR groups at each testing point.

The results of the repeated-measures ANOVAs for each group are as follows. Test questions: for both the paper-based and VR groups, results indicated a main effect of Test. For the paper-based and VR groups, there was a significant difference between the pre-test and post-test scores, the pre-test and retention pre-test scores, and the post-test and the retention post-test scores (Table 7). The retention pre-test and the retention post-test scores approached significance for the paper-based group but not the VR group. Control questions: there was no significant main effect of Test for the paper-based group or the VR group, thus no further post-hoc analyses were conducted.

Group	**Question Type**	***F***	**dof**	***MSE***	**Sig. (two-tailed)**
Paper-based	Test Questions	18.19	3, 96	217.79	<.001
	Control Questions	1.05	3, 96	221.02	.374

VR	Test Questions	21.53	3, 90	184.08	<.001
	Control Questions	.330	3, 90	340.90	.804

Table 6. Repeated measures ANOVAs for each group for each question type.

Test Questions	**Group**	***t***	**dof**	**Sig. (two-tailed)**
Pre- vs. Post-test	Paper-based	6.75	32	<.001
	VR	7.16	30	<.001
Pre- vs. Retention Pre-test	Paper-based	2.42	32	.021
	VR	6.76	30	<.001
Pre- vs. Retention Post-test	Paper-based	4.85	32	<.001
	VR	4.17	30	.001
Post- vs. Retention Pre-test	Paper-based	-3.73	32	.001
	VR	-1.62	30	.115
Post- vs. Retention Post-test	Paper-based	-4.05	32	<.001
	VR	-2.71	30	.011
Retention Pre- vs. Retention Post-test	Paper-based	1.96	32	.059
	VR	-.847	30	.403

Table 7. Paired samples t-tests for the Test questions for each group.

Qualitative results

When asked to rate on a scale of 1-5 (1 = strongly disagree, 5 = strongly agree) the statement 'This method should be used in the curriculum', 97% of participants in the VR group either strongly agreed or agreed and the VR group showed significantly higher agreement than the paper-based group, $t(62) = 8.32$, $p < .001$. When asked to rate 'I feel less afraid with the complexity of neuroanatomy', 84% of the participants in the VR group either strongly agreed or agreed; whereas, only 12% of the participants in the paper-based group agreed, $t(62) = 6.73$, $p < .001$, suggesting decreased neurophobia following VR learning.

Discussion

Our results provide evidence that learning neuroanatomy in an immersive and interactive VR environment leads to knowledge retention that is equivalent, and may even surpass, traditional book learning methods. In contrast to the control questions, whereby no significant

differences were found between the tests or the groups, both groups showed significant improvement in scores from pre- to post-test which persisted at the retention test, regardless of question type, thus providing evidence that both methods were successful learning techniques. As a main effect of group was found for the test questions, whereby the VR group had significantly greater accuracy than the paper-based group, it suggests that VR may be a superior learning tool for understanding the complex spatial relationships between different structures of the brain. Although both groups were not shown to significantly differ in accuracy on the post-test, participants in the VR group had significantly greater accuracy than the paper-based group in the retention pre-test questions, suggesting that they retained knowledge that they had not specifically been tested on following exposure to the VR environment. This is an interesting finding, as the paper-based group appeared to have stronger maintenance of knowledge for the questions that they were tested on after study than the questions they were tested on prior to study, suggesting that paper-based group did not generalize as well to the unpracticed questions. In contrast, the VR group showed maintenance of knowledge for both the pre- and post-test questions, suggesting that they were able to retain more neuroanatomy knowledge after exposure to the VR environment.

These findings are relevant when evaluating immersive and interactive 3D VR as a learning tool since the primary goal of neuroanatomy learning is to obtain and maintain knowledge that is essential to subspecialty practice (1). Based on both the quantitative and qualitative results of this study, there is evidence that VR technology can provide an efficient and effective supplemental learning tool for neuroanatomy by decreasing neurophobia and increasing knowledge retention. Our results are in concordance with studies using virtual 3D models (25-27), and suggest that learning the complex, 3D relationships between neural structures is

facilitated by training in a 3D VR environment that may also increase retention. Our findings also corroborate those of Armstrong and colleagues (28) showing qualitative benefits of immersive and interactive VR compared to other methods, and extends them into the quantitative domain.

While we sought to investigate knowledge retention, a limitation of this study is that it was relatively short term and employed a limited number of questions. Future research should examine retention outcomes from VR neuroanatomy training over a longer time-course with a greater amount of to-be-learned information to provide further evidence of its efficacy and recall sustainability. Further, there is an inherent learning curve when learning a new technology and the relatively short period of training and study time on the VR system may have decreased study time compared to the paper-based group, even with the training module. Our results are currently only generalizable to a particular population and future studies should examine other student populations, including neurology and neurosurgery trainees. Future VR studies could incorporate pathological processes such as brain tumors or aneurysms where VR may be used for better understanding the structural effects of tumors in displacing brain structures or white matter pathways, and the orientation of aneurysms and other vascular lesions to facilitate surgical planning. It is also important to expand the number of structures, and integrate training of functional relationships between structures into the VR environment, to examine whether training benefits of VR extend beyond understanding 3D relationships of structures but also to functional aspects of complex neural pathways (e.g., direct and indirect pathways of the basal ganglia), that are difficult to visualize using 2D methods (31). Incorporating disruptive processes on brain anatomy such as mass lesions or ischemic patterns may further define the benefits or limitations of immersive VR in learning and retention.

Conclusions

The results of this study suggest that integration of immersive and interactive VR into neuroanatomy training may help to improve knowledge attainment and retention, increase study motivation, and decrease neurophobia. As the technology of immersive VR technology evolves and becomes more cost-effective, the feasibility of integrating this technology into medical curricula could be vastly improved. The potential applications and benefits of this technology may extend beyond undergraduate medical education into more specialized neurological based fields, such as neurosurgery, making learners more prepared to navigate the complexities of the human brain in clinical practice. Virtual Reality technology is in its infancy when related to its potential applications as a tool to facilitate medical education and clinical practice and this potential and limitations deserves further evaluation and study.

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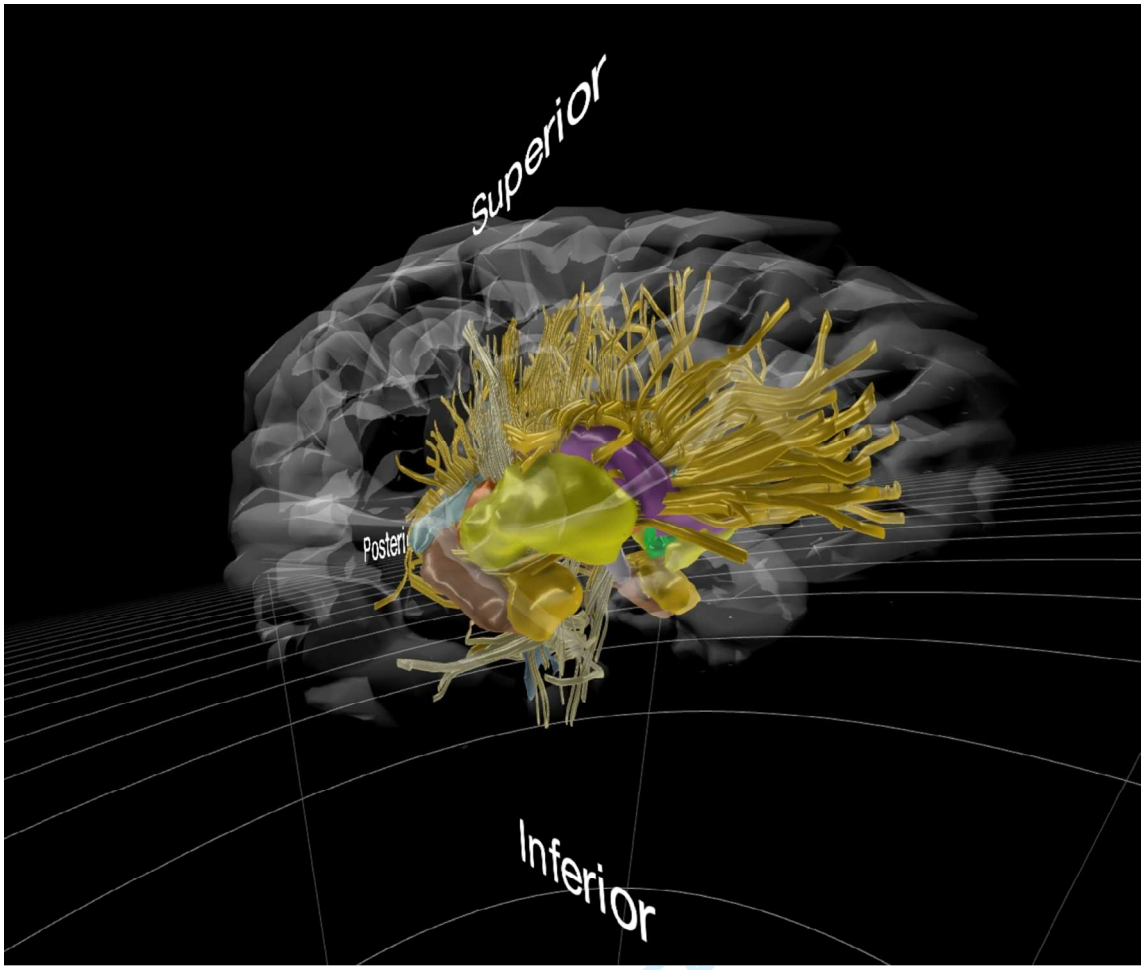
Appendix A

Representative depiction of the VR hardware. The participant was able to interact with the VR brain presented via the headset using two handheld remotes.



Example of the VR brain within the VR environment. Visibility of the structures and their identity could be toggled by the participant.

CONSORT 2010 checklist of information to include when reporting a randomised trial*

Section/Topic	Item No	Checklist item	Reported on page No
Title and abstract			
	1a	Identification as a randomised trial in the title	1
	1b	Structured summary of trial design, methods, results, and conclusions (for specific guidance see CONSORT for abstracts)	2
Introduction			
Background and objectives	2a	Scientific background and explanation of rationale	3-4
	2b	Specific objectives or hypotheses	4
Methods			
Trial design	3a	Description of trial design (such as parallel, factorial) including allocation ratio	4-6
	3b	Important changes to methods after trial commencement (such as eligibility criteria), with reasons	5-7
Participants	4a	Eligibility criteria for participants	4-5
	4b	Settings and locations where the data were collected	4
Interventions	5	The interventions for each group with sufficient details to allow replication, including how and when they were actually administered	4-6
Outcomes	6a	Completely defined pre-specified primary and secondary outcome measures, including how and when they were assessed	4-6
	6b	Any changes to trial outcomes after the trial commenced, with reasons	6-7
Sample size	7a	How sample size was determined	4
	7b	When applicable, explanation of any interim analyses and stopping guidelines	N/A
Randomisation:			
Sequence generation	8a	Method used to generate the random allocation sequence	4
	8b	Type of randomisation; details of any restriction (such as blocking and block size)	4
Allocation concealment mechanism	9	Mechanism used to implement the random allocation sequence (such as sequentially numbered containers), describing any steps taken to conceal the sequence until interventions were assigned	4
Implementation	10	Who generated the random allocation sequence, who enrolled participants, and who assigned participants to interventions	4
Blinding	11a	If done, who was blinded after assignment to interventions (for example, participants, care providers, those	7

		assessing outcomes) and how	
	11b	If relevant, description of the similarity of interventions	N/A
Statistical methods	12a	Statistical methods used to compare groups for primary and secondary outcomes	6-11
	12b	Methods for additional analyses, such as subgroup analyses and adjusted analyses	6-11
Results			
Participant flow (a diagram is strongly recommended)	13a	For each group, the numbers of participants who were randomly assigned, received intended treatment, and were analysed for the primary outcome	4
	13b	For each group, losses and exclusions after randomisation, together with reasons	4
Recruitment	14a	Dates defining the periods of recruitment and follow-up	4-6
	14b	Why the trial ended or was stopped	N/A
Baseline data	15	A table showing baseline demographic and clinical characteristics for each group	7
Numbers analysed	16	For each group, number of participants (denominator) included in each analysis and whether the analysis was by original assigned groups	4
Outcomes and estimation	17a	For each primary and secondary outcome, results for each group, and the estimated effect size and its precision (such as 95% confidence interval)	9
	17b	For binary outcomes, presentation of both absolute and relative effect sizes is recommended	
Ancillary analyses	18	Results of any other analyses performed, including subgroup analyses and adjusted analyses, distinguishing pre-specified from exploratory	6-11
Harms	19	All important harms or unintended effects in each group (for specific guidance see CONSORT for harms)	N/A
Discussion			
Limitations	20	Trial limitations, addressing sources of potential bias, imprecision, and, if relevant, multiplicity of analyses	12-13
Generalisability	21	Generalisability (external validity, applicability) of the trial findings	11-13
Interpretation	22	Interpretation consistent with results, balancing benefits and harms, and considering other relevant evidence	11-13
Other information			
Registration	23	Registration number and name of trial registry	N/A
Protocol	24	Where the full trial protocol can be accessed, if available	N/A
Funding	25	Sources of funding and other support (such as supply of drugs), role of funders	1

*We strongly recommend reading this statement in conjunction with the CONSORT 2010 Explanation and Elaboration for important clarifications on all the items. If relevant, we also recommend reading CONSORT extensions for cluster randomised trials, non-inferiority and equivalence trials, non-pharmacological treatments, herbal interventions, and pragmatic trials. Additional extensions are forthcoming: for those and for up to date references relevant to this checklist, see www.consort-statement.org.