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Exploring the Potentials of Integrating Immersive Virtual Reality (VR) into Neuroanatomy Education

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Abstract

Neuroanatomy teaching requires students to understand complex spatial relations of the brain structures, traditionally accomplished using a cadaver. However, dissecting neuroanatomical structures remains a challenge due to their intricate nature. Digital technology is increasingly being adopted as a three-dimensional (3D) visualization tool, and immersive virtual reality (VR) has attracted great interest. A literature review was conducted using EMBASE, MEDLINE, Web of Science, Scopus, and ProQuest databases. Studies published from 2015 onwards that compared VR-based neuroanatomy teaching with traditional methods were included. Only English-language, peer-reviewed articles with quantitative learning outcomes were analyzed. This review included 6 studies and suggests that VR is non-inferior to other teaching methods and performs better in spatial-related questions. VR is also favored to increase student motivation and engagement. These positive learning experiences are expected to diminish neurophobia. Meanwhile, as a novel technology, challenges for incorporating VR into neuroanatomy education include costly technical requirements, inadequate image resolution, anatomy details, absence of texture perception, and health concerns such as cyber-sickness. Future studies should employ a large sample size (>100), assess participants' working memory and spatial abilities, conduct longer experiment duration, and examine long-term retention. Digital simulation through VR is also attainable and can be implemented further for neurosurgical training. As technology advances, immersive VR technology can potentially be an effective teaching tool for neuroanatomy.

Keywords: Virtual Reality; Neuroanatomy; Medical Education

1. Introduction

Neuroanatomy is one of the most dreaded topics in the anatomy curriculum.[1] The nervous system, is comprised of numerous intricate structures, both central and peripheral, thus commonly identified as more complex than other anatomical systems.[2] The spatial complexity of the brain structures is also a considerable challenge while learning neuroanatomy.[3,4] Students rely heavily on the relationship among 3D brain structures to understand neuroanatomy comprehensively and it is typically achieved through cadaver dissection which allows for the viewing and manipulation of spatial relations.[5,6]

Despite being a valuable resource and long being considered as the gold standard in anatomy teaching, cadaver dissection has some drawbacks.[7,8] Students spend a considerable amount of time dissecting cadavers rather than observing and memorizing structures.[9] Regarding neuroanatomy, the nervous system has plenty of tiny anatomical parts that are difficult to dissect, and removing the brain from the skull is a strenuous procedure.[10] As a result, traditional gross anatomy teaching is non-interactive and limits students from experiencing the three-dimensional (3D) relationships between neuroanatomical structures.[9] Furthermore, the shelf life of fresh brain specimens is limited, whereas fixed tissue is brittle and toxic due to fixatives such as formaldehyde.1 In practice, there is a significant decline in the use of cadavers due to the paucity of specimens and expert anatomists as well as the high expense of infrastructure maintenance.[5–7]

Medical education has undergone significant changes, reinforced with the COVID-19 pandemic. These changes highlight communication skills and clinical work, thus compromising allocated hours for anatomy teaching, and neuroanatomy suffers from these reductions inevitably.[2,3,6] All these modifications might cause a student's performance to be below an acceptable level.[11] Research on graduating medical students revealed a decline in their recollection of neuroanatomy, which fell short of safe practice standards.[6]

Given the complexity inherent to understanding the morphology of intricate nervous systems and difficulties with specimen preparation, the need for employing innovative methods that can enable 3D visualization of structures becomes fully evident.[2,10] Nowadays, a variety of tools have been implemented in anatomy courses to optimize learning during the limited hours dedicated to neuroanatomy teaching. One of the most widely developed tools is an electronic 3D model, which could display complex anatomical structures and replicate a dissection course.[12,13]

Alongside electronic 3D models, Virtual Reality (VR) also has the potential to reproduce the three-dimensional visualization of anatomical structures, enabling students to learn interactively.[5,14] VR technology allows real-time exploration and manipulation of computer-generated 3D multimedia environments.[15–17] The user is submerged in this artificial environment, which is perceived through sensory stimuli (sight, hearing, and motion) that mimic real-life scenarios through continually updating high-resolution head-mounted displays, stereo headphones, and motion-tracking systems.[18]

A review has examined the effectiveness of VR integration in anatomy education. Most of these studies found no significant differences regarding student output between VR and traditional or other digital tools, but student engagement is seen better in VR groups.[13] As for neuroanatomy, the usefulness of such a system remains unclear, though the use of VR has immense potential as neuroanatomy learning relies heavily on spatial relationships, and students' acceptance remains at an individual or limited level.[1] This review evaluates the prospect of incorporating VR into neuroanatomy teaching to determine its value before the widespread use of this novel technology.

2. Methods

2.1. Information sources and search strategy

A literature search used the terms 'neuroanatomy', 'virtual reality', 'VR', 'digital anatomy', and 'medical education'. Titles and abstracts were reviewed to identify papers that could contribute to discussion and full-text versions were acquired. Databases in EMBASE, MEDLINE, Web of Science, Scopus, and ProQuest were examined. A manual search of bibliographies found in studies was also performed.

2.2. Selection process

Inclusion criteria were articles published from January 2015 to the present, written in English, peer-reviewed, original research adopting VR technology into neuroanatomy teaching, evidence of comparison to other teaching methods, and availability of quantitative assessment of learning outcomes. Exclusion criteria were qualitative studies and systematic reviews or meta-analyses.

3. Results

Six studies met the inclusion requirement, all conducted in different countries. Four studies were two-arm parallel randomized trials; the remaining were three-arm parallel trials. The studies included a total of 490 participants, and 78% of them were medical students. Most studies were small, with only two containing more than 70 participants; the largest study included 169 participants. The duration of the study varied between 12 and 60 minutes.

Four studies assessed VR using head-mounted displays, one study used interactive stereoscopic VR, and one study used a stereoscopic projection VR system. As shown in Table 1, comparators include conventional lectures, textbooks, booklets/modules, radiological data, and 3D-printed models. Three studies measured participants' knowledge scores only by post-test. One study measured knowledge by pre-tests and post-tests, and two studies performed additional retention tests in 7 days and 8 weeks post-intervention. Most of the studies conducted subjective measurements.

4. Discussion

4.1. Interpretation

The neuroanatomy learning method was previously accomplished through lectures, anatomical atlas, and brain dissections and to help 3D visualization, it uses plastic anatomical models, 3D printed models, and plastinated prosections. In one study, 3D printed models outperformed physical models regarding long-term memory. This might be related to the likelihood of nearly 1:1 student-to-printed specimen ratios, enabling individualized learning and detailed examination. Although both models allow for examination in 3D spatial terms, they limit the user's interaction with the model. Thus, technological innovations have been suggested as a valuable addition to optimizing learning within the constrained hours of neuroanatomy education.[5,12] These technological innovations include various forms of electronic 3D models, such as mobile applications, games, computer simulations, and virtual dissection tables.

Over the past ten years, electronic 3D models have become increasingly popular and plenty of universities worldwide developed models on their own based on consecutively stacked 2D data, including radiological imaging data (e.g., CT and MRI).[12,19] Students can digitally rotate, magnify, and dissect these electronic 3D models to perform complex cognitive reconstructions.[6,20] A cross-over design study evaluated the possible advantages of studying neuroanatomy through cadaveric and 3D computer-based methods. On the post-test, students allocated to the 3D neuroanatomy module did better; following crossover, both groups fared similarly, and switching from cadaveric to 3D learning boosted results significantly.[21] Numerous studies also demonstrated that students prefer 3D visualization over conventional approaches using textbooks and cadavers.[22] While reconstruction from radiological data still lacks in-depth resolution, adopting the digital model is proposed to improve students' spatial comprehension of neuroanatomical structures.[1,13] Educators should employ various teaching strategies to ensure successful retention of material.[23]

Table 1. Characteristics of the Included Studies

No.	**Authors (Year)**	**Participants (Country)**	**Course**	**Intervention**	**Comparison**	**Number of Participants (Intervention/ Comparison)**	**Duration of Study**	**Timepoint of Assessment**	**Outcomes**		**Limitations**
									Objective Measurement	**Subjective Measurement**	
1	Kockro *et al*. (2015)	Medical Students (Germany)	Third Ventricle	VR environment - stereoscopic projection system	Automated PowerPoint presentation	169 (89/80)	20 minutes	Post-test	VR group showed better results than presentation	VR was evaluated as superior in spatial understanding, effectiveness, and enjoyableness	Only one timepoint assessment, motivation bias
2	De Faria *et al*. (2016)	Medical Students (Brazil)	Limbic System	VR interactive non-stereoscopy and stereoscopy	Conventional lecture	84 (28/28/28)	60 minutes	Post-test	VR groups were significantly better than conventional lectures, non-stereoscopic VR did not differ statistically from stereoscopic VR	Not assessed	Possibility of improper topic selection, insufficient anatomical annotations
3	Stepan *et al*. (2017)	Medical Students (USA)	Brainstem, Ventricular System and Cerebral vasculature	VR	Online Textbook	66 (33/33)	20 minutes	Pre-test, Post-test, 8 weeks post-intervention test	No significant difference between methods	VR was superior in engagement, enjoyment, usefulness, and motivation	Possibility of selection bias, limited study duration
4	Ekstrand *et al*. (2018)	Medical Students (Canada)	Basal Ganglia, Ventricles, Diencephalon, Limbic System,	VR	Paper-based booklet	64 (31/33)	12 minutes	Pre-test, Post-test, 7 days post-intervention	No significant difference between methods	Increased study motivation and decreased neurophobia	Short follow-up

			Lateral Corticospinal Tract, and Spinothalamic Tract					test			period, a limited number of questions in retention quiz, short training duration
5	Deursen *et al*. (2021)	Social Sciences Students (Netherlands)	Ventricular System, Internal Capsule, Basal Ganglia, and Limbic System	VR	Radiological data (MRI)	47 (23/24)	30 minutes	Pre-test, Post-test	No significant difference between methods	VR was perceived as more motivating, interesting, useful and fun	Small sample size, lack of comparison to conventional methods
6	Aridan *et al*. (2023)	Not specified (Israel)	White Matter Structures and Tracts	VR photogrammetry-based 3D brain models	Module and 3D-printed models	60 (20/20/20)	30 minutes	Post-test	VR and physical models groups perform significantly better in questions that require spatial understanding	VR had a higher rating of learning experience compared to physical models, was rated as more interesting, effective, and fun	Small sample size, no prior assessment of cognitive abilities, lack of comparison to other various traditional methods

In the past decade, VR has been used to teach fundamental and advanced anatomy, supplementing and sometimes replacing cadaver dissection.[4,24] Evidence strongly recommends the application of VR during the learning process.[1] VR has been introduced in medical education to teach various topics, including emergency medicine, orthopedic surgery, dentistry, and anatomy.[25] VR has drawn attention as a cutting-edge method for facilitating immersive, interactive, and efficient learning in anatomy.

Immersive VR allows learners to visualize spatial information from different angles, which can help them better understand complex neural structures.[26] Direct manipulation through VR is more beneficial than passive viewing as the degree of interaction with VR is an essential factor in knowledge retention and short-term recall.[11,27] The role of proactivity, being able to analyze in detail the neuroanatomical structures, magnify and rotate the model, and touch the structures, is influential in increasing spatial understanding, particularly in students with low spatial ability.[28,29]

Currently, most students don't have access to VR at home; it is most likely used on campus during classes or complementary study. VR technologies allow students to interact with them in repetitive and controllable settings. This contributes to the student's learning ability, promoting intrinsic benefits such as learner engagement and motivation.[16]

Studies on VR for anatomy teaching have increased in the past decade, yet they are still insufficient. As a result, the number of VR studies on neuroanatomy teaching included in this review is limited. The number of participants in each study is also minimal (less than 100). However, all studies have developed and used VR for 3D visualization of deep brain structures. The most common topics addressed were the ventricular system, limbic system, and gray matter structure, such as basal ganglia, which are basic concepts in neuroanatomy. These topics have moderate complexity and are difficult to visualize,[26] but VR has been demonstrated to be a valuable tool for exploring spatial relationships between neuroanatomical structures.[22] This finding supports one study highlighting the beneficial effects of physical models that heavily manipulate deep brain areas.[25] One thing that educators should be aware of is the ability to modify structure effectively in addition to being able to demonstrate it.[5]

This review examined the effectiveness of VR-based technology in neuroanatomy teaching. VR yielded inconsistent findings as it outperformed conventional lecture but showed no significant difference compared to the remainder (textbook/module, 2D images, 3D-printed model) despite the prospect of VR in helping students reconstruct the spatial understanding required while learning neuroanatomy. This might be attributed to several factors. Students in the control group did not have access to any 3D visualization tools, but they had an edge in studying at their own pace and style, which might have affected the outcome. In one study, the VR group performed better merely in questions that require spatial understanding. Most of the included studies simply concentrate on recalling 2D structures rather than testing spatial relationships between neuroanatomical structures.[30] This could also explain the lack of discernible differences between VR and other approaches. Limited experiment duration could also affect the results, given that some people need more time to familiarize themselves with the new technology.

None of the studies compared VR to dissection, the gold-standard teaching method for anatomy; therefore, the efficiency of VR remained elusive. In practice, VR could be utilized in addition to in-class dissection, thus requiring fewer laboratory hours and supplies. Additionally, these studies only compared VR to traditional methods; considering that digital-based methods enabled 3D visualizations, it would be more insightful to compare VR to other digital-based methods.

4.2. Comparison with previous studies

The varied findings in this review agreed with the distinct results of two meta-analyses on the effectiveness of VR in anatomy teaching. Meta-analysis of randomized controlled trials, which included 15 studies, showed that VR moderately improved test scores compared to other teaching methods (SMD=0.53; 95% CI [0.09–0.97], $p < 0.05$).13 Meanwhile, other meta-analyses demonstrated different outcomes. In 4 studies comparing VR to traditional teaching, the pooled treatment effect was only 5.8 percentage points (95% CI [-4.1 15.7], p = 0.25); thus, test performance can't be substantially increased.[17]

The overall evidence suggests no discernible difference in learning between VR and traditional methods, suggesting the feasibility of using VR in the class. VR is non-inferior to conventional methods and can be an ideal replacement or supplementary in neuroanatomy courses.

This review also confirmed that students favored VR as more enjoyable, fun, motivating, engaging, stimulating, and practical than other teaching methods. Students rated higher learning experiences while learning neuroanatomy using VR, which decreased neurophobia.[31] In another study of using VR in musculoskeletal systems, adding features such as game simulation has evoked more attractive learning tasks.[25] This finding is consistent with other studies that utilize VR in other anatomy-related topics, and it could be associated with the fact that VR is a relatively recent and intriguing approach, as the novelty effect plays a vital role in the studies examining the significance of technological innovations. Prior studies have pointed out that students might lose interest as the novelty effect subsided, and the previously described subjective assessment could no longer be relevant. As there are still limited studies on the impact of employing VR in neuroanatomy teaching over a longer duration, it remains unclear whether VR's perceived values will persist in future encounters.[17,32]

4.3. Limitations

There are possible reasons for impending VR adoption in neuroanatomy teaching, mainly due to health and safety concerns. VR participants often report cyber-sickness symptoms, such as dizziness, headache, fatigue, nausea, disorientation, discomfort, motion sickness, blurred vision, and eye strain.[7,18] Safety concerns are addressed when multiple students use VR in the same space; thus, students are encouraged to view and interact with models while seated, and the institution is advised to build a dedicated VR room.[20] VR applications might be hindered by limited scalability and a lack of haptic feedback. Using VR to teach multiple students at once is challenging by nature. Additionally, students cannot feel the weight and texture of neuroanatomical structures.[5,9]

VR integration into neuroanatomy teaching requires significant expenses for hardware investment, license maintenance, and technical training. VR still requires a lot of software development as recent software has unsatisfactory resolution, making it challenging to see some small blood arteries, nerves, and nuclei in great detail.[9] Sometimes, when universities wish to build their module, it might require many resources.26 VR is also limited to shorter annotations as it can't fully display information, as seen better in 3D digital models.[20]

This review has several limitations. Only two studies evaluate long-term recall; based on these studies, the VR group showed a better score, albeit not significantly. Half of the studies did not perform a pre-intervention test, relying solely on the post-intervention results. Most studies did not assess cognitive abilities; only one study performed a mental rotation test. As a result, we cannot confirm if a student's proactive use of VR is advantageous for individuals with low visuospatial abilities in particular.

4.4. Implications

In addition to being an effective teaching tool for neuroanatomy, VR can be implemented into neurosurgery to leverage the potential of VR as a means of surgical training.[26] Junior surgeons currently have fewer opportunities to learn surgical anatomy in an operating room; VR can be a feasible alternative by using it to demonstrate a virtual patient simulating real-life scenarios or as an operative assistant. This setting will increase their confidence and procedural competency while offering a safe training environment.[5,33] Moreover, VR can also be utilized for patient-centered activities, such as preoperative planning and patient education, which can be a valuable instructional resource for caregivers. Future studies should include a large sample size (>100), conduct longer experiment duration, perform complete assessment (pre-test, post-test, and long-term retention), evaluate participants' cognitive abilities (e.g. working memory and visuospatial skills), and compare VR to other digital-based models. Virtual reality (VR) technologies are improving in quality and accessibility. Continued technical developments will accelerate VR integration into neuroanatomy education.

5. Conclusion

With the advancement of technology, VR is feasible for integration into the neuroanatomy curriculum as a complement or substitute for cadavers. While learning outcomes are comparable to traditional methods, VR offers unique advantages in promoting student engagement and providing interactive 3D visualization of complex neural structures. Future research should focus on conducting larger-scale studies with longer experimental durations to better evaluate VR's long-term effectiveness in neuroanatomy education. Studies should incorporate comprehensive assessments. Direct comparisons between VR and other digital teaching tools, rather than just traditional methods, would provide more valuable insights. Additionally, institutions planning to implement VR should consider developing dedicated spaces for VR learning and establishing protocols to address cyber-sickness concerns while ensuring proper technical support and maintenance.

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