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Comparison and Evaluation of the Effectiveness of Traditional Neuroanatomy Teaching in Medical Education with Virtual-Reality Application Based On 3D Virtual

Tıp Eğitiminde Geleneksel Nöroanatomi Öğretiminin Etkinliğinin 3 Boyutlu Sanal Gerçekliğe Dayalı Uygulama ile Karşılaştırılması ve Değerlendirilmesi

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ABSTRACT

Objective: Learning neuroanatomical structures is difficult in traditional medical education. Knowledge and visual materials in neuroanatomy books or atlases are static and limited to two dimensions. The limitations of cadaver and plastic models have been overcome by developing three-dimensional (3D) anatomical models using digital visualization technologies. Medical students are better able to understand the spatial topography of a large number of neuroanatomical structures that are condensed into a small region when they use 3D visualization technologies, such as virtual reality (VR) and augmented reality. In our study, which will provide a new window to classical neuroanatomy education, we aimed to evaluate how much 3D neuroanatomical models based on VR applications affect the success and motivation of medical school students enrolled in neuroanatomy courses.

Methods: For this purpose, four exams were given to second-year medical faculty students before the classical theoretical course, after the theoretical course, after VR training and application, and six months later to evaluate the long-term effects of the training.

Results: The success averages were assessed on a scale of 10; the average score was 3.38 for students who participated in the evaluation after traditional theoretical training and 4.55 for the VR training group. In the long-term evaluation after six months, the average score was found to be higher in the VR training group.

Conclusion: Our study contributes to the literature by demonstrating the positive long-term effects of VR-based neuroanatomy training on memory.

Keywords: Neuroanatomy, medical education, virtual reality, augmented reality, anatomic models, long-term effects

ÖZ

Amaç: Geleneksel tıp eğitiminde nöroanatomik yapıları öğrenmek zordur. Nöroanatomi kitaplarında veya atlaslarında bulunan bilgi ve görsel materyaller statik olup iki boyutla sınırlıdır. Kadavra ve plastik modellerin kısıtlılığı, dijital görselleştirme teknolojileri kullanılarak üç boyutlu (3D) anatomik modellerin geliştirilmesiyle çözülmüştür. Tıp öğrencileri, sanal gerçeklik (VR) ve artırılmış gerçeklik gibi 3D görselleştirme teknolojilerinden yararlandıklarında, küçük bir bölgeye yoğunlaştırılmış birçok nöroanatomik yapıların uzamsal topografisini daha iyi anlayabilirler. Klasik nöroanatomi eğitimine yeni bir pencere açacak olan çalışmamızda, VR uygulamasına dayalı 3D nöroanatomik modellerin, tıp fakültesi öğrencilerinin nöroanatomi derslerindeki başarı ve motivasyonunu ne kadar etkilediğini değerlendirmeyi amaçladık.

Yöntemler: Bu amaçla, ikinci sınıf tıp fakültesi öğrencilerine klasik teorik ders öncesinde, teorik ders sonrasında, VR eğitimi ve uygulaması sonrasında ve eğitimin uzun vadeli etkilerini değerlendirmek için altı ay sonra olmak üzere toplam dört sınav yapıldı.

Bulgular: Başarı ortalamaları 10 üzerinden değerlendirilmiştir; geleneksel teorik eğitim sonrası değerlendirmeye katılan öğrenciler için ortalama puan 3,38, VR eğitimi grubunda ise 4,55 olmuştur. Altı ay sonraki uzun vadeli değerlendirmede, VR eğitimi grubunun ortalama puanı daha yüksek bulunmuştur.

Sonuç: Çalışmamız, VR tabanlı nöroanatomi eğitiminin hafıza üzerindeki olumlu uzun vadeli etkilerini göstererek literatüre katkı sağlayacaktır.

Anahtar Sözcükler: Nöroanatom, tıp eğitimi, sanal gerçeklik, artırılmış gerçeklik, anatomik modeller, uzun vadeli etkiler

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INTRODUCTION

Due to the increasing effect of technological development, 21st-century anatomy education has undergone dynamic changes compared to traditional anatomy education in the 19th and 20th centuries. On the other hand, the increase in the number of students applying to medical schools and changes in the anatomy curriculum (1) have caused a decrease in the time allocated to anatomy (2-4). This situation results in a decline in the anatomy knowledge of young doctors (5).

Neuroanatomy is one of the most difficult anatomy subjects for medical students to learn and for young doctors to apply their basic neurological knowledge in the clinic. The challenges of neurology are explained by poor anatomical knowledge and limited patient contact. One of the most effective ways to reduce negrophobia is to teach neuroanatomy and neurophysiology successfully (6).

Neuroanatomy, as a component of the anatomy curriculum, has been impacted by the overall decline of the entire anatomy curriculum. Moreover, it stands out as one of the most disliked and challenging sections for students in the entire anatomy curriculum (7). There are two important reasons for this: Firstly, the central and peripheral nervous systems are more complex than other anatomical systems, and second, the neuroanatomy models, atlases, or computer software provided by educational institutions are insufficient and fail to meet expectations.

Detailed examinations of the central and peripheral nervous systems in cadavers create limitations for educators in undergraduate and graduate education in neuroanatomy. For example, it is almost impossible to demonstrate anatomical structures, such as cranial nerve nuclei and descending-ascending pathways, contained within the brain stem, which measure approximately 7.5 cm in length. Additionally, fixed cadaver tissue is not robust and exhibits toxic properties due to fixation solutions (8-11). Furthermore, computed tomography and magnetic resonance imaging images taken from patients still lack the detail required to adequately display these structures.

The innovative approach in neuroanatomy education predominantly revolves around three-dimensional (3D) modeling on computers, virtual reality (VR), and augmented reality (AR). Although the history of 3D anatomical modeling, which forms the foundation of VR and AR, can be traced back to ancient times, the first modern computer graphic models were created in 1979 by Dietrichs and Walberg (12), focusing on the cat's fastigial nucleus. 3D anatomical models are effective learning tools for two reasons: their capacity to elucidate complex neuroanatomical structures in a simple and comprehensible manner, and individuals' inherent motivation to study and understand these structures (13). The preparation of 3D anatomical models based on digital visualization formats has addressed the limitations of cadaver and plastic models and is poised to replace them in the coming years. The utilization of 3D visualization technologies such as VR and AR aids in comprehending the spatial topography of numerous neuroanatomical structures concentrated within a confined area.

Our recent literature reviews indicate that the use of VR and AR applications for 3D imaging of the nervous system has risen to 18 and 20 publications, respectively, since 2006 (14,15). Undoubtedly, the decrease in equipment costs (computers, glasses, software) has played a significant role in this (16).

Although classical physical brain anatomy models or those obtained from 3D printers allow examination in 3D spatial terms, they limit interaction with the model (17). We now have scientific evidence strongly recommending the use of VR applications in teaching and learning processes. Additionally, they have been shown to significantly enhance students' imagination, creativity, and learning (16,18).

The best method for teaching neuroanatomy remains an unresolved issue. Consequently, research on this subject persists and will continue in the coming years (7). Neuroanatomy education is more receptive to innovations as a balancing factor compared to the anatomy of other organ systems.

In our retrospective studies, it is evident that providing infrastructure for cadaver dissection, which held significant importance in anatomy education in the 20th century, and maintaining expertise in this field incurs high costs. Consequently, there has been a decline in medical students' utilization of cadaver dissection as a means of familiarizing themselves with anatomy (19,20).

There is a limited number of articles on the use of VR to teach neuroanatomy and its educational contributions (21). In addition, research on the effectiveness of such systems and their acceptance by students has remained at an individual or limited level. The findings obtained mostly consist of studies focusing on student satisfaction. Furthermore, there are very few studies measuring short-term and long-term learning success, as well as the efficacy of the devices used in education. In this study, we developed an original VR brain model and examined its effects on long-term learning, recall, satisfaction, and motivation. In the future, we plan to transform this model into a web-based application that can be accessible to users worldwide.

MATERIALS AND METHODS

Participants

Our study is an intervention study planned to implement a new education model and measure its effectiveness. The application was carried out with 170 volunteers: 102 female (60%) and 68 male (40%) students from Gazi University Faculty of Medicine, term 2 students. Participants signed a consent form indicating their voluntary participation. Additionally, approval was obtained from the Ethics Commission of Gazi University for this study (approval number: E-77082166-604.01.02-275165, date: 27.01.2022). There were no stereographic visual disturbances reported by the students.

Materials and VR Model Preparation Steps

3D digital models were prepared to depict anatomical structures in the central nervous system (including superficial and deep structures), cranial nerves, vestibular structures, and the brainstem in detail. For this purpose, we utilized a 3D digital modeling and animation program called Cinema 4D (Maxon Computer, Friedrichsdorf, Germany). These innovative models were meticulously crafted. Initially, we encountered difficulty in finding existing models and 3D visuals that provided detailed representations of the cranial nerve nuclei and ascending and descending pathways in the brainstem in the literature and visual scans we conducted. Therefore, we developed a unique brainstem VR model. These structures are closely aligned with the topics covered in the neuroanatomy curriculum.

Subsequently, we transferred the models to a VR editor program called ROT (Infotron, Ankara, Türkiye) and integrated them with anatomical information to enhance interactivity. ROT is a unity-based VR editing program capable of seamlessly importing models in .fbx format and textures in .png format. Once the models and anatomical information were integrated and made interactive, they became readily available for use. The program is fully compatible with "HTC Vive Pro" and "Oculus Quest II," enabling users to navigate the virtual environment and interact with the models using handheld controllers. Furthermore, ROT offers additional features such as segmenting models and annotating them with text via handheld controllers to enhance student engagement during virtual presentations.

Traditional 2D Lecture and 3D-VR Training

Within the scope of the study, one lecture was conducted for the students in the amphitheater using a familiar PowerPoint presentation, projected onto the screen from a computer. The presentation was designed by anatomists with an interest in clinical anatomy teaching. This course was delivered in the format of a traditional 2D lecture lasting 40 minutes. Following this, the use of 3D imaging glasses and handheld controllers was explained to the students, and subsequently, a VR-supported training session was conducted. The students wore glasses to interact with the models prepared using the VR program. This VR practice session also lasted 40 minutes, mirroring the duration of the traditional 2D lesson. An assessment was conducted by evaluating the students' performance on the subject and gathering their feedback in a focus group.

Study Design of the Quantitative Measurements with the Contents of the Pre-Lecture, Post-Lecture, and Post-VR and Long-Term Exams

To assess students' understanding of the subject matter, a total of 10 questions focused on the three parts of the brainstem were administered to the participating students. Three questions included visuals obtained from models of the brain module, while seven were multiple-choice questions. The questions presented in the model required the students to fill in the blanks. An example of such a test is provided in Table 1. These questions were developed and agreed upon by the anatomists responsible for both theoretical and practical training. The students did not see the questions before the examination.

The first exam was conducted before the lesson, without providing any explanation of the subject matter to the students. Subsequently, a theoretical lecture on the topic was delivered. Following the lesson, a second exam, consisting of different questions but covering the same content, was administered to the students who had attended the theoretical lecture.

After the theoretical lecture, 60 volunteers from among these students underwent the VR application during which the structures learned in the theoretical lesson were demonstrated using the brain module. At the conclusion of this session, a third test, which featured different questions on the same content, was administered.

Six months after the conclusion of the neurological sciences committee, another exam, with content identical to the previous ones but featuring different questions, was administered to the same participants. The purpose of the final test was to assess the retention of the learned information.

In our literature review, we found no studies that measured the short- and long-term success and retention of knowledge in neuroanatomy lessons using VR. Thus, our study represents the first of its kind in the world.

Statistical Analysis

All statistical analyses and calculations were conducted using the SPSS statistical program (version 21.0, SPSS Inc., Chicago, IL, USA). The normal distribution of the obtained numerical data was assessed using the Shapiro-Wilk test. Non-parametric tests were employed if $p<0.05$, while parametric tests were applied if $p>0.05$. Subsequently, comparisons between groups were performed. Statistical significance was determined by considering values with $p\leq0.05$.

RESULTS

Demographic Data

One hundred seventy students volunteered to participate in this study. As no student reported any abnormality in stereoscopic vision, all volunteers were randomized to either the 3D or 2D teaching groups. One hundred seventy medical students (100%) attended the pre-test (first test) before the theoretical lecture, with 168 (98.8%) attending the 2D, PowerPoint-based theoretical lecture and second test. Sixty students (35.2%) underwent 3D-VR training and subsequently attended the third test. Six months later, 162 students participated in a fourth exam to assess the long-term effects of the training. Demographic details were available for all students, with the gender distribution consisting of 102 females (60%) and 68 males (40%). The average age of the students was 19.8 years (range: 19-22 years). All students had completed two semesters of medical school; they were in their third semester when the first three tests were administered and the fourth semester was when the fourth test was administered.

Examination Results of Four Tests with Ten Questions

The class average of the 10-question first test, which was given to 170 second-year students immediately before the lecture, was 1.92 out of 10. The average score for female students, who make up 60% of the class, was 2 out of 10, while the average for male students, comprising 40% of the class, was found to be 1.82 out of 10.

The group average of the second exam, administered to 168 students who listened to the 2D theoretical lecture in the lecture hall, was 3.38 out of 10. The average score for female students was 3.51 out of 10, and for male students, it was 3.16 out of 10.

For the third exam, the group average after the 3D-VR training and application, with 60 voluntary participants out of 170, was 4.55 out of 10. The average score for female students was 4.5 out of 10, and for male students, it was 4.62 out of 10.

Six months after the completion of the neurological sciences committee, the group average of the fourth exam, administered to

Table 1. A sample of tests containing multiple choice questions on theoretical and applied anatomy of the brain stem

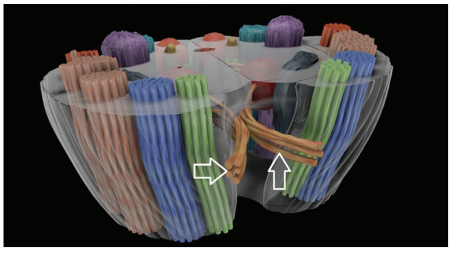
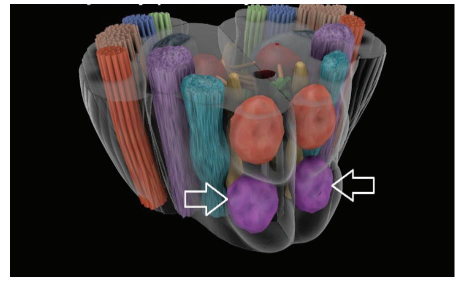
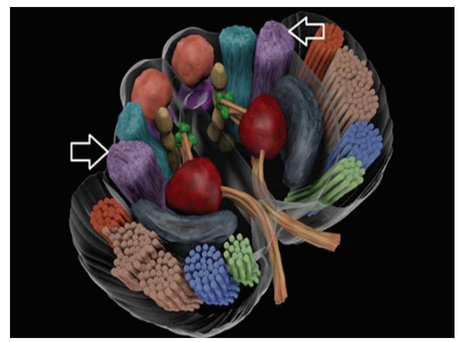
1. Which of the following correctly represents the parts of the brain stem? I. Midbrain II. Internal capsule III. Pons IV. Medulla oblongata V. Cerebellum	a) I, II, III, IV b) II, III, V c) ***I, III, IV*** d) I, III, IV, V e) II, IV, V
2.Which of the following has the highest number of dopaminergic neurons?	a) Area pretectalis b) Tectum mesencephali c) Tegmentum mesencephali d) ***Substantia nigra*** e) Nucleus ruber
3.Which nucleus is located between the substantia nigra and aquaduct of midbrain?	a) Nucleus of the oculomotor nerve b) Nucleus of the trochlear nerve c) ***Red nucleus*** d) Pontine nuclei e) Edinger-Westphal nucleus
4.Which center plays a role in the reflex movements of the head, neck and eyes against sudden auditory, somatic, and visual stimuli?	a) The inferior colliculus b) ***Superior colliculus*** c) Pretectal area d) Tectum of midbrain e) Substantia nigra
5.Which of the information about medulla oblongata is false?	a) It is the most caudal part of the brain stem. b) Connected to the cerebellum with the inferior cerebellar peduncle. c) The last 4 cranial nerves leave the brain stem from the medulla oblongata. d) ***The basilar artery sits on the basilar groove on its anterior surface*** e) It is separated from the pons with bulbopontin groove.
6. Which cranial nerve gets out from the bulbopontin groove?	a) IX. cranial nerve b) X. cranial nerve c) V. cranial nerve d) ***VI. cranial nerve*** e) XI. cranial nerve
7. Which of the statements about the pons is false?	a) It is adjacent to the cerebellum through the 4th ventricle b) It is adjacent to the clivus through the cisterna pontis c) It is separated from the bulbus by the sulcus bulbopontinus d) ***Inferior cerebellar pedincle is connected with the cerebellum*** e) The basilar artery sits on the basilar groove on its anterior surface
8. Write the name of the indicated structure. **<u>Oculomotor nerve</u>**	

Table 1. Continued

9. Write the name of the indicated structure. **Inferior colliculus**	
10. Write the name of the indicated structure. **Medial lemniscus**	

Correct answers in bold italic font.

162 students out of 170, was 4.61 out of 10. The average score for female students was 4.73 out of 10, and for male students, it was 3.85 out of 10.

Statistical Evaluation of Results

The class average of the 10-question first test, administered to 170 second-year students immediately before the lecture, was 1.92 out of 10. Among the students, females, who constitute 60% of the class, achieved an average score of 2 out of 10, while males, comprising 40% of the class, attained an average score of 1.82 out of 10.

Although the number of students participating in the exams varied, 60 students who took the third exam participated in all other exams. To assess statistical significance, the success rates of the 60 students who participated in all four exams were evaluated internally. Additionally, the success rates of the 170 students who took the first exam, the 168 students who took the second exam, and the 162 students who took the fourth exam were evaluated independently within their respective groups.

The figure below (Figure 1) illustrates the results of four exams taken by 60 second-year students from Gazi University Faculty of Medicine, who were taught about the brain stem in an anatomy lecture and subsequently underwent a 3D-VR application related to the subject. Among the 60 students who took each exam, the average score for the first exam was 1.767 (p=0.0005), for the second exam was 3.267 (p=0.0148), for the third exam was 4.550 (p=0.0078), and for the fourth exam was 4.867 (p=0.0595). Accordingly, a statistically significant difference was observed between the first and second exams, the second and third exams, the first and third exams, and the first and fourth exams. However, although there was a difference between the third and fourth examinations, the difference was not statistically significant.

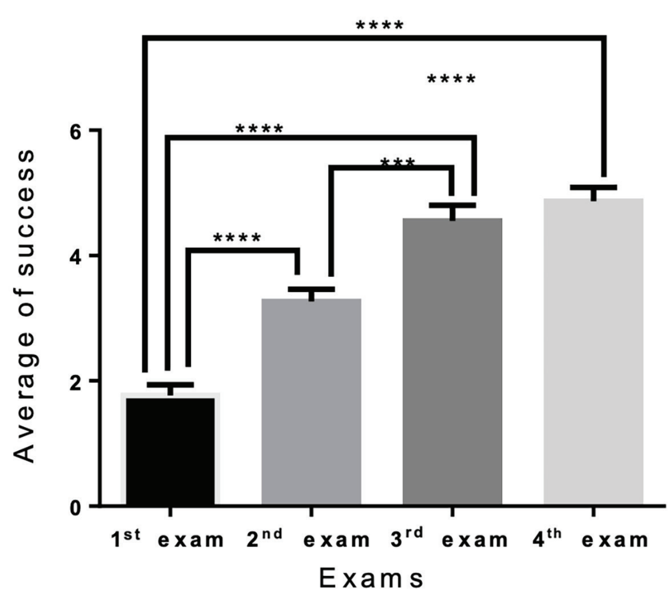


Figure 1. The graph shows the average success rate of the students who participated in the 1st, 2nd, 3rd, and 4th exams.

****p<0.0005; ****p<0.001 difference between groups.*

When evaluating the success in the exams according to gender among the 60 students who participated in all four exams, a statistically significant difference was observed in the results of the second exam. Although the average success rate of the girls was higher than that of the boys in the first, second, and fourth exams (Figure 2), the difference was not statistically significant (p≤0.05).

When comparing the exam results of the 36 female students and 24 male students out of the 60 students who took all the exams, it was observed that the average success rate increased progressively in consecutive exams. There was no statistical significance between the third and fourth examinations in both groups ($p=0.18$ for females; $p=0.14$ for males) (Figure 3).

When conducting a statistical evaluation among the 170 students who took the first exam, the 168 students who took the second exam, and the 162 students who took the fourth exam, statistical significance was found between the first and second exams, the second and fourth exams, and the first and fourth exams (Figure 4) ($p<0.001$, $p<0.001$, $p<0.001$, respectively).

The purpose of our research was not to evaluate the examination performance of students but rather to assess the influence of different anatomy instruction techniques on students. You can watch the video we prepared by holding your smartphone's camera to the QR code (Figure 5).

DISCUSSION

The rise in the utilization of educational technologies and tools over the last two decades has facilitated the emergence of digital education (17,22). Today, applications such as electronic resources,

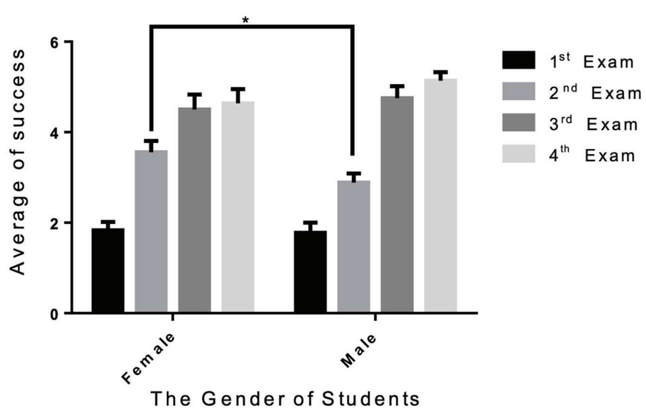


Figure 2. The graph shows the average success rate of the students who participated in all 4 exams by gender.

**p≤0.05 difference between groups.*

game-based learning, and VR are being extensively utilized for learning and acquiring professiona practice skills.

The use of tablets and smartphones in neuroanatomy education has facilitated the comprehension of complex deep brain structures (17,23). However, these technologies only offer two dimensional (2D) views, limiting students' ability to grasp the subject from a 3D perspective and fully understand the dimensions, volumes, and relationships of anatomical structures within the depths of the brain and brainstem.

Error-free 3D brain models, developed for academic purposes and accredited by experts in the subject, can be easily integrated into a VR environment. This allows detailed examination of numerous structures in the normal human brain that are not visible to the naked eye. The only disadvantage of this method is its inability to replicate the textural stimuli experienced during cadaver dissection. However, wearable technologies developed using today's advancements have addressed tactile feedback issues.

Moreover, VR technologies enable students to interact with such technology in reproducible and controllable environmen (17,24). This technology enables students to experience learning content through various sensory inputs, including sight, sound, and touch, thereby immersing them in the virtual environment (25). Additionally, its repeatability allows students to enhance their learning in the classroom beyond the predetermined study program (17,26).

Examination of the literature on 3D visualization of the nervous system revealed a significant increase in interest. In 2011, only 4 articles on VR and AR emphasized this topic, a number that increased to 18 and 10 by today. This trend highlights VR's advantageous position among new technologies for viewing and manipulating neuroanatomical structures with interactivity. It signifies a significant shift in how people learn about neuroanatomy, with the cadaver-based learning method being increasingly replaced by technology between 2011 and 2018. Additionally, eight studies utilizing educational technologies such as VR and AR have been documented to explore the use of 3D in neuroanatomy (13). Some of these methods include local VR-based stereo-imaging techniques for learning about the ventricular system and neurovascular structures (27), skull (28,29), brain structures, and cranial nerves (28).

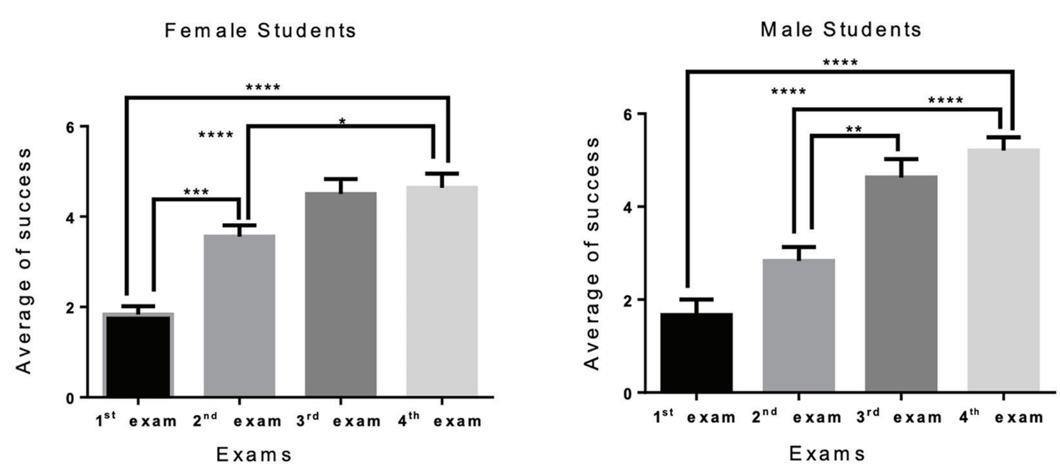


Figure 3. The graph shows the average success rate of female students on the left and male students on the right who took the 1st, 2nd, 3rd, and 4th exams.

**p≤0.05, **p≤0.01, ***p≤0.001, ****p<0.001 difference between groups.*

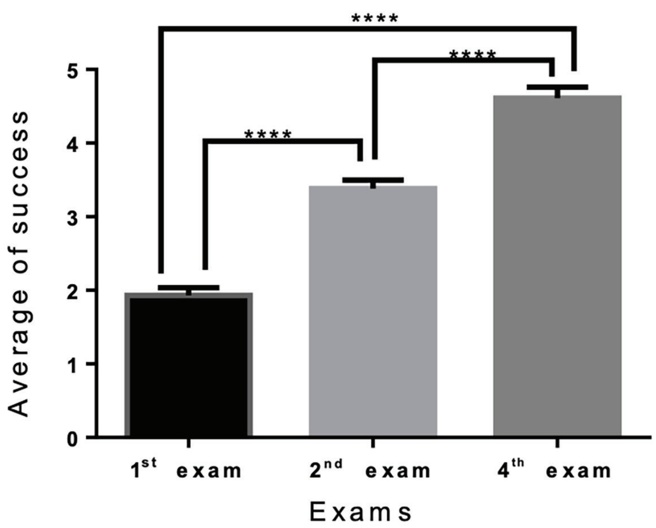


Figure 4. The graph shows the average success rate of the students who took the 1st, 2nd, and 4th exams.

****p<0.001 difference between groups.

Our observations indicate that although the number of these studies has increased, they remain insufficient. Furthermore, these studies have predominantly focused on superficial brain structures to demonstrate neuroanatomical structures to students. However, it would be intriguing to develop and utilize VR and AR applications for 3D visualization of deep brain structures in neuroanatomy education (13). In a study conducted by Estevez et al. (30) in 2010, they emphasized that physical models that allow for high levels of manipulation of deep brain structures yield positive result.

The brain module developed in this study aims to address the shortcomings identified by the limited number of studies on this subject. An important innovation introduced by our brain module is its ability to enlarge the brain stem, along with its deep structures, by 10-15 times, enabling interaction with the student. This feature represents the world first.

In our study, we evaluated the results of tests conducted to assess the understanding and retention of superficial and deep brain stem structures by a group of 60 students who participated in neuroanatomy training activities. According to the results obtained, the average score on the first test, administered before the traditional 2D theory course, was 1.767. After completing the traditional 2D theory course, the average score on the second test was 3.267. Following the 3D-VR training and application, the average score on the third test for this group was 4.55. Six months after the training and practices, the group's average score on the fourth test was 4.867. Comparatively, the average score of 102 students who did not receive 3D-VR training or application was found to be 4.46. These results indicate that VR, either alone or in combination with classical methods, can be beneficial for learning deep neuroanatomical structures.

The learning style is widely recognized as a crucial element of the learning process. Experimenting with different teaching techniques and recognizing students' individual learning preferences will aid in determining the ideal length for efficient study sessions and enhance academic performance. Ogut et al. (31) conducted a study on anatomy teaching techniques to investigate the impact of four distinct learning styles on student education. They utilized "Kolb's Learning Style Inventory" model for their analysis. Their findings confirmed that learning style affects both the length of study and the scores achieved in theoretical anatomy courses (31). Engaging in practical exercises to apply knowledge strengthens the learning process. Consistent practice aids in solidifying information, thereby facilitating students' ability to remember and utilize their knowledge across diverse situations. Maintaining a positive attitude fosters a growth mindset, which motivates students to tackle challenges and learn from mistakes. This mindset improves their capacity to acquire new knowledge and adapt to various subjects.

Ferrer-Torregrosa et al. (32) and Kugelmann et al. (33) reported that 62% of the students surveyed expressed interest in using AR

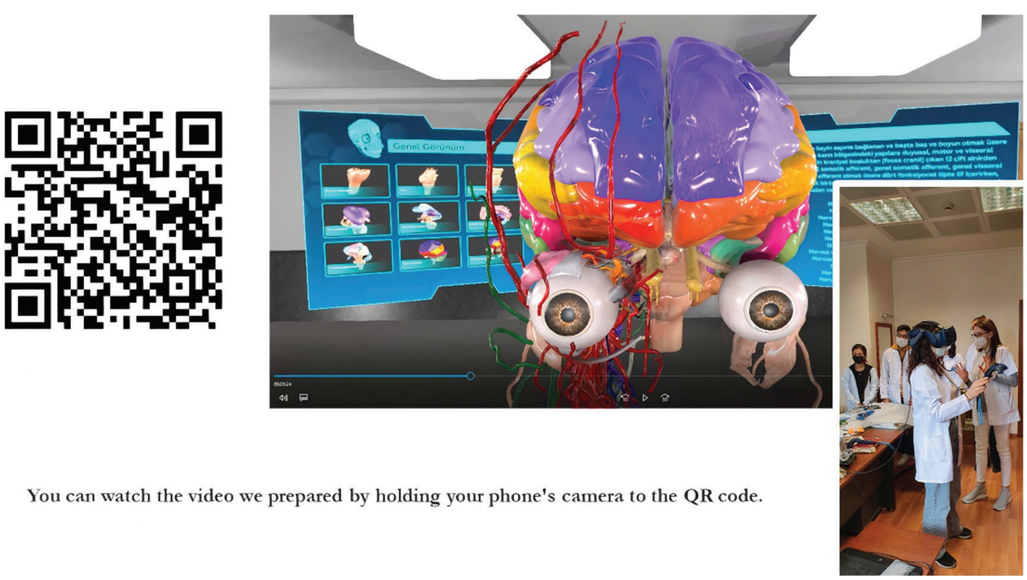


Figure 5. VR Brain Module QR code.

VR: Virtual reality.

for anatomy work. However, Kugelmann et al. (33) did not provide statistical analysis on the subject. This suggests that the effects of VR and AR application tools on student motivation in both general anatomy and neuroanatomy education have not been fully explored. A comprehensive examination of the literature on motivation reveals four important motivational concepts (34). These are attention, relevance, gratification, encouragement, and sustainability, respectively. In our study, students who experienced VR provided feedback indicating that the subject matter became ingrained in their memory, facilitated their learning, and heightened their interest and motivation. Additionally, we conducted statistical and comparative analyses of the test results obtained from the target groups in our study.

Much of the research on medical education has emphasized the learning process of students, often overlooking their emotional experiences (35). Perhaps the primary reason for this is that traditional teaching has predominantly emphasized the cognitive and behavioral development of students for knowledge acquisition (36). However, although emotions associated with the events experienced by students facilitate the retention of learned material, the learning processes persist longer in students' memories (37). Negative emotions, such as boredom, anxiety, and frustration, can impede the storage and retrieval of information from memory when needed for a task (38). According to mixed education methodologies, Stepan et al. (27) reported that students exhibit higher motivation, participation, and understanding in lessons when virtual environments were utilized. Studies have demonstrated that the knowledge acquired for learning anatomy and neuroanatomy is often forgotten even just a few months after the completion of the course (4,39). The Neurosurgical atlas, prepared by anatomists, neurosurgeons, and 3D computer graphic artists, was published in an article in 2019. This article featured a series of interactive 3D VR models that provide a tour of the neurosurgical operating room as well as several critical aspects of cranial surgical anatomy (40). Both in this study and in our work, innovations in 3D and VR digital technology are thought to not only enable the creation of much more sophisticated and realistic educational resources compared to traditional 2D materials but also to support the advancement of medical education by starting with basic anatomy knowledge in the early years and further enhancing the quality of education. In this study, we compared traditional and VR applications in neuroanatomy education. Upon reviewing the literature, we found a lack of significant studies that incorporate statistical data and evaluate long-term information retention among students. Our study revealed a significant correlation between student motivation and success, particularly in the VR group. We observed that VR applications in neuroanatomy education, which utilize accredited models prepared by experts and error-free neuroanatomical structures, meet students' educational expectations. Comparing the exam results, which aimed to demonstrate the long-term effects of VR-supported education, with those of students who did not receive VR training, we concluded that Virtual Reality Application Based on 3D Virtual Neuroanatomic Models, an innovative approach in medical education, aids students in retaining the subject matter. Considering that cadaveric brain dissections were the gold standard in neuroanatomy education in the 19^{th} and 20^{th} centuries (41), it is unsurprising that VR and AR will likely play a central role in the field in the next decade.

Nevertheless, our study also has its limitations. VR glasses used in education can only accommodate one student at a time and may induce dizziness, nausea, or vomiting in users. Despite these drawbacks, the VR application offers significant advantages. Immersing learners in a virtual environment provides the sensation of being within the anatomical structure, enabling real-time exploration and interaction. Hence, there is a pressing need for new neuroanatomy curricula that integrate clinical aspects and emerging technologies, catering to students' intrinsic motivation, and facilitate both short-term and long-term learning.

CONCLUSION

Neuroscience, or neuroanatomy, stands as the most daunting subject among anatomy courses in medical faculties. Complexity often leads students to dread neurological sciences in their career planning, potentially exacerbating public health challenges for an aging population grappling with neurological diseases. Our study, leveraging today's 3D technology in anatomy education, has the potential to elevate classical neuroanatomy education to new heights, contributing significantly to medical education. In addition, by demonstrating the long-term positive effects of VR training on memory, our study fills a crucial gap in the literature.

Ethics

Ethics Committee Approval: Additionally, approval was obtained from the Ethics Commission of Gazi University for this study (approval number: E-77082166-604.01.02-275165, date: 27.01.2022).

Informed Consent: Participants signed a consent form indicating their voluntary participation.

Authorship Contributions

Concept: E.A., Ö.C., T.V.P., Design: E.A., Ö.C., T.V.P., Supervision: Ö.C., T.V.P., Resources: E.A., T.V.P., Materials: E.A., T.V.P., Data Collection or Processing: E.A., T.V.P., Analysis or Interpretation: E.A., Ö.C., T.V.P., Literature Search: E.A., T.V.P., Writing: E.A., T.V.P., Critical Review: Ö.C., T.V.P.

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