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Evaluation of an Augmented Reality Application for Learning Neuroanatomy in Psychology

Magdalena Mendez-Lopez, [1,2]* **M. Carmen Juan,**[3] **Ramon Molla,**[3] **Camino Fidalgo**[1,2]
[1]*Department of Psychology and Sociology, Faculty of Social and Human Sciences, University of Zaragoza, Teruel, Spain*
[2]*Aragon Health Research Institute (IIS Aragón), University of Zaragoza, Zaragoza, Spain*
[3]*Institute of Industrial Control Systems and Computing, Universitat Politècnica de València, Valencia, Spain*

Neuroanatomy is difficult for psychology students because of spatial visualization and the relationship among brain structures. Some technologies have been implemented to facilitate the learning of anatomy using three-dimensional (3D) visualization of anatomy contents. Augmented reality (AR) is a promising technology in this field. A mobile AR application to provide the visualization of morphological and functional information of the brain was developed. A sample of 67 students of neuropsychology completed tests for visuospatial ability, anatomical knowledge, learning goals, and experience with technologies. Subsequently, they performed a learning activity using one of the visualization methods considered: a 3D method using the AR application and a two-dimensional (2D) method using a textbook to color, followed by questions concerning their satisfaction and knowledge. After using the alternative method, the students expressed their preference. The two methods improved knowledge equally, but the 3D method obtained higher satisfaction scores and was more preferred by students. The 3D method was also more preferred by the students who used this method during the activity. After controlling for the method used in the activity, associations were found between the preference of the 3D method because of its usability and experience with technologies. These results found that the AR application was highly valued by students to learn and was as effective as the textbook for this purpose. Anat Sci Educ 0: 1–17. © 2021 The Authors. Anatomical Sciences Education published by Wiley Periodicals LLC on behalf of American Association for Anatomy.

Key words: neuroanatomy education; neuroscience education; undergraduate education; psychology education; 3D imaging techniques; augmented reality; learning; learning goals; psychology; spatial ability; computers in anatomical education

INTRODUCTION

Anatomy is a complex discipline, but teaching anatomy has been made easier due to the use of technological advances. In particular, the technologies that facilitate the spatial visualization and comprehension of anatomical structures have shown some advantages for students in comparison with non-computer-assisted classical methods. For example, a meta-analysis showed that three-dimensional (3D) visualization helped undergraduate and graduate students of health professions to

*Correspondence to: Dr. Magdalena Mendez-Lopez, Departamento de Psicología y Sociología. Universidad de Zaragoza. IIS Aragón. Facultad de Ciencias Sociales y Humanas. Campus Ciudad Escolar s/n. E-44003 Teruel, Spain. E-mail: mmendez@unizar.es

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improve their factual and spatial knowledge when compared with traditional methods, such as two-dimensional (2D) textbook images, lectures, and prosections (Yammine and Violato, 2015). Also, the students' perceptions of the 3D visualization methods were very positive in aspects such as satisfaction and usefulness. Virtual reality (VR) and augmented reality (AR) are examples of new visualization technologies that provide 3D visualization and manipulation of anatomical structures. In VR-based applications, the learning contents are computer simulations that replace the real world. In AR-based applications, digital learning contents are added to the existing reality. Both types of technologies seek to improve undergraduate and graduate students' learning of anatomy. For example, computer software was developed to learn gross anatomy (e.g., heart, pelvis, neck, and head) and neuroanatomy (e.g., cranial nerves and vascular system) using non-stereoscopic 3D images (Peterson and Mlynarczyk, 2016). Depth perception can be achieved using autostereoscopic displays. For example, dental students learned about both teeth placement and morphology using an autostereoscopic screen and gesture interaction (Rodríguez-Andrés et al., 2017). Other examples of VR applications were developed to learn neuroanatomical structures that were visualized in 3D using a wearable device, such as a stereoscopic glass (Kockro et al., 2015) or a headset (Stepan et al., 2017; Ekstrand et al., 2018). In the case of AR, this technology was used in applications to learn gross anatomy (Kurniawan et al., 2018; Layona et al., 2018; Bork et al., 2019), dental morphology (Juan et al., 2016), the lower limbs (Bogomolova et al., 2020), the parts of the skull (Chien et al., 2010; Moro et al., 2017), the head and neck (Weeks et al., 2021), the pathways of the medulla spinalis (Küçük et al., 2016), the flow of cerebral spinal fluid and the touch-stimulus pathway (Weeks and Amiel, 2019), and the subcortical structures of the brain (Henssen et al., 2020). In addition, VR- and AR-based applications to train surgical skills facilitated both fast learning and assessment (Sheik-Ali et al., 2019), although the AR tools need to improve their usability and accuracy (Cho et al., 2020).

Innovative 3D anatomical models based on digital formats of visualization can complement or replace the more traditional models (e.g., cadaveric models, plastic models, textbooks, videos, or slides). In some cases, the innovative models have not been as good as classic models for learning. For example, for the learning of the pelvis, knowledge gains were greater if students used a plastic model of the pelvis than if they visualized a slide presentation containing photographs of key views of the plastic model or a 3D model based on nonstereoscopic VR (Khot et al., 2013), or VR-based models with different degrees of stereopsis (Wainman et al., 2020). A similar conclusion was reached when the learning effectiveness of a plastic model of an equine foot was compared with a textbook and a 3D model based on nonstereoscopic VR for computers (Preece et al., 2013). However, most studies indicate that learning using models based on VR and AR is motivating, easy, or entertaining, even if it does not involve a significant knowledge gain compared to other types of traditional models (Hackett and Proctor, 2016). Furthermore, a recent meta-analysis confirms the educational potential of VR and AR despite not achieving better knowledge scores than other methods (Moro et al., 2021a).

Visualization technology based on AR and VR is helpful to learn certain anatomical contents of high spatial complexity, as is the case of neuroanatomy. Hence, many systems based on VR and AR have been developed to improve the study of neuroanatomy in the last decade. The VR videos based on stereoscopic 3D visualization are useful to teach future neurosurgeons. The discrimination of a target neuroanatomical region from others was facilitated with these videos, thanks to the high quality of the images. However, negative factors, such as cybersickness and the high cost of some equipment, prevent further implementation in teaching routines (Rubio et al., 2020). A description of the AR-based methods to learn neuroanatomy is provided below.

There are many factors to consider for the successful implementation of educational technologies. Some of them are related to the learners' characteristics. Considering, in particular, the learning of anatomy, spatial skills have been extensively investigated. However, the user's experience with information and communication technologies (ICTs) and their attitude toward the learning process are factors that have been poorly studied in the context of teaching anatomy with VR and AR technologies (Uruthiralingam and Rea, 2020).

There is a wide range of healthcare professions that requires knowledge of neuroanatomy (Moxham et al., 2015). The students of health sciences may differ in their area of specialization at the university and pre-university contexts. Most of the studies about how new visualization technologies facilitate the learning of neuroanatomy were restricted to medical students, as a review pointed out (Preim and Saalfeld, 2018). Little is known about how these technologies can be applied to psychology students.

Degree in Psychology and Learning Difficulties in Neuroanatomy

It has been shown that students with an educational background in natural sciences, technology, and mathematical reasoning have better spatial and visual skills than students with a more heterogeneous educational background (Peters et al., 2006). In the psychology degree, the area of specialization is mainly related to natural sciences, but also to social sciences and humanities. Neuroanatomy is part of the teaching program during the first two years of this degree and is taught in subjects related to behavioral neurosciences (Moxham et al., 2015). The main materials used by psychology students for the visualization of neuroanatomical contents are static: textbooks, atlases, and slides. However, other web-based sources with images and animations in 3D are also available for students as a compliment in their education (e.g., Allen Human Brain Atlas, 2010; Hawrylycz et al., 2012). Based on students' learning outcomes and the informal observations made by the authors during teaching and tutoring, it is difficult for psychology students to learn neuroanatomy. This fact can be extrapolated to the students of several healthcare disciplines. Medical, dental surgery, occupational therapy, and speech-language sciences students perceived neuroanatomy as the most difficult area among other areas of anatomy (Javaid et al., 2018). This perception of difficulty was related to these students' lower levels of interest and knowledge but there are also several intrinsic factors of neuroanatomy that explain its difficulty: the terminology, the vast body of information, the relationship among micro (e.g., genetic) and macro systems (e.g., neuroendocrine pathways), and the spatial visualization of structures (Javaid et al., 2018).

Different educational pedagogies have been developed to overcome these difficulties. An analysis of the perception of the usefulness of three methods (computer-based tools, prosection-based tutorials, and bedside teaching) in students of preclinical and clinical years showed that computer-based tools helped more in the study of neuroanatomy during the clinical years. Also, the qualitative assessment of the students' opinions showed that computer-based tools were of particular interest, facilitating the visualization of structures of the deep brain (Javaid et al., 2018).

Augmented Reality Tools of Neuroanatomy

In AR applications, virtual objects are superimposed on the real-world viewed through mobile devices or headsets. Using AR applications, students can interact both with real-world and virtual items in real-time without experiencing the negative side effects typically associated with VR technology (e.g., vertigo or nausea) (Johnson, 2005). The discomfort due to the use of VR is stronger than the discomfort due to the use of AR. A study compared the symptoms associated with three types of interactive technologies that were used for the learning of the skull (Moro et al., 2017). Students engaged in a lesson about the skull visualized and manipulated a digital model of the skull using one of the following systems: a headset for the full immersion of the user in a virtual environment that included the 3D virtual model, a tablet-based AR application on which the 3D model was superimposed onto the real-world, or a tablet application that showed a pseudo-3D model. The immersive VR system caused more discomfort, headache, dizziness, nausea, and disorientation than the AR and tablet applications. All the systems were effective in teaching skull, but the students enjoyed, engaged in, and interacted more using the VR and AR systems. Thus, the study confirms that adopting the AR technology in the design of tools for the instruction of neuroanatomy has additional advantages.

An important advantage of AR applications for the education of anatomy is associated with the 3D visualization of anatomical structures from different angles. For example, the musculoskeletal system of the lower leg was studied using an application that represented a stereoscopic AR model. The AR application facilitated the dynamic exploration of the model. The learning results with this application were compared with the learning results obtained after using a monoscopic 3D model and a 2D atlas. The students with lower spatial skills had better results in a knowledge test using the AR method than using the other two methods (Bogomolova et al., 2020). The authors suggested that the quality of the model and the dynamic exploration contributed positively to the learning effectiveness of the AR.

Another interesting feature of AR in the teaching of anatomy is that the virtual anatomical images can be superimposed onto the real bodies of students, teachers, or cadavers. The body works as a reference to which internal anatomical structures are added. An example of this type of AR tool is the mirror system, in which the virtual anatomy model is superimposed on top of the user's digital mirror image (Bork et al., 2019). This system was compared with a system that used photographs of cryosections in medical students who were learning gross anatomy. The AR system used a screen for the presentation of the digital images and hand-gesture interaction for their manipulation, whereas the photographs of cryosections were presented on a large touch-screen in the alternative system. The AR-based system was more effective for teaching gross anatomy in medical students with low spatial skills than the alternative system (Bork et al., 2019).

A literature review conducted from an engineering approach was centered on considering AR applications developed with contents of the nervous system and based on gesture interaction (Wirza et al., 2020). The review showed that the use of AR technology for the visualization of the nervous system increased over the last three years. Only four papers considered this technology in 2011, but there were fifteen papers in 2018. This fact suggests that AR has a very advantageous position in the group of technologies used to display and manipulate the nervous system. Also, a review of educational strategies for teaching neuroanatomy has documented that eight studies have tested 3D methods (Sotgiu et al., 2020). Some of these methods were VR-based and stereo viewing methods that have been developed and tested for the learning of vascular and ventricular systems (Stepan et al., 2017), skull (Kockro et al., 2015; Goodarzi et al., 2017), and brain structures and cranial nerves (Kockro et al., 2015). However, only one of these 3D methods consisted of an AR application, which is described below (Küçük et al., 2016). Therefore, more research is needed to document the effectiveness of AR from an educational perspective.

Küçük et al. (2016) developed a mobile AR application for the learning of pathways of the medulla spinalis. The content of the application was selected according to the opinions of medical students, who indicated that the medulla spinalis is the most difficult subject of anatomy. These authors used the idea of the MagicBook, which was first proposed by Billinghurst et al. (2001). The MagicBook is an AR interface that uses a real physical book and augments its pages with virtual content. The virtual content is shown on the pages when the images of the pages are captured by the camera of the mobile device and recognized by the mobile app. Küçük et al. (2016) created their MagicBook using the Aurasma platform. Their augmented content consisted of a 3D human anatomy model, video animations (six animations lasting three to five minutes), and two diagrams. This application showed positive results in 34 students, who used it as an additional learning methodology. The control condition was followed by 36 students, who only used traditional methods (i.e., text, graphs, and 2D images), and was used to establish comparisons. The results indicated that students who used the application achieved higher learning outcomes and lower cognitive loads than those who did not use them (Küçük et al., 2016).

Other researchers applied the possibilities of AR to develop mobile applications to visualize the anatomy of the human head but these applications were only tested technically (Soeiro et al., 2015; Jain et al., 2017). Soeiro et al. (2015) developed an application that shows the cortical areas of the brain to facilitate the location of target regions where transcranial magnetic stimulation therapy can be applied. The application allows the user to select the cortical area to be displayed. Then, the selected area is visualized in a different color. This AR application works in combination with a physical model of the human head with several markers, which were used as image targets. The application of Jain et al. (2017) allows the 3D visualization of different anatomical systems of the head and neck: muscular, vascular, skeletal, and nervous. These images are shown when the camera of the device focuses on an image target, which is printed on paper. This application allows examining the virtual models from different viewpoints and selecting/deselecting or highlighting various systems. The level of manipulation of the images is high in this AR application but it is not focused on the specific structures of the neuroanatomy of the brain. Also, AR was used to develop applications to visualize and manipulate the subparts of different pathways of the nervous system (e.g., the touch-stimulus pathway). A headset was used to present an immersive 3D visualization. A pilot study with medical students showed that the application was effective for learning and was more positively evaluated by the students in comparison with other resources that were not specified (Weeks and Amiel, 2019). Also, the same 3D immersive AR system was further exploited to present other learning contents (e.g., vascular system of the head and neck, and larynx), and was compared with the visualization in 2D of these contents using a laptop. The results confirmed that AR facilitates learning. The advantage of the AR method was related to students' higher motivation and the facilitation of spatial understanding (Weeks et al., 2021).

From the viewpoint of education in neuroanatomy, it would be interesting to develop an AR application for the 3D visualization of structures of the deep brain (Sotgiu et al., 2020). Also, the level of manipulation of the digital images should allow the options of selecting/deselecting particular structures (nuclei and ventricles). In line with this, physical models with a high level of manipulation of structures of the deep brain have shown positive results (Estevez et al., 2010). However, these physical models have disadvantages because of their cost and the inevitable damage caused by repeated handling. The mobile AR application of Henssen et al. (2020) meets many of the requirements that were previously mentioned. The application presents digital 3D images of internal parts of the brain and information about their function. The control of the application and rotation of the images is made by touching the screen of the mobile device used to run the application. The subcortical structures can be rotated, selected, and deselected, and different colors are used to differentiate each particular region. The application was tested in medical students, and drawings of cross-sections were used as the alternative method. Learning gains after using each method and students' opinions were compared. The results indicated that the AR application can be a good complement for the teaching of internal parts of the brain. Both methods were effective for learning and motivated the students in their learning process. More recently, Moro et al. (2021b) compared learning gains and usability factors of an AR application of the brain that was run on a tablet-based or a HoloLens-based device. Lessons with the application involved the visualization of the regions of the brain in 3D and the rotation of the images. Also, the application allows learning more about the main parts of the brain through animated tutorials with audio, where the different parts of the 3D model are highlighted according to the narration. The results of the comparisons between the devices showed that both methods were effective. However, the study also suggests that the tablet is the device of choice to prevent dizziness.

Characteristics of the Learners

Because of the spatial complexity of anatomy, many studies have explored the impact of visuospatial skills on its learning. In most of the studies, the level of spatial ability was determined with psychometric tests consisting of the spatial visualization and mental rotation of figures (Langlois et al., 2017). The scores of standardized tests of visuospatial ability were significantly related to the learning outcomes obtained in neuroanatomy (Levinson et al., 2007; Allen et al., 2016) and in other anatomical systems (Stull et al., 2009; Nguyen et al., 2012, 2014; Jamil et al., 2019). However, the students' subjective evaluations of the learning method used were not significantly related to their level of visuospatial ability (Ruisoto et al., 2014).

The type of visualization used for learning might not be equally effective in all students. In line with this, Nguyen et al. (2012) showed that a computer software enhancing dynamic visualizations in 3D of tubular anatomical structures was suitable for students with a high level of visuospatial ability, whereas students with a lower level of visuospatial ability learned better with the static visualization of geometric anatomical models (Nguyen et al., 2012). However, another study reported that dynamic visualizations were useful for students with a low level of visuospatial ability (Berney et al., 2015). For other researchers, 3D visualization using computer software was effective to improve students' knowledge, regardless of their level of visuospatial ability (Allen et al., 2016; Jamil et al., 2019). Some visual aids could help, for example, in the case of a learning activity about the brain surface anatomy using key views displayed on a computer. This activity facilitated the learning of the students with lower spatial ability, but they learned worse with an activity that used multiple views of the surface of the brain (Levinson et al., 2007). Also, the addition of orientation references facilitated the learning of the anatomical parts of bones (e.g., cervical vertebra) in students with lower spatial ability. They used a computer to visualize virtual models, which could be rotated using the keyboard to view them from different angles. These references helped the students to interpret the spatial position of the virtual models when they were rotated to uncommon perspectives of visualization (Stull et al., 2009).

The type of assessment approach had an impact, revealing significant associations between visuospatial ability and learning outcomes when the learning outcomes were measured using approaches based on practical testing or tasks involving some level of visuospatial reasoning (Langlois et al., 2017). In contrast, no associations were found when knowledge about anatomy was tested using written responses, multiple-choice tests, or labeling images (Sweeney et al., 2014). In addition, the contribution of the students' level of spatial ability in explaining their success in the learning of anatomy was directly related to the level of specialization of the course (Sweeney et al., 2014).

Students' prior knowledge is another factor that influences the effectiveness of a learning method. Postgraduate students in medicine or neuropsychology with professional experience performed better in the identification of brain structures than graduates in medicine and psychology (Ruisoto et al., 2012). A factor that could mediate the relationship between the learning outcomes in neuroanatomy and prior knowledge is the level of visuospatial ability. Knowledge about the spatial relationships among regions of the nervous system has also been positively associated with spatial ability assessed using a standardized test (Allen et al., 2016). In line with this, and as suggested by other studies, experience in neuroanatomy not only helps the understanding of neuroanatomic tasks (Ruisoto et al., 2012) but also improves the level of visuospatial ability through a training process (Fernandez et al., 2011; Vorstenbosch et al., 2013).

Research indicates that students' previous experience with ICTs has contributed positively to the acceptance of technologies for anatomy education (Yeom et al., 2017). University students with experience in the use of 3D computer visualization methods scored higher in computer software about several anatomical systems, which combined visual information about anatomical structures and the possibility of selecting and rotating these structures using a haptic device. The positively affected scores were the usability of the method and the willingness to use it in the future. Also, the students' previous experience with 3D visualization was directly related to higher learning outcomes but these outcomes were measured using the same system as used for learning the anatomy concepts. Therefore, familiarity with some aspects of the system could explain this relationship (Yeom et al., 2017). In contrast, several studies have shown that previous experience with ICTs did not affect the learning outcomes when they were assessed using traditional questions (Yammine and Violato, 2015). Previous experience with 3D visualization software or the frequency of computer use, mainly to play games, did not improve the learning outcomes in neuroanatomy when these outcomes were measured through questions about the identification of structures and/or spatial relationships among structures (Berney et al., 2015; Yammine and Violato, 2015).

The attitude toward the learning process and its relationship with the success of innovative new methods to learn anatomy have been poorly studied in higher education. One study showed that the type of learning style of medical students is a factor that influences their confidence in the usefulness of a method to improve their knowledge of Anatomy (Gradl-Dietsch et al., 2016). An approach to study students' success and motivation in the use of certain technology for learning is to consider the students' type of learning goal orientation. Based on the Situated Goals Questionnaire (Alonso-Tapia et al., 2018), which was developed for assessing learning goals in higher education according to the person-situation interaction model, there are three types of learning goals: learning orientation, performance orientation, and avoidance orientation. The learning orientation is defined as the desire to learn and be useful to others; the performance orientation is related to the desire to pass and obtain good grades; the avoidance orientation is associated with the desire to evade work and to avoid failure. The learning orientation is positively related to satisfaction with tuition mediated by technology and to academic performance (Klein et al., 2006), although students' learning goal orientation is a variable that has not yet been considered in the study of the feasibility of new methods for education in Anatomy.

The Current Study

Taken into account the following: (i) students of psychology could benefit from 3D visualization methods for learning neuroanatomy; (ii) applications based on AR technology have been poorly exploited in the field of neuroanatomy education but the 3D visualization and manipulation of images facilitates it and does not cause side effects; the purposes of this study were: (i) to develop a mobile AR application aimed at providing morphological and functional information of the brain. The morphological information should be visualized in 3D and from multiple angles and should include deep and superficial structures of the brain. (ii) To conduct a study of the feasibility of this AR application for the teaching of neuroanatomy in comparison with a textbook (i.e., 3D method vs. 2D method) in psychology students.

A mixed design was applied, where experimental and correlational methods were combined. Concerning the experimental design, psychology students were assigned to one of the two learning conditions to acquire knowledge about several structures of the brain: a 3D method of learning through the AR application or a 2D method of learning through the textbook. Differences between the methods in the primary outcome (i.e., knowledge acquired after using the method) and secondary outcomes (i.e., perceptions of satisfaction with the experience and the method) were studied. The authors hypothesized that the primary outcome obtained with the use of the 3D method would be similar, or potentially superior, to the primary outcome obtained with the use of the 2D method. Additionally, the secondary outcomes were expected to be significantly higher after using the 3D method.

MATERIALS AND METHODS

Participants

A sample of 69 students (4 males) in the second year of their psychology degree in a Spanish University voluntarily participated in the study. They were taking the subject neuropsychology and had previously completed two other subjects with neuroanatomical contents. These students were taught according to traditional 2D methods and were not mediated by ICTs. No student had any experience with AR technology. The participants signed written informed consent to participate in the study. This consent form consisted of information about the aims and procedures of the study. It also indicated that participants were free to leave the study at any time. The research protocol was approved by the University of Zaragoza (Spain) under the reference PIIDUZ_15_012 and the Ethics Committee of the Universitat Politècnica de València under the project AR3Senses.

The final studied population consisted of 67 students because 2 students did not complete all the sessions of the study. Students were pseudorandomly assigned to learning specific contents of neuroanatomy following one of the two visualization methods: a traditional 2D method, or a 3D method. For the assignment, the students were ordered on a list according to the time of signing the informed consent. Then, the listed students were alternatively assigned to one of the methods, starting with the 2D method (i.e., the first on the list was assigned to the 2D method, the second on the list was assigned to the 3D method, and so on). In order to maintain a comparable number of males engaged in each method, this assignment procedure was performed separately in the case of the male students. The resulting groups (2D group and 3D group) were comparable according to students' characteristics. These characteristics are shown in Table 1.

Course Description

As stated above, the curriculum of the psychology degree comprised three compulsory subjects with neuroanatomical contents. These subjects were taught within a semester and were: Foundations of Psychobiology I (first year and first semester), Foundations of Psychobiology II (second year and first semester), and Neuropsychology (second year and second semester). Each subject consists of 60 teaching hours, which are distributed in four sessions a week for 15 weeks. Each week includes two hours of lectures and two hours of laboratory sessions. The hours of lectures include the slide projection of images from the following sources: specimens, atlases, neuroimaging techniques, and didactic drawings. The hours of laboratory sessions include the use of a microscope

Table 1.

Demographic Characteristics and Previous Experience with Technologies of the Studied Population by Group

	Groups	
Characteristics	**2D Method *n* (%)**	**3D Method *n* (%)**
Total number of students	33 (100.0)	34 (100.0)
Age, years, mean (±SD)	20.2 (±2.1)	20.0 (±1.2)
Females	31 (94.0)	32 (94.1)
Males	2 (6.0)	2 (5.9)
Right-handed	29 (87.9)	32 (94.1)
Students who repeated the subject	1 (3.0)	1 (2.9)
Students who owned a tablet	11 (33.2)	14 (41.1)
Previous experience with technologies used for learning or entertainment purposes,[a] mean (±SD)	4.08 (±0.41)	4.22 (±0.18)

[a]The score was obtained from the Experience with Technologies Survey reported as mean (±SD), maximum score = 5 points; the groups did not differ in their level of previous experience ($t_{(65)} = 1.06$, $P = 0.29$); *SD* = Standard Deviation.

with glass histologic slides, plastic models, atlases, presentation slides, clinical cases, and drawings. Cadaveric brains for dissection or prosections are not used. The neuroanatomical contents are taught using a functional approach, the topics of neuroanatomy are taught due to their relevance in a specific psychological function.

The learning contents of neuroanatomy in the subject neuropsychology differ from the learning contents of the two previous subjects. On the one hand, in Foundations of Psychobiology I, students learn about the general organization and development of the nervous system. Deepening into the functional circuits and their detailed components is not provided. On the other hand, Foundations of Psychobiology II involves the description of the functional circuits of the hypothalamus and the limbic system, and their role in sleep, ingestive, emotional, learning, and sexual behavior. Finally, neuropsychology consists of the description of the functional circuits for motor responses and cognitive processes, on which subcortical and cortical structures interact.

In the psychology curricula, knowledge of neuroanatomy is assessed with a written examination. No practical examination is used. Regarding the course of the study, students' knowledge of neuroanatomy was assessed using the compulsory final examination and monthly exercises or reports. The visual understanding of neuroanatomy was specifically assessed with questions about the spatial identification of a set of given regions in three to six 2D images. There were also questions about the identification of regions, given an explanation of functions or a set of symptoms associated with a certain lesion.

Visualization Methods and Learning Materials

Two visualization methods were considered for the learning intervention. Both methods are used to learn the morphology and function of the human brain. The first consisted of a 2D visualization using a traditional textbook designed, among others, for psychology students (Diamond et al., 2010). The textbook contains pictures to color to facilitate learning. The second method consisted of a 3D visualization using an AR application developed by the Universitat Politècnica de València and designed for mobile devices.

The AR application shows up to seventy-two 3D structures of the brain on a tablet or smartphone screen when the camera of the device focuses on an image target (Fig. 1). The AR application shows the selected structures in three dimensions and the technical name and additional information associated with each structure. Brain structures are displayed on the image target using the coordinate system located in the center of this image target. As soon as the image target is detected, the volume containing all of the brain structures is superimposed on this image, with a high level of transparency (Fig. 1A). After this detection, the camera of the device can be zoomed in, zoomed out, rotated, raised, lowered, and moved at the user's discretion to observe the structures from any position. Another possibility is to move the image target so that the virtual 3D structures move according to the image target's size and position. The 3D structures can also be rotated by the touch capabilities of the mobile device. That is, the user drags their finger across the screen, and all of the structures rotate around the image target (*Y* axis) in the direction of the finger (Fig. 1B). A menu appears on the right-hand side of the screen that shows the following options: ADD ALL, CLEAR ALL, TEXT, GET TARGET. The ADD ALL option allows selecting all the structures (Fig. 1B). The CLEAR ALL option allows deselecting all the structures. The TEXT option enables the text to be displayed for the structure that is being viewed at a certain moment (Fig. 1C). The GET TARGET option allows downloading the target to be used. To the right of this menu appear 72 structures that can be selected/deselected just by clicking on the structure's name (Fig. 1D). The application was developed using the Unity multiplatform videogame engine, version 3.5 (Unity Technologies ApS, San Francisco, CA), with

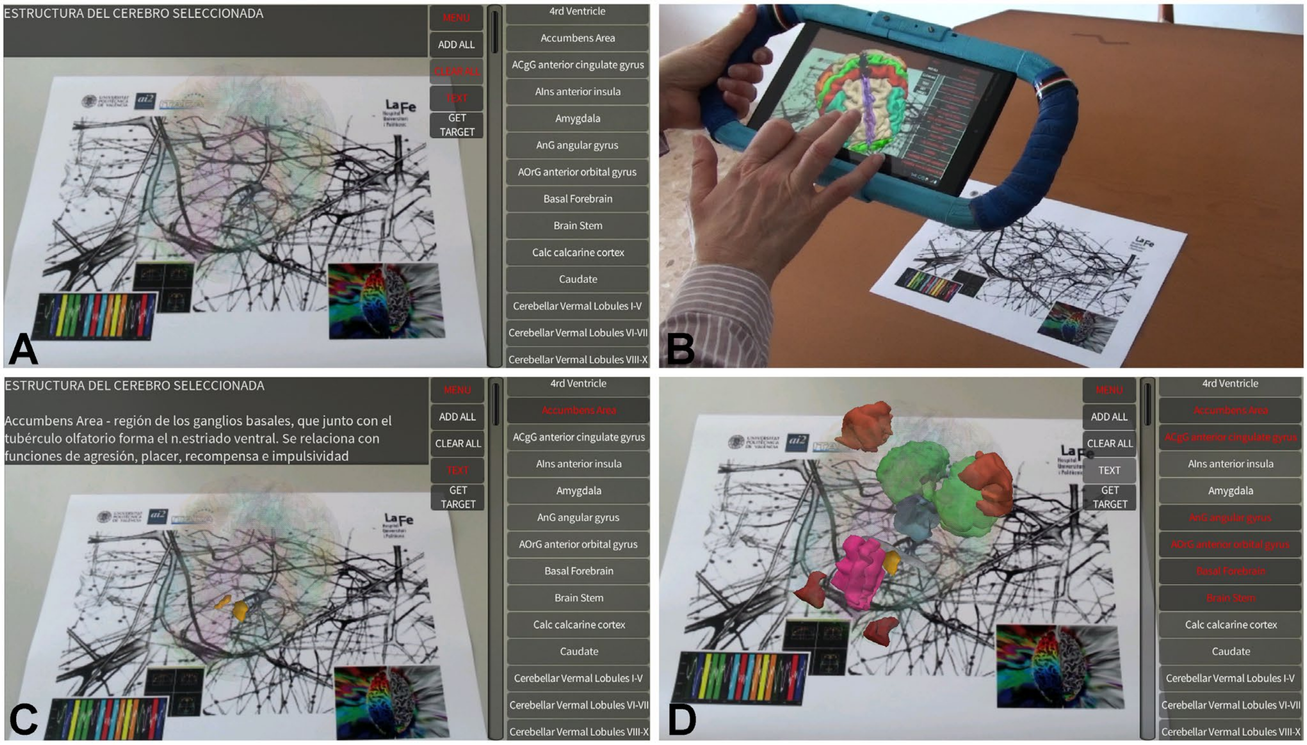

Figure 1.

The augmented reality (AR) application developed and used for the intervention using the 3D method. A, A screenshot of the initial screen of the application, which displays the image captured by the device's camera where all of the brain structures are transparently superimposed on the image target; B, A user is moving the image target. The ADD ALL option has been selected, and all the structures are shown with different colors; C, An example where the "Accumbens Area" structure has been selected. The text option is on and the name and related information of the selected structure are displayed at the top of the screen; and D, A screenshot of the application where a user is selecting different structures.

the integration of Vuforia software development kit (SDK) version 2.0.31 (Qualcomm's Austria Research Center GmbH, Deutschlandsberg, Austria). The scripts were written in C#. The 3D meshes of the brain structures were provided in (.STL) file format with a very large number of polygons. This large number of polygons was reduced using Autodesk® 3ds Max® (Autodesk Inc., San Rafael, CA). The development and validation of the AR application were achieved using a mobile device, a Motorola XOOM 2 MZ615 tablet (Motorola Mobility LLC, Chicago, IL) with Android OS, version 3.2 (Honeycomb, Open Handset Alliance, Mountain View, CA). The main features of this tablet are: screen size: 8.2″; resolution: 1280 × 800 pixels; weight: 396 grams; and camera of 5-megapixel resolution. All the students used the AR application with this tablet for the 3D visualization condition. However, the application can run on any Android device. An external case, which was designed and printed by the authors of the study on a RapMan 3.1 3D printer (Bits From Bytes Ltd., Clevedon, UK) was used to facilitate handling and protecting the device (Juan et al., 2014).

The learning intervention was proposed by the teacher as a voluntary activity for the 103 students of the subject neuropsychology. Students were informed that they would participate in an anatomy learning activity using certain methods. It would imply that they should participate in two sessions and that they would complete information about themselves, in aspects related to their knowledge of neuroanatomy, learning goals, spatial ability, and opinions of the methods. The sessions were scheduled at different times from those scheduled for the subject. There were 69 volunteers. They participated individually in the learning activity monitored by the teacher for about 1 hour. The principal aim of the activity was to engage each student in a learning experience about the location and function of certain regions of the brain using one of the two methods considered: textbook or AR application. After that, each student would use the alternative method to comment on their preference. Each student played an active role during the learning activity. Each student had a tutorial that was written and printed on a sheet of paper to guide them in the activity and the use of the method. Two tutorials were adapted for each visualization method. Both tutorials shared a common format: (i) a description of the method with instructions on how to use the textbook/application to view and read neuroanatomical information; and (ii) instructions about the learning goals: to learn the location and function of nine regions with the textbook/application (i.e., lateral ventricle, pallidum, putamen, caudate, thalamus proper, amygdala, hippocampus, postcentral gyrus, and precentral gyrus). The teacher also gave a brief verbal explanation of the use of the textbook/application and the learning goals. After this, the teacher only took part if a student raised any questions. Then, students freely explored the assigned method to learn the neuroanatomical information. The learning goals involved a review of the function and location of some parts of the brain, which had already been learned in previous subjects (i.e., ventricles and diencephalon), and also learning new information about the regions involved in motor and memory functions (i.e., basal ganglia, motor cortex, and medial temporal lobe). Three–four weeks before, these new contents were described to the students who attended the lectures (i.e., verbal explanations and projection of didactic drawings and neuroimaging images). In this learning activity, information about the location and functional role of structures was provided in the same format (i.e., AR application or textbook). Besides this, the use of the AR application facilitated, for example, observing the structures in 3D and from any position, selecting those structures of interest at a certain moment, adding more structures to check their spatial relationship, and reading about them easily by clicking on the TEXT option.

Questionnaires for Testing Students' Satisfaction with the Learning Experience and the Learning Visualization Method

These questionnaires were developed by the authors, who have extensive experience in the design of questionnaires for the validation of educational tools (e.g., Furio et al., 2013; Juan et al., 2016). The questionnaires were not tested prior to administration.

Learning experience survey (LES). This survey was developed to assess self-reported satisfaction with the learning experience. The LES consisted of four items that were rated on a five-point Likert scale. Two examples of items of the LES are: I would repeat this experience this way (Item #1); and This learning experience, compared to other learning experiences that I have had, is … (Item #3). The LES is provided as Supplemental Material File S1. The mean score of all items was calculated (minimum score is 1 point and maximum score is 5 points). The LES had high reliability in this study, Cronbach's $\alpha = 0.76$.

Learning method survey (LMS). This survey was developed to assess self-reported satisfaction with the learning visualization method. The LMS consisted of nine items that were rated on a five-point Likert scale. Two examples of items of the LMS are: The method is easy to use (Item #1); and The visualization method helped me to get an idea of how regions in the brain are related spatially (Item #5). The LMS is provided as Supplemental Material File S2. The mean score of all items was calculated (minimum score is 1 point and maximum score is 5 points). The LMS had high reliability in this study, Cronbach's $\alpha = 0.79$.

Preference assessment. To assess students' preference for one of the two visualization methods used in this study, they completed two statements that were considered separately for analysis: I find it easier to learn with …, and I would rather learn with …, with one of these options: textbook (2D), and tablet (3D). Frequencies were considered for analyses (minimum frequency was 0 and maximum frequency was 67).

Questionnaire for Testing Previous Experience with Technologies

Experience with technologies survey (ETS). This survey was developed by the authors to assess the self-reported level of previous experience with technologies for learning or entertainment purposes. The ETS consisted of four items on which the students determined the frequency of use of technologies from 1 (never) to 6 (more than 3 hours a day). An example of an item of the ETS is: I use the smartphone or tablet to view or check information (Item #1). The ETS is provided as Supplemental Material File S3. The mean score of all items was calculated (minimum score is 1 point and maximum score is 6 points).

Instruments for the Assessment of Students' Knowledge of Neuroanatomy

Knowledge questionnaire (KQ). A questionnaire to assess students' knowledge of neuroanatomy was designed using eight questions (an example of the questionnaire can be seen in Fig. 2). The KQ comprised a written list of six regions of the brain for their identification in black-and-white images and two brain regions for the recalling of their functional role. The images used for identification were selected from the modified (Hawrylycz et al., 2012) Allen Human Brain Atlas (2010). These brain regions included regions of the brain's surface area and regions of internal parts of the brain. The questions about identification determined whether the learners could infer the spatial location of brain regions in images other than those used for learning. The KQ had a minimum score of 0 points and a maximum score of 8 points. The KQ had two forms, depending on when it was completed by the students. The Prior Knowledge Questionnaire (P-KQ) was completed at the beginning of the study to compare the baseline knowledge between the groups of students assigned to each of the two visualization methods considered. The Acquired Knowledge Questionnaire (A-KQ) was completed two months later, after the learning activity with one of the two visualization methods considered. All results of the KQ have been provided in percentages to facilitate comparability with other studies.

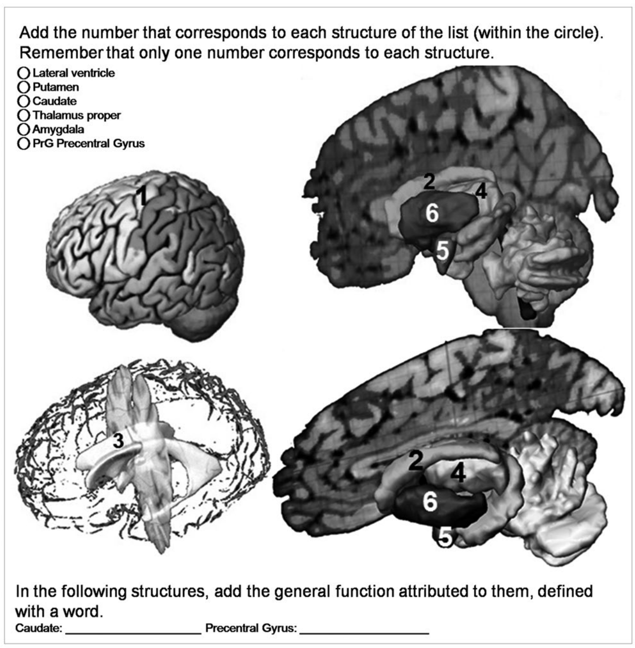

Figure 2.

The Knowledge Questionnaire used for the assessment of participants' knowledge of Neuroanatomy. The images were taken with permission from the Allen Human Brain Atlas (2010), Allen Institute, Seattle WA.

Psychometric Tests

Solid figures rotation test (SFRT). The SFRT was used to assess the students' spatial ability of mental rotation. The SFRT is a paper-and-pencil test composed of 21 items that measure the ability to recognize and interpret objects in space (Yela, 1968). The direct scores on the test were obtained for analysis using following formula: direct score = successes – errors / 4 (minimum direct score is –5 points and maximum direct score is 21 points).

Situated goal questionnaire for university students (SGQ-U). The SGQ-U was used to assess the students' learning goal orientations (Alonso-Tapia et al., 2018). The SGQ-U consists of 30 items rated on a five-point Likert scale. The SGQ-U assesses six goals (desire to learn, desire to be useful, desire to obtain good grades, desire to pass, desire to avoid failure, and desire to avoid work), related to five different types of tasks (examinations, projects, exercises, group tasks, and public presentations). Three learning goals are obtained with the SGQ-U: Learning Orientation (LO), Performance Orientation (PO), and Avoidance Orientation (AO). The questionnaire has good psychometric properties (Alonso-Tapia et al., 2018). The LO, PO, and AO scores were considered for analysis (minimum score is 10 points and maximum score is 50 points).

Procedure

First, potential participants were contacted and received information about the study. Once they consented to participate, they were scheduled for a collective session of approximately 40 minutes. In this session, they completed (in order of administration): SFRT, the P-KQ, SGQ-U, ETS, and a brief questionnaire of sociodemographic information. Two months later, they were scheduled for an individual session of approximately 45 minutes in which they received the learning intervention with the assigned method. To avoid an additional source of stress, no time limit was established. After the learning session, they completed the LES and the LMS. After a five-minute break, they filled out the A-KQ. Then, the teacher showed the alternative learning method and asked the participants to use it to consult a certain brain structure. The aim of this phase was to provide students with basic knowledge about how they could learn using the alternative method but they did not engage in a learning activity similar to that experienced during the learning intervention. Finally, they answered the two statements about their method of preference. A schematic diagram of the procedure is shown in Figure 3.

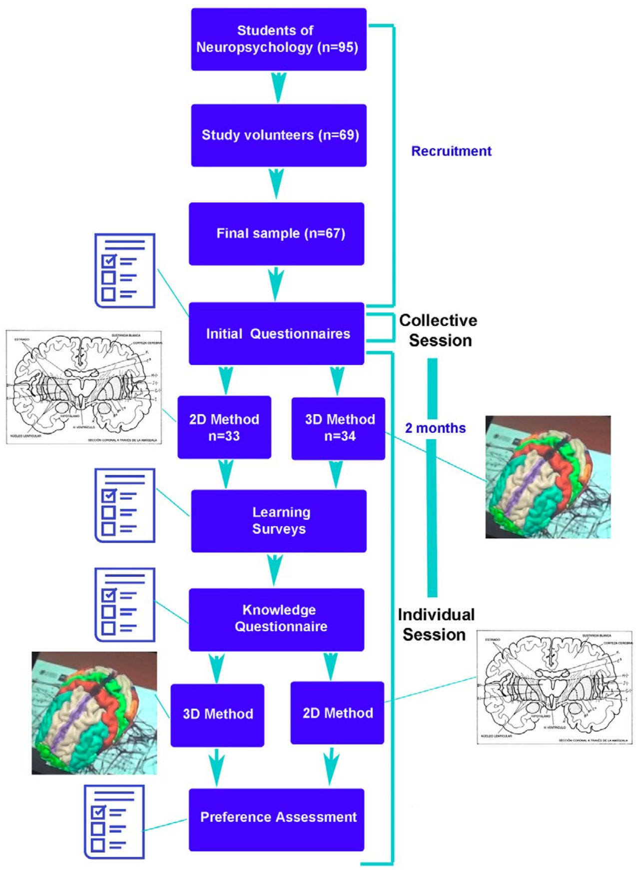

Figure 3.

Design of the procedure.

Statistical Analyses

The Shapiro-Wilk test was applied to check the normal distribution of the data set. The tests showed that only the ETS, the LMS, the SFRT, and the AO variables followed a normal distribution. However, Levene's tests showed that the variances between the 2D group and the 3D group were not homogeneous for the LMS variable. Therefore, Mann–Whitney tests were used to test group differences in the variables of satisfaction (LES and LMS), and performance (A-KQ). Pearson's chi-square was used to compare the groups' frequency of preference for the 3D method. Wilcoxon's signed-rank test was used to test intra-group differences between the scores of knowledge about Neuroanatomy obtained before and after the learning intervention (P-KQ vs. A-KQ). Partial Spearman correlations, controlling for the influence of the visualization method used in the learning intervention, were applied to determine the relationship between students' factors and their preference for the 3D method, regarding both their preference as an easy method for learning and their preference as a method used for learning.

The principal component analysis (PCA) was conducted to identify the presence of possible underlying factors in the sum of items of the LES and LMS. Before that, the sampling adequacy for PCA was conducted on the 13 items with the Varimax orthogonal rotation method. Sampling adequacy was good, as indicated by the Kaiser–Meyer–Olkin measure (KMO = 0.837; Kaiser, 1974), and Bartlett's sphericity test (χ^2 (78) = 382.52, $P < 0.001$; Bartlett, 1954). The limit of acceptance was < 0.50 for both statistics (Field, 2009). An analysis was conducted to obtain eigenvalues for each component of the data. The factor scores were calculated using the regression method, and the studied variables were grouped into four components. Then, Mann-Whitney tests were used to test differences between learning methods in the four components, as the data of these components were not normally distributed.

All P values were two-tailed, and the level of significance was $P < 0.05$. The IBM SPSS statistical package, version 26.0 (IBM Corp., Armonk, NY) was used to perform these statistical analyses. The data set is provided as Supplemental Material File S4.

RESULTS

Satisfaction, Performance, and Preference

After engagement in the learning activity, the students who used the 3D method reported higher satisfaction both with the learning experience and the visualization method than the students who used the 2D method ($U = 277.5$, $z = -3.7$, $P < 0.001$, $r = -0.45$ and $U = 334.0$, $z = -2.8$, $P = 0.004$, $r = -0.34$, respectively). Figure 4 shows the students' responses to the LES, and Figure 5 shows the students' responses to the LMS. The mean score of all of the items of each survey was considered for comparisons.

The two visualization methods used during the activity were similarly effective for learning. There were no differences between the scores of the A-KQ obtained by the groups of students that used each method (2D method: 75.0%, and 3D method: 62.5%; $U = 444.0$, $z = -1.5$, $P = 0.134$). The median values of these scores were considered. Table 2 shows the A-KQ scores, which were obtained after the activity, and the baseline score of knowledge, which was 37.5% for the two groups and was obtained from the P-KQ.

Once the students had tested both methods, they were asked about their preference using a preference assessment questionnaire that consisted of completing two statements (i.e., "I find it easier to learn with …" and "I would rather learn with …"). The students found it easier to learn with the 3D method. Based on the odds ratio, the odds of the students who considered the 3D method easier for learning were 12.3 times higher when they learned with the 3D method than when they learned with the 2D method (χ^2 (1) = 12.3, $P < 0.001$). Table 2 shows the number of students who preferred each of the two visualization methods. Similarly, the students preferred to use the 3D method for learning anatomy. The odds of the students who preferred to use the 3D method for learning were 5.9 times higher when they learned with the 3D method than when they learned with the 2D method (χ^2 (1) = 5.6, $P = 0.018$; Table 2).

Prior Knowledge versus Acquired Knowledge

Student's knowledge after the learning activity was tested with a knowledge questionnaire. The same questionnaire was administered two months before to obtain an index of the students' baseline level of knowledge (Fig. 2). Knowledge about Neuroanatomy was significantly higher after the learning intervention in both groups of students (2D group: $z = -4.5$, $P < 0.001$, $r = -0.78$; and 3D group: $z = -4.5$, $P < 0.001$, $r = -0.77$; Table 2). The improvement of the median score was 37.5% in the group that used the 2D visualization method and 31.25% in the group that used the 3D visualization method. This improvement did not differ significantly between the methods ($U = 505.0$, $z = -0.7$, $P = 0.478$).

Students' Factors Related to Preference for the 3D Method

The students' decision about the preference for the 3D method was conditioned by the method used for the learning intervention, as can be seen in the results of the preference assessment (Table 2). After extracting this factor, the students' factors that could be related to their preference for the 3D method were analyzed (Table 3). There was no significant relationship with the factors of satisfaction, knowledge, spatial ability, or learning goals. The students' experience with technologies was the only variable related to their preference. More specifically, the more experience with technologies the students had, the greater their preference for the 3D method as an easy method for learning ($r = 0.307$, $P = 0.012$). The correlation represents a small association.

Differences between the Learning Methods in the Students' Subjective Experience

Four factors were identified after conducting the PCA on the items of the LES and the LMS. These surveys tested the students' satisfaction both with the learning experience and the visualization method, respectively. Four components had

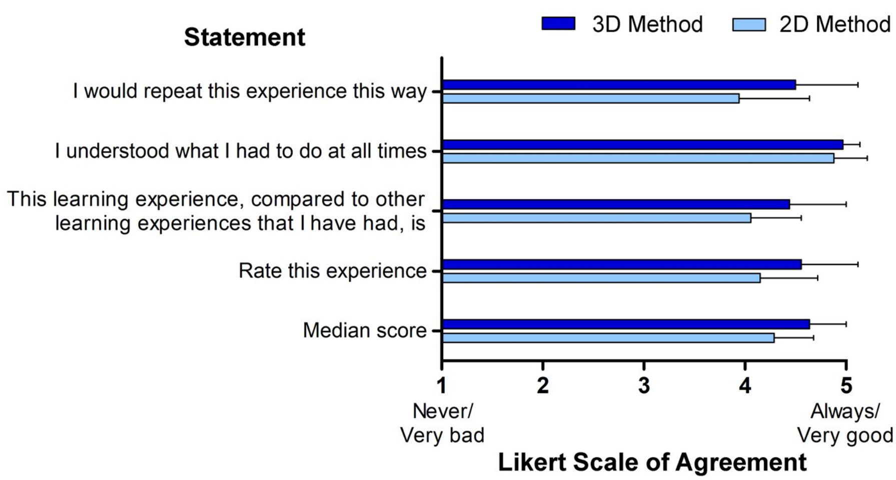

Figure 4.

Learning Experience Survey (LES) ratings after each learning activity with three-dimensional (3D) or two-dimensional (2D) method. Scores are reported as mean ± standard deviation. The comparison of the mean score of all of the items showed that the learning activity with the 3D method obtained significantly higher ratings.

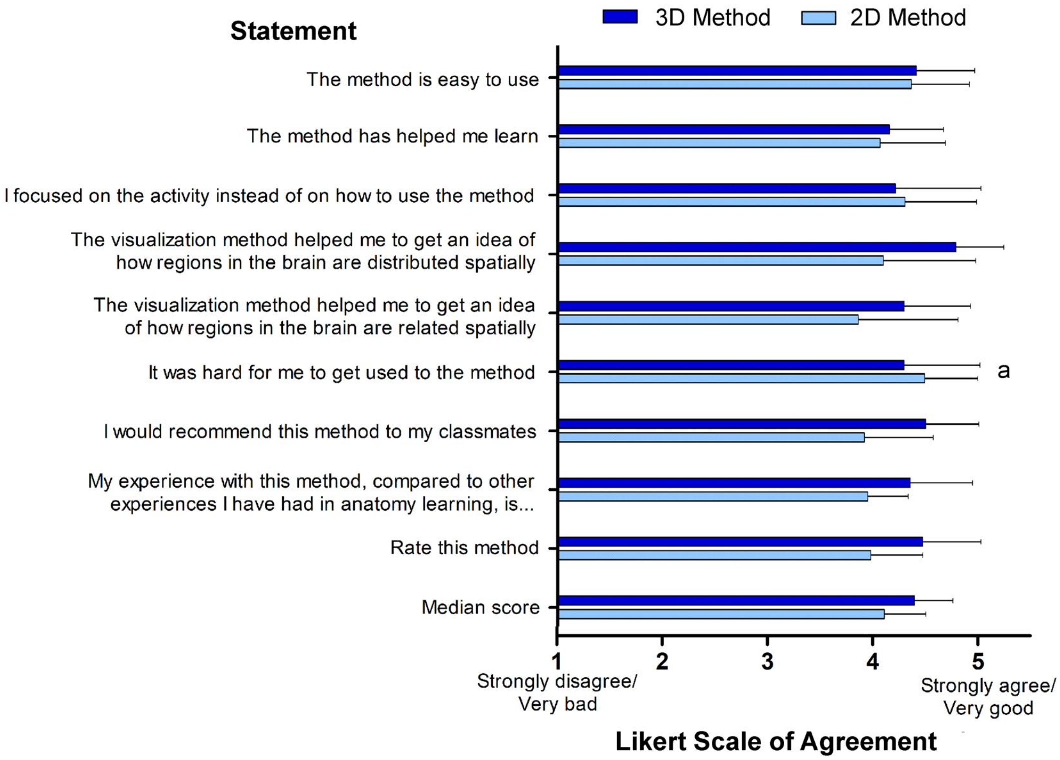

Figure 5.

Learning Method Survey (LMS) ratings after each learning activity with three-dimensional (3D) or two-dimensional (2D) method. Scores are reported as mean ± standard deviation. The comparison of the mean score of all of the items showed that the 3D method obtained significantly higher ratings. [a]Scores for this statement were reversed.

eigenvalues over Kaiser's criterion of 1 (Kaiser, 1960), and combined, they explained 68.83% of the variance. Factor loadings lower than 0.50 were not interpreted (Stevens, 2002). Table 4 shows the factor loadings of the items after rotation. Factor 1 represents "satisfaction," which involves the students' satisfaction both with the method of learning and the experience of learning using the method. Factor 2 represents "spatial understanding," which involves the utility of the method in the interpretation of both the spatial distribution and the spatial relationship among regions of the brain. Factor 3 represents

Table 2.

Comparison between the Two-Dimensional (2D) and Three-Dimensional (3D) Groups both in their Knowledge of Neuroanatomy and their Preference Assessment

	Groups	
Assessment	**2D method**	**3D method**
Total Number of Students, ***n*** (%)	33 (100.0)	34 (100.0)
Students' Knowledge		
Prior Knowledge Questionnaire, Mdn % (±SD)	37.5 (±18.3)	37.5 (±23.0)
Acquired Knowledge Questionnaire, Mdn % (±SD)[a]	75.0 (±20.2)	62.5 (±23.0)
Preference assessment[b]		
I find it easier to learn with 3D, ***n*** (%)	19 (57.5)	32 (94.1)
I would rather learn with 3D, ***n*** (%)	24 (72.7)	32 (94.1)

[a]Knowledge increased after the learning activity in both groups (comparison between Prior Knowledge Questionnaire and Acquired Knowledge Questionnaire);[b]The students preferred the 3D method over the 2D method; Mnd = Median; SD = Standard Deviation.

Table 3.

Partial Spearman Correlations Calculated

	Preference of the 3D method			
	Easy for learning		Used for learning	
Individual Factor	r[a]	P-value [b]	r[a]	P-value[b]
Satisfaction				
Learning Experience Survey	0.078	0.532	0.135	0.279
Learning Method Survey	0.119	0.343	0.101	0.419
Experience				
Experience with Technologies Survey[c]	**0.307**	**0.012**	–0.004	0.975
Knowledge				
Prior Knowledge Questionnaire	0.002	0.984	–0.173	0.166
Acquired Knowledge Questionnaire	0.065	0.605	0.053	0.671
Spatial Ability				
Solid Figures Rotation Test	0.211	0.089	0.102	0.413
Learning Goal				
Learning Orietantion	0.108	0.387	0.195	0.117
Performance Orientation	0.063	0.616	0.223	0.071
Avoidance Orientation	–0.062	0.620	–0.034	0.778

[a]Correlation coefficient values of ±0.1 represent a small effect, ±0.3 represent a medium effect, and ±0.5 represent a large effect;[b]The correlation coefficient is interpreted as significant when $P < 0.05$;[c]Students' previous experience with technologies was significantly related to their preference for the 3D method as an easy method for learning; bold type is used to indicate this significant relationship. Number of participants ($n = 67$).

"usability and utility," which involves the students' general perception of the ease of use of the method and the utility of the learning method. Finally, Factor 4 represents "cognitive load," which involves the students' perceived mental workload during the performance of the learning activity using the method.

Considering these factors, the comparison between each learning method revealed that the factor Satisfaction was higher in the students engaged in the activity with the 3D method than the students engaged in the activity with the 2D method ($U = 262.0$, $z = -3.7$, $P < 0.001$, $r = -0.45$). There were no other significant differences between the methods in the remaining factors that were compared (spatial understanding: $U = 414.0$, $z = -1.8$, $P = 0.065$, $r = -0.22$; usability and utility: $U = 442.0$, $z = -1.4$, $P = 0.136$, $r = -0.17$; cognitive load: $U = 557.0$, $z = -0.05$, $P = 0.96$, $r = -0.01$).

DISCUSSION

The AR application developed met the requirements proposed. The students could obtain information about the morphology and functionality of brain regions of interest with the AR application. The tablet was a suitable device for the implementation of the AR application, and the students learned quickly and intuitively to select and deselect the regions of interest and to view the structures from different angles. There were three possible ways to view the structures from different angles: by moving the position of the tablet's camera, rotating or moving the image target, while holding the camera in the same position, or by rotating the brain structures using the fingers, while keeping the tablet and the image target in the same position. The rotation of the image target was the students' preferred option according to informal observations about their use of the AR application. This option prevented them from moving around the table where the image target was placed. Also, no participants reported side effects. This advantage of AR applications developed for the education of Anatomy in comparison with applications based on fully immersive VR applications has been shown previously. For example, the students who used a tablet-based AR application for learning about the skull obtained similar learning gains as students who used both an immersive VR application and a tablet-based application with basic digital images. However, using the method based on AR, the students engaged in a satisfying and enjoyable learning experience, without the symptoms of discomfort observed with the use of VR (Moro et al., 2017). Also, a tablet device presents the best features to help prevent dizziness during lessons with an AR application in comparison with HoloLens (Moro et al., 2021b).

Based on the analysis of satisfaction with the visualization and the experience, the AR application with images of

Table 4.

Summary of Principal Components Analysis Results

	Rotated Factor Loadings			
Items	Satisfaction	Spatial understanding	Usability and utility	Cognitive load
Rate this experience	0.85			
This learning experience, compared to other learning experiences that I have had, is …	0.83			
I would repeat this experience this way	0.82			
My experience with this method, compared to other experiences I have had in anatomy learning, is …	0.76			
I would recommend this method to my classmates	0.70			
Rate this method	0.70			
The visualization method helped me to get an idea of how regions in the brain are distributed spatially		0.83		
The visualization method helped me to get an idea of how regions in the brain are related spatially		0.74		
It was hard for me to get used to the method			0.83	
The method is easy to use			0.61	
The method has helped me learn			0.51	
I focused on the activity instead of on how to use the method				–0.80
I understood what I had to do at all times				0.65

The items from the Learning Experience Survey (LES) and Learning Method Survey (LMS) are grouped into four factors. Number of participants (n = 67).

structures of the brain in 3D achieved higher scores than the textbook with pictures in 2D to color. Also, the PCA conducted on the items of the questionnaires LES and LMS confirmed that the superiority of the 3D method was specifically related to the satisfaction experienced by the students. In fact, no other factor measured with these questionnaires was superior in the group of students who used the AR application (i.e., spatial understanding, usability and utility, and cognitive load). In addition, the AR application was preferred for learning Neuroanatomy, especially if it was the tool used in the learning intervention. These results showed that the success of the AR-based 3D visualization method was specifically related to the satisfaction of the students using this method. For all the students, it was their first experience with AR. The innovative nature of the AR technology could have facilitated their satisfaction and preference for the 3D method. A study that examined how the novelty effect of biometric technology influences users' acceptance concluded that the adoption of this technology was related to their perception of its novelty (Wells et al., 2010). Also, the same study showed that the perception of the technology's novelty facilitated the perception of its benefits. A meta-analysis also indicated that the novelty effect of methods based on 3D anatomical images contributed to the higher effectiveness perceived by students in comparison with methods based on 2D (Yammine and Violato, 2015). The present study did not analyze the qualitative information about the students' verbal reactions during or after the learning activity with the AR application, but the analysis of the factors comprising the survey feedback indicated that learning with the images in 3D presented in the mobile AR application was more preferred and recommended than learning with the pictures of the textbook. Also, the students valued the AR application as the preferred source for learning Anatomy in comparison with all the other methods that they had ever used and they were interested in repeating the AR application. Other qualitative studies found that learning Anatomy with AR applications had several positive aspects. In particular, when the AR was used to visualize neuroanatomical pathways, students reported that learning with AR was clear, facilitated both the memorability and the exploration of the different learning modules, and was better than learning with other resources that they had used previously (Weeks and Amiel, 2019). In the same line, the students who used AR for the visualization of the head and neck reported that images presented in AR facilitated the spatial understanding of both of the structures and the connection among the structures than images presented in a textbook (Weeks et al., 2021). Regarding the study of structures of the brain with a mobile AR application, the students valued the high quality of the images and reported that AR helped them to discriminate among the structures (Henssen et al., 2020). In the present study, the AR application scored high in the factor spatial understanding, but the statistical comparison revealed that the score was comparable with that of the textbook. In the authors' opinion, the statistical comparison of the scores of different learning methods in the feedback questionnaires better determines the users' true perception of the advantages of a new method.

There are some functional aspects of the AR application that contributed to students' higher satisfaction. The application allows viewing in 3D and selecting 72 structures of the brain separately and independently from each other. Students of brain anatomy valued these characteristics in a physical model (Estevez et al., 2010) and on a mobile AR-based model (Henssen et al., 2020). The physical model has the advantage of incorporating the sense of touch during manipulation but it has disadvantages in terms of cost, maintenance, and storage. In addition, the virtual models allow separating as many structures as necessary but without the risk of losing pieces of the model. The AR application of Henssen et al. (2020) is very similar to the application of the present study. Both applications were used with a tablet, the visualization, and manipulation of the structures are comparable, but the AR application of the present study includes cortical structures. In addition, an external case facilitates handling the tablet with one hand. This facilitated the learning process because it allowed holding the tablet and taking notes at the same time. The study of Henssen et al. (2020) states that the use of both hands to hold the tablet caused discomfort and made it very difficult to take notes.

Despite the greater satisfaction of students learning with the AR-based 3D method, the knowledge acquired by the students after the use of the 3D method was not different from the knowledge acquired after the use of the 2D method. In addition, both methods were effective for the tuition of the morphological and functional contents of the brain regions, as both methods were associated with an improvement in the score of the knowledge questionnaire completed after the learning intervention. Although the same questionnaire was used to measure the level of knowledge before and after the learning intervention, in the authors' opinion, this fact cannot explain the improvement of the score in the posttest version for two reasons. There was a temporal difference of two months between the measures, and no feedback was given to the students after the first completion. Identifying and coloring the brain regions in 2D was effective for the identification of the regions in 3D images. The knowledge questionnaire was based on 3D images but this did not produce bias in favor of the 3D method over the 2D method in terms of learning acquisition. In the authors' view, the coloring task would require paying attention to the morphological aspects of the regions and the spatial relationship between them, similar to the AR application. Also, the students performing the coloring task adopted an active role in their learning, which was also presented in the method of the AR application. Active methodologies applied to education in Anatomy improve learning outcomes (Singh and Kharb, 2013). Besides, both methods allow taking notes. Other immersive VR techniques do not offer this possibility (e.g., head-mounted displays), which is a problem that was previously mentioned in the literature (Chittaro and Ranon, 2007).

The learning gains obtained with each method were assessed with six questions of spatial reasoning and two questions of factual knowledge. The first type of questions assessed the ability to identify a set of structures of the brain in images of 3D virtual models that were printed on a sheet of paper. The name of the structures for identification was given, and the structures for identification were labeled with numbers for matching. The students had not previously seen these images. In comparison with the questions for testing learning gains used in other studies, the questions of the present study have a low level of spatial reasoning, and this might have explained the similar effectiveness between the AR application and the textbook. In the study of Estevez et al. (2010), the learning gains obtained with the physical model of the brain were significantly greater than the learning gains obtained with other traditional methods. However, the differences only emerged with questions that assessed the ability to interpret and label unfamiliar images of brain dissections in 3D. The learning gains obtained with verbal questions about spatial relationships among structures were similar between methods. Also, the study of Henssen et al. (2020) presented clear evidence about the relevance of the type of questions included in the learning questionnaire in determining significant differences in the effectiveness of the methods. The authors studied the learning gains in brain anatomy obtained by students who used an AR application with 3D images of the brain and students who used cross-sections. There were three different types of questions: multiple choice questions, matching questions, and questions for naming several structures in images of cross-sections. The questions for the identification of structures in images of cross-sections biased the learning gains in favor of the learning method based on cross-sections. However, the learning gains were similar between the two methods when the questions for the identification of cross-sections were discarded in the comparison. Based on this result, the authors suggested that learning about the brain with methods based on 3D and 2D images involves considering different spatial references. For this reason, they concluded that the effectiveness of a learning method should be analyzed using an assessment method based on images that require similar spatial references for their interpretation as the images used for learning. This suggestion would not only improve the analysis of the effectiveness of a method but would also reduce the students' frustration during the evaluation process.

The students who choose the 3D method because of its usability were significantly more accustomed to using ICTs. This was the only factor that showed an association with the perception of ease of use of the 3D method, but the coefficient indicates a small effect. The significant correlation supports previous studies, indicating that methods based on novel technologies are appreciated more by more technologically skilled students, and a transfer of skills might occur. For example, the usability of a virtual learning environment for the study of business administration was higher in students with a higher interest in trying out any technological advance (van Raaij and Schepers, 2008). Similarly, the usability of a new computer-based method for the study of several organ systems was higher in students with previous experience in 3D visualization and with a higher interest in trying out the method (Yeom et al., 2017). Finally, there were no significant associations between the individual factors considered and the preference for the 3D method for learning. Taken together, these results are positive because they suggest that this AR application, based on the 3D visualization of neuroanatomy contents, is valid for psychology students, and there are no motivational or cognitive factors that could hinder its potential as an educational tool.

The application currently works on devices with an Android operating system. However, this is not a problem because projects created with Unity engine can be deployed on different platforms such as Android (Google LLC., Mountain View, CA) or iOS (Apple Inc., Cupertino, CA). The programmer only needs the correct setup of all software development kits and plugins required for the desired platform. Therefore, authors intend to adapt the application to iOS operating system in the future.

Limitations of the Study

Several limitations should be considered. The sample was mainly composed of females. There were five male students enrolled in the course, and four of them participated in the study. Therefore, this is a representative sample of the studies of psychology in Spain. Males and females were considered separately for the assignation of participants to the methods. This procedure was performed to maintain a comparable number of males assigned to each of the learning methods, as gender differences may exist in the acceptance of technologies for learning (Yeom et al., 2017). However, the number of males who participated was not sufficient to reveal potential gender effects, so the randomization of the whole sample would have been more appropriate. The proportions of repetition rate and experience with ICTs were equally distributed between the students assigned to each of the methods, but it would also have been desirable to control their area of specialization in pre-university education. Moreover, the data set did not follow a normal distribution. This limited the type of analyses that could be used.

Regarding the AR application, the contents of the curricula included in the application are limited. For example, it would be interesting to include more content related to the cranial nerves and some important neural pathways. The learning intervention was carried out individually in one session, and all of the students used the same tablet, which was provided by the authors of the study. However, it would be interesting for students to be able to use the application on their mobile devices. This would facilitate the use of the application by all the students of the subject. Thus, the learning intervention could be prolonged. This would also facilitate studying the effects of collaborative learning in comparison with individual learning.

It would be useful to know the procedural aspects related to each of the two methods considered, comparing the time that the students spent using the textbook and the AR application to achieve the learning goals. Also, it would be useful to supplement the quantitative information obtained from the questionnaires about the students' subjective perceptions of the methods with relevant qualitative information obtained with open-ended questions.

The design of the study could be improved. The students performed the learning activity using one of the two methods and then they used the alternative method briefly, to gain a basic understanding of its characteristics and to evaluate their preference. However, it would be better for each student to rate their preference after having carried out a similar learning activity with each of the methods. Besides, the questionnaire for the assessment of the students' knowledge of anatomy could be improved. More questions, and with different degrees of spatial reasoning, could have been included. Also, the questionnaires for testing students' satisfaction with the learning experience and the learning visualization method were not tested before using them to collect data or for validity, although they were tested for reliability with good results. These procedures would guarantee the quality of LES and LMS as assessment tools. Altogether, these changes would enrich the interpretation of results.

CONCLUSIONS

The current results support previous research in favor of including AR-based applications for the 3D visualization of the morphology of brain regions and the search for their functional information. Psychology students are receptive to this technology for learning neuroanatomy. They appreciate the visualization improvements that an AR-based application achieves in comparison with the format of a textbook to color. This AR-based application is as effective as the textbook for learning. Preference for this application is independent of students' learning goals and cognitive factors. It is important to advance further in the incorporation of AR-based teaching tools for the neuroscience education of psychology students.

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NOTES ON CONTRIBUTORS

MAGDALENA MENDEZ-LOPEZ, Ph.D., is an associate professor at the Department of Psychology and Sociology, Faculty of Social and Human Sciences at the University of Zaragoza, Teruel, Spain. She teaches neuropsychology, physiological psychology, and psychopharmacology, and leads the psychobiology curriculum for the psychology degree program. Her research interest is in identifying novel tools for the understanding of spatial cognition and its improvement.

M. CARMEN JUAN, Ph.D., is a full professor at the Institute of Industrial Control Systems and Computing of the Universitat Politècnica de València, València, Spain. Her research interests include: computer graphics, virtual and augmented reality, advanced user interfaces, and their applications to education-entertainment, medicine, and psychology.

RAMON MOLLA, Ph.D., is an associate professor at the Institute of Industrial Control Systems and Computing of the Universitat Politècnica de València, València, Spain. His areas of interest include: real-time computer graphics, video games, and real-time simulation.

CAMINO FIDALGO, Ph.D., is an assistant professor at the Department of Psychology and Sociology, Faculty of Social and Human Sciences at the University of Zaragoza, Teruel, Spain. She has experience in teaching neurosciences and educational psychology. Her area of interest is in application of information and communication technologies to psychology and education.

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