Can virtual reality improve traditional anatomy educational programmes?A mixed-method study on the use of a 3D skull model

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Research article

Keywords: virtual reality; anatomy; medical education

Posted Date: May 1st, 2020

DOI: https://doi.org/10.21203/rs.2.23443/v2

Version of Record: A version of this preprint was published on October 31st, 2020. See the published version at https://doi.org/10.1186/s12909-020-02255-6.

Abstract

Background: Realistic, portable, and scalable lectures, cadaveric models, 2D atlases and computer simulations are being combined more frequently for teaching anatomy, resulting in major increases in user satisfaction. However, while digital simulations may be more portable, interesting, or motivating than traditional teaching tools, it is unclear whether they are superior in terms of student learning. This paper presents a study in which the educational effectiveness of a virtual reality (VR) skull model is compared with that of cadaveric skulls and atlases. The purpose of this study was to compare the results of teaching with VR with those of traditional teaching methods by administering objective questionnaires and perception surveys.

Methods: A mixed-method study with 73 medical students was carried out with three different groups: the VR skull (N=25), cadaveric skull (N=25) and atlas (N=23) groups. Anatomical structures were taught through an introductory lecture and model-based learning. All students completed the pre- and post-intervention tests, which were composed of a theory test and an identification test.

Results: The participants in all three groups had significantly higher total scores on the post-intervention test than on the pre-intervention test; the post-interview test score in the VR group was not statistically significantly higher than those of the other groups (VR: 30 [22-33.5], cadaver: 26 [20-31.5], atlas: 28[20-33]; $p=0.571$). The participants in the VR and cadaver groups provided more positive feedback on their learning models than the atlas group (VR: 26 [19-30], cadaver: 25 [19.5-29.5], atlas: 12 [9-20]; $p<0.0001$).

Conclusions: The VR skull model was equally efficient as the cadaver skull and atlas in terms of enabling students to learn anatomy. In addition, VR can aid participants in understanding complex anatomy structures with a higher level of motivation and mild adverse effects.

Background

Although anatomy serves as the basis for other medical courses for medical students[1], universities have decreased the hours allocated to anatomy education in favour of applied clinical work[2]. Medical students need to supplement their anatomy education with plenty of traditional resources, including cadaveric dissection, preserved specimens, and various 2-dimensional (2D) image representations (e.g., textbook illustrations, atlases, tomographic scans)[3]. The recent advancements in computer technology have led to many different forms of digital anatomy simulations[4]. Among them, virtual reality (VR) technology is one of the most promising teaching tools in medical education. VR can be used to deliver a highly immersive experience through head-mounted displays (HMDs) and a less immersive experience through a desktop system[5]. A wide range of virtual learning resources (VLRs) have been developed using 3-dimensional (3D) visualization technologies to supplement and even replace traditional instructional materials such as cadaver dissections[3]. Users can interact with vivid imagery for an active and self-directed learning experience without the limitations of ethical concerns, donation shortages[6,7] or having to enter an anatomy laboratory[4]. In a few studies, the educational value of VLRs has been compared with that of conventional methods, and the results are generally inconsistent. When used either alone or to complement traditional written and online materials, VLRs showed better or similar effectiveness in terms of enabling students to learn anatomy[2,8-11]. More importantly, VLRs are rated as more interesting and engaging[8], enjoyable[8,9,11], motivating[8,12-14] and useful for understanding spatial relationships[11,13,15] than traditional tools. There is inherent appeal in these newer and more advanced visualizations in addition to their novelty[4]. However, studies have shown that compared with cadaver dissection and physical modes, VLRs are less effective in improving learning outcomes[16,17]. The lack of tactile experience is regarded as a disadvantage.

Although current studies suggest that VLRs cannot replace cadaver and physical models, they are perceived as promising supplementary resources in anatomy education. It is therefore important to evaluate the evidence from different aspects. However, current research is largely focused on the comparison between VLRs and 2D textbooks, online materials or physical models. Petersson et al.[16] and Codd et al.[17] both compared VLRs with cadaver dissection, but neither study used VLRs to deliver a highly immersive experience. Recent studies by Birbara et al.[18] and Shao et al.[10] did provide a fully immersive experience, but neither of the research groups compared VLRs with cadaver dissection, and the former group used only perception questionnaires. Therefore, immersive VLRs and traditional teaching modalities, such as cadaver dissection and 2D atlases, should be compared further, and the different aspects of the assessments should also be considered to evaluate the impact of VLRs on anatomy education.

Neurosurgery comprises some of the most challenging surgical procedures, and mastering the intricacies of cranial anatomy is a career-long endeavour for every neurosurgeon[10]. In this study, a coloured and detachable VR skull model was constructed. The purpose of this study was to compare the results of teaching with VR with those of traditional teaching methods by administering objective questionnaires and perception surveys.

Material And Method

3D skull model based on VR technology

The virtual 3D skull model used in this study was constructed from computed tomography (CT) scans of a human skull from the Peking Union Medical College (PUMC) Anatomy Teaching Collection (Fig. 1). The CT scans were imported into Mimics 17.0 (Materialise NV, Leuven, Belgium) and converted into STL (stereolithography) files. The method used to create a 3D model from CT scans was previously published by Shui et al.[19]. Several defective structures (ethmoid plate, crista galli, anterior clinoid process and inferior orbital fissure) on the 3D skull model were modified using 3D Studio Max 2016 (Autodesk Inc, San Rafael, CA). In addition, each bone was isolated from the whole skull and painted in a different colour (Fig. 2c & d). The model was then imported into the Unreal Engine VR platform (Fig. 2a)) through the HTC VIVE software development kit (High Technology Computer Corporation, Taiwan) and Unreal

Engine 4.15 (Epic Games Inc, Cary, NC), which is compatible with HTC VIVE CE (High Technology Computer Corporation, Taiwan), a VR HMD with a resolution of 2160´1200. Users could rotate and scale the model through handheld controllers. In addition, each cranial bone could be isolated from all other bones, allowing the user to view an individual selected bone and its position in space relative to the other bones. When the isolated structure was placed back in its original position, the model was reset.

Participants

Seventy-four clinical undergraduates from PUMC who had just finished a pre-medical programme at Tsinghua University and had not yet begun an anatomy course were recruited for the study. The students were randomly divided into three groups: 1) the VR skull group (VR group, n = 25), cadaveric skull group (cadaver group, n = 25), and 2D atlas group (atlas group, n = 24). Seventy-three participants completed the trial, while one participant in the atlas group dropped out of the study for personal reasons before the pre-intervention test.

Design

A flowchart of the study design is displayed in Fig. 3. All participants finished pre-intervention tests. Then, they attended a 30-min PowerPoint-based introductory lecture on cranial anatomy, including the characteristics of each cranial bone, feature structures and spatial relationships. The lecture was taught by a teacher from PUMC who the students had not met before. During the lecture, each participant received a single sheet of paper about the teaching outline, which could also be used for note-taking. Afterwards, the three groups were assigned to three separate rooms for a 30-min self-directed learning session using VR skulls, cadaveric skulls, and 2D atlases. The students in the VR group received 2 min of instructions about the manipulation of VR equipment before learning. Study mentors were assigned to each room to prevent intragroup communication, and they were forbidden to answer questions related to anatomy. The participants took turns so that each participant had 7.5 min to manipulate and observe the model in the first perspective, and they observed the 3D model on the computer screen for the remaining 22.5 min. The participants in the cadaver group and atlas group also had the same amount of time to hold the cadaver skull or atlas, while the other participants could only observe, without manipulation. To compensate for the inability to view the teaching outline on paper in the simulated environment, a projector was used to project the teaching outline on a screen (Fig. 2b). A post-intervention test was conducted immediately after the learning session to evaluate the educational efficacy of each model. Finally, each participant completed a perception survey.

The pre- and post-intervention tests were composed of the same set of theory test and identification test (Supplementary file 1.1 & 1.2). The theory test consisted of 18 multiple-choice questions that mainly covered basic knowledge on the skull. Each correct answer was awarded 1 point, and the examination lasted 15 min. The identification test consisted of 25 fill-in-the-blank questions on labelled anatomical structures about the skull. All structures were labelled on the cadaveric skulls. The participants had 45 seconds to observe each structure and write down its name. Each correct answer was awarded 1 point.

The content was based on the syllabus from the PUMC anatomy course, and all the test questions are available in Supplementary file 1.

To assess the potential efficacy of the teaching tools, in addition the objective learning efficiency determined by the test scores, a perception survey was designed (Supplementary file 1.3). The questions were based on those included in several previous studies conducted to evaluate the efficacy of other 3D models[8,20,21]. The perception survey used consisted of five parts that addressed the participants' enjoyment, learning efficiency, attitude and intention to use and the tool's authenticity, and a standard five-point Likert scale was used to quantify the responses (1-strongly disagree, 5-strongly agree with the statement).

Data collection and marking

Demographic information, including each participant's age, sex, self-reported VR headset experience and video game experience, was collected during the trial. Participants recorded their group and individual identification numbers on the sign-in sheet. The previous grade point average (GPA) of each participant was obtained from the grade counsellor. The demographic and grouping information were hidden from the test mentor, study mentor and study staff until the trial was completed. The study staff scored each answer sheet, and the results were reviewed by the investigators (Zhu J and Cheng C) twice.

Statistical analysis

The previous GPA, test scores and perception survey scores are expressed as medians (interquartile ranges, [IQRs]), and the categorical variables are expressed as numbers (%). The participants' ages are expressed as the means [±SDs]. A p-value of <0.05 was considered to indicate statistical significance. Statistical analysis was performed using SPSS 23.0 (IBM Corp, Armonk, NY).

The data distributions were assessed using the Kolmogorov-Smirnov test. The between-group differences in the pre- and post-intervention test scores, changes in the scores, and perception survey scores were assessed using the Kruskal-Wallis H test because they were found to be non-normally distributed. If there was a significant difference with the Kruskal-Wallis H test, the Mann-Whitney U test was employed for pairwise comparisons. The participants' ages were compared with ANOVA. The categorical variables, except for video game experience, were compared with the chi-square test; video game experience was compared with Fisher's exact test.

Result

Participant demographics

A total of 73 third-year medical students (39 females, 53.42%) were included in the study (Table 1). Most participants were between the ages of 20 and 21 years. There were no statistically significant differences across the 3 groups in terms of gender, age, the previous GPA in the pre-med programme at Tsinghua

University in Beijing, VR experience or video game experience (p=0.425, 0.981, 0.500, 0.823, 0.600, respectively).

Comparison of the test scores across groups

The scores for the theory test and identification test were included in the total scores. The maximum scores of the theory test, identification test, and both tests together were 18, 25, and 43 points, respectively. Within-subject analysis showed overall improvement in the test scores from before to after the intervention, and the magnitude of improvement was significantly different across the three groups of participants (p<0.001). Table 2 displays the results on the pre- and post-intervention tests.

In terms of the pre-intervention test, the analysis revealed no statistically significant differences across the three groups (p=0.634, 0.667, 0.176 for the total score, theory score, and identification score, respectively).

There were no statistically significant differences across the three groups in the post-intervention total score or theory score (p=0.571, 0.824 for the total score and theory score, respectively), although the scores of the VR group were higher, but not significantly higher, than those of the cadaver group and atlas group in the identification test (VR: 15 [IQR: 10-18], cadaver: 12 [IQR: 8-15.5], atlas: 13 [IQR: 8-18]; p=0.511), as shown in Fig. 4.

The differences between the pre- and post-intervention test scores of the individual students was considered the change in scores. Kruskal-Wallis H analysis revealed that the changes in the scores were not significantly different across the three groups (p=0.317, 0.524, 0.278 for the total, theory, and identification scores, respectively), as shown in Fig. 4.

Responses to the perception survey

The results of the perception survey are compared across the three groups in Table 3. Overall, the participants in the VR group and cadaver group found their assigned learning models to be more enjoyable (VR: 4 [IQR: 3-5], cadaver: 4 [IQR: 3-5], atlas: 2 [IQR: 1-3]; p<0.001), more interesting (VR: 4 [IQR: 3-5], cadaver: 4 [IQR: 3-4.5], atlas: 2 [IQR: 1-3]; p<0.001), more authentic (VR: 4 [IQR: 3-5], cadaver: 4 [IQR: 3-5], atlas: 2 [IQR: 1-3]; p<0.001), and more efficient for memorization (VR: 3 [IQR: 2-4], cadaver: 3 [IQR: 3-4], atlas: 2 [IQR: 1-4]; p<0.001) and spatial understanding (VR: 4 [IQR: 4-5], cadaver: 4 [IQR: 3-4.5], atlas: 1 [IQR: 1-3]; p<0.001). The VR group and cadaver group reported having a higher likelihood of promoting the study material for use in standard anatomy education (VR: 3 [IQR: 2-4], cadaver: 4 [IQR: 2.5-4], atlas: 1 [IQR: 1-2]; p<0.001).

Discomfort during the learning session

During the learning session, conditions causing discomfort, such as headache, blurred vision and nausea, were reported in the three groups. Although more participants exhibited adverse effects in the VR group than in the other groups, there were no statistically significant differences across groups (VR group: 24%, cadaver group: 12%, atlas group: 8.7%, p=0.357), as shown in Supplementary file 2. The total scores of the participants with discomfort and those without discomfort were nearly the same in the VR group (30 [IQR: 19.25-32.5] vs. 30 [IQR: 22-34], p=0.726).

Discussion

The aim of this study was to compare the educational effectiveness of a skull VLR with a cadaver skull and a 2D atlas for anatomy education. In most previous studies, VLRs have been compared with traditional written and online materials and different teaching modalities have been compared through a single assessment method. This study addressed these limitations and is the first study in which a VLR was compared with two different traditional teaching methods with a randomized controlled study design, as well as both objective assessments and perception surveys, which are considered "various question types"[21]. The objective assessments comprised a theory test and an identification test. The perception survey was a crucial part of assessing the participants' spatial ability since structure identification is more important than theoretical knowledge in the study of anatomy, and it is considered a predictor of improved learning outcomes following 3D learning[21,22].

The results of the objective assessment demonstrated that the skull VLR had the same efficiency in enabling students to learn anatomy as the cadaver skull and atlas, despite the relative simplicity of the model used in this study, which lacked texture and haptic feedback. Because the VR model is stereoscopic and three-dimensional, the intrinsic spatial relationships of the anatomical sites studied are directly incorporated and thus may confer a spatial knowledge advantage[11], which is consistent with the results showing the post-identification score of the VR group was higher, though not significantly, than those of the other two groups. The results of the perception survey in the VR group and cadaver group also showed a more positive attitude towards the learning model than those of the 2D atlas group, indicating that the two groups had similar levels of enjoyment and the skull models had similar levels of learning efficacy and authenticity. Novel interventions usually spark participants' curiosity and lead to better results[4], and all participants in the VR group were willing to promote the use of this skull VLR in anatomy education. Similarly, previous studies comparing the 3D VR model with traditional 2D materials also reported that VR was considered a more enjoyable and useful educational tool[8,11,23].

Cadavers offer high levels of realism, haptic feedback, and the opportunity to use real instruments and tools, which is thought to be the gold standard in anatomical learning[24-26], particularly in surgery[27]. However, they are expensive, are a limited resource and offer no objective feedback regarding skill. 3D VLRs, which provide rapid and feedback-based modifications, offer an opportunity for repetitive practice[23]. Another advantage of VLRs is that students are able to observe and receive instant visual feedback based on predefined practical tasks[28]. Critics have argued that this approach lacks expert guidance during the learning process, which plays an important role in forming the basic framework[29]. In fact, teachers can also assess students' learning performance and mistakes through digital reports to further improve students' skills. Moreover, participants in our trial conducted self-learning in the absence of guidance and gained substantial progress in learning anatomical knowledge, which is consistent with the results in a previous study[30]. It has been suggested that self-learning in private places is a feasible way to implement VR simulation learning without constraints of the place or time provided for learning[30]. In addition, 3D models are likely to enhance rather than replace lecture-based teaching by experts[23]. Individuals can first practice with VR simulation rather than on cadavers so that they can practice the procedures and acquire basic skills before using expensive laboratory facilities[30].

In our trial, the scores of the cadaver skull group showed no statistically significant differences from those of the VR group or atlas group. This discrepancy might partially result from structural variations and damage in the structures in the cadaveric skulls and the negative psychological reactions from participants triggered by the cadaveric skulls[31,32]. In addition, we combined lecture and model learning to simulate the real learning process. The lectures allowed participants to learn information important for the tests and narrowed the differences between the three groups. Moreover, all these participants practiced and took the examinations together, introducing a competitive element.

Our study incorporated a room-scale HMD unit, which was available for the individuals. Many more manipulations can be achieved easily, such as rotating to a suitable view, segmenting a single bone and scaling up the model, making it a better tool in understanding difficult anatomical structures. This HMD unit provides a completely immersive experience with a high-resolution display, a high refresh rate, and highly precise, low-latency constellation head tracking. However, the highly immersive experience and the device being positioned in front of the eyes also caused adverse effects, which were regarded as negative aspects of the VLR[18]. Adverse effects, including headaches, dizziness, sore eyes, blurred vision and motion sickness, have been reported[2,33 34]. A previous study reported a high adverse effect rate in a VR group (headaches 25%; blurred vision 35%)[2], but this rate was lower in our trial (headaches 20%, blurred vision 4%). It can be inferred that the discomfort caused by the virtual environment were relieved with increased resolution and lower latency. Newer VR designs are being designed to overcome motion sickness and other VR-associated adverse effects. These designs include grounding the user by allowing their eyes to fix on a constant object such as a virtual nose or hand and decoupling the axes of movement from the visual plane[18].

In addition to adverse effects, the high degree of immersion in stereoscopic environment and the novelty of an immersive learning experience might make the learning process more mentally taxing[11,15]. Khot et al.[35] suggested that the extraneous load of the virtual delivery modalities in their study may explain why students using these modalities performed worse than those using a physical model. Birbara et al. (2019) found that students with minimal prior anatomy knowledge in the stereoscopic cohort had a higher cognitive load. As the participants in our study completed a pre-medical course, they might have had a more mentally taxing experience, which might have affected their performance during the learning session. Additional studies should be performed with a large number of participants at various stages in their careers, such as resident physicians, nursing students, and related educators.

Our study had several limitations. First, in our study, the self-directed learning session was limited to 30 min, and we failed to let the participants become accustomed to the virtual world without a learning model in advance. The participants in the VR group received only 2 min of instructions about the VR equipment. Second, we failed to disclose the aim of our study in advance, as the participants required access to the different interventions. The study design does not represent a single- or double-blinded trial. Knowledge of the grouping and interventions affected the students' performance to some extent. Third, the pre-intervention and post-intervention tests were identical so that the differences could be compared easily. Since the interval between the tests was short, the participants might have tried to figure out the answers to the pre-intervention test during the learning session. This strategy can result in an artificial learning experience and may have influenced their responses in the post-intervention test. Longer learning sessions should be taken into consideration in future studies.

Conclusion

The VR skull model was equally efficient in enabling students to learn anatomy structures as the cadaver skull and atlas. It can aid individuals in understanding complex anatomical structures with a high level of motivation and tolerable adverse effects. VR simulations can be powerful supplementary tools to traditional anatomy teaching tools and facilitate the learning process. With an increase in free 3D anatomical models, the widespread implementation of individual VR simulations for learning is possible.

Abbreviations

VR: Virtual Reality; VLR: Virtual Learning Resource; 2D: Two-dimensional; 3D: Three-dimensional; HMD: Head-mounted Display; GPA: Grade Point Average.

Declarations

Ethics approval and consent to participate

The study was approved by the Institutional Review Board of the Institute of Peking Union Medical College Hospital (PUMCH) (Project No: ZS-1724), and written informed consent obtained from all the participants. Study methods were performed in accordance with approved guidelines.

Consent for publication

Not applicable, no individual person's data in any form.

Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

Competing Interests

The authors declare that they have no competing interests.

Funding

This work was supported by grants from funds for Young Teachers Training Program (No.2014zlgc0721), and Education Reform Program (No.2014zlgc0141) of Peking Union Medical College. There was no financing from public funds or from third parties.

Author's contributors

S.C. and J.Z. wrote the paper. Z.P., C.C., L.L., J.D. and X.S. conducted the experiment and analyzed and interpreted the results. J.L. and Z.S. constructed the model. H.Y. collected data. H.Z. and C.M. reviewed the paper. H.P. designed the trial. All authors reviewed the manuscript.

Acknowledgements

The authors appreciate the support from Mr. Zhang Di, Mrs. Li Wenting and other members in Department of Anatomy in PUMC for provision of cadaveric materials and test questions, and all participants from third grade of eight-year program of clinical medicine in PUMC.

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Tables

	VR skulls (N = 25)	Cadaveric skulls (N = 25)	Atlas (N = 23)	p-value
Gender [n (%)]				
Male	9 (36%)	13 (52%)	12 (52.17%)	0.425[a]
Female	16 (64%)	12 (48%)	11 (47.83%)	
Age (Median [IQR])	21.22±0.69	21.15±0.54	21.19±0.78	0.948[b]
Previous GPA (Median [IQR])	3.28 [3.14-3.43]	3.30 [3.06-3.47]	3.23 [3.21-3.40]	0.780[c]
Self-reported VR headset experience [n (%)]				
	9 (36%)	7 (28%)	7 (30.43%)	0.823[a]
Video game experience [n (%)]				
Always	2 (8%)	0 (0%)	1 (4.35%)	0.696[d]
Occasionally	4 (16%)	4 (16%)	2 (8.70%)	
Rarely	19 (76%)	21 (84%)	20 (86.95%)	

Table 1 Demographic information in the three groups. [a]Chi-square test. [b]ANOVA. [c]Kruskal-Walis H. [d]Fisher's Exact test.

	VR skulls (N = 25)	Cadaveric skulls (N = 25)	Atlas (N = 23)	p-value
Pre-intervention score (Median [IQR])				
Total	9 [6.5-13]	8 [7-11]	10 [7-14]	0.634[c]
Theory test	7 [5-9]	7 [5-9]	7 [6-10]	0.667[c]
Identification test	3 [1.5-4.5]	2 [0.5-3]	2 [1-5]	0.176[c]
Post-intervention score (Median [IQR])				
Total	30 [22-33.5]	26 [20-31.5]	28 [20-33]	0.571[c]
Theory test	15 [12.5-16]	14 [12.5-15.5]	14 [11-16]	0.824[c]
Identification test	15 [10-18]	12 [8-15.5]	13 [8-18]	0.511[c]
Change in score (Median [IQR])				
Total	18 [14.5-21.5]	18 [12.5-21.5]	16 [10-20]	0.317[c]
Theory test	7 [5-9]	7 [4.5-10]	6 [3-8]	0.524[c]
Identification test	12 [8-12]	9 [7.5-13.5[	9 [7-13]	0.278[c]

Table 2 Pre- and post-intervention tests score in the three groups. Full scores of theory test, identification test, and total score were 18, 25, and 43 points, respectively. The median and quartiles of the total scores were not simply equal to the sum of the theory score and the identification score. [c]Kruskal-Walis H.

		VR skulls (N = 25)	Cadaveric skulls (N = 25)	Atlas (N = 23)	p-value
Enjoyment	Enjoyable	4 [3-5]	4 [3-5]	2 [1-3]	<0.001[c,*]
	Interest	4 [3-5]	3 [3-4.5]	2 [1-3]	<0.001[c,*]
Authenticity		3 [2.5-4]	3 [3-4]	2 [1-3]	0.001[c,*]
Learning Efficiency	Memorize	3 [2-4]	3 [3-4]	2 [1-4]	0.029[c,*]
	Spatial	4 [4-5]	4 [3-4.5]	1 [1-3]	<0.001[c,*]
Attitude		3 [2-3]	3 [2-4]	1 [1-2]	<0.001[c,*]
Intention to use		3 [2-4]	4 [2.5-4]	1 [1-2]	<0.001[c,*]
Total		26 [19-30]	25 [19.5-29.5]	12 [9-20]	<0.001[c,*]

Table 3 Results of perception survey in the three groups. Full score of perception survey is 35. [b]Kruskal-Walis H. [*]p<0.05.

Figures

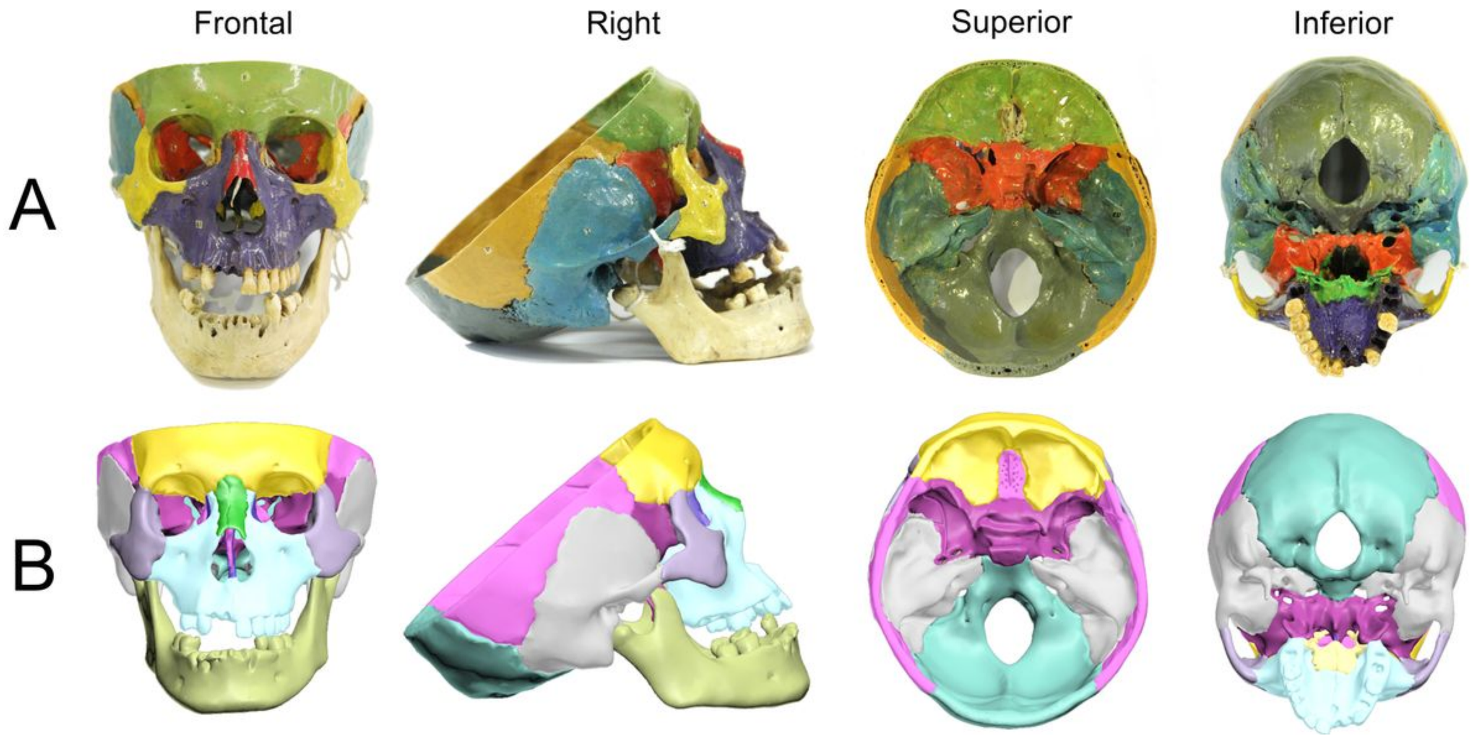

Figure 1

Photos of cadaveric skull and VR skull. (A) Cadaveric skull is showed in frontal, right, superior and inferior views, respectively. (B) VR skull is showed in frontal, right, superior and inferior views, respectively.

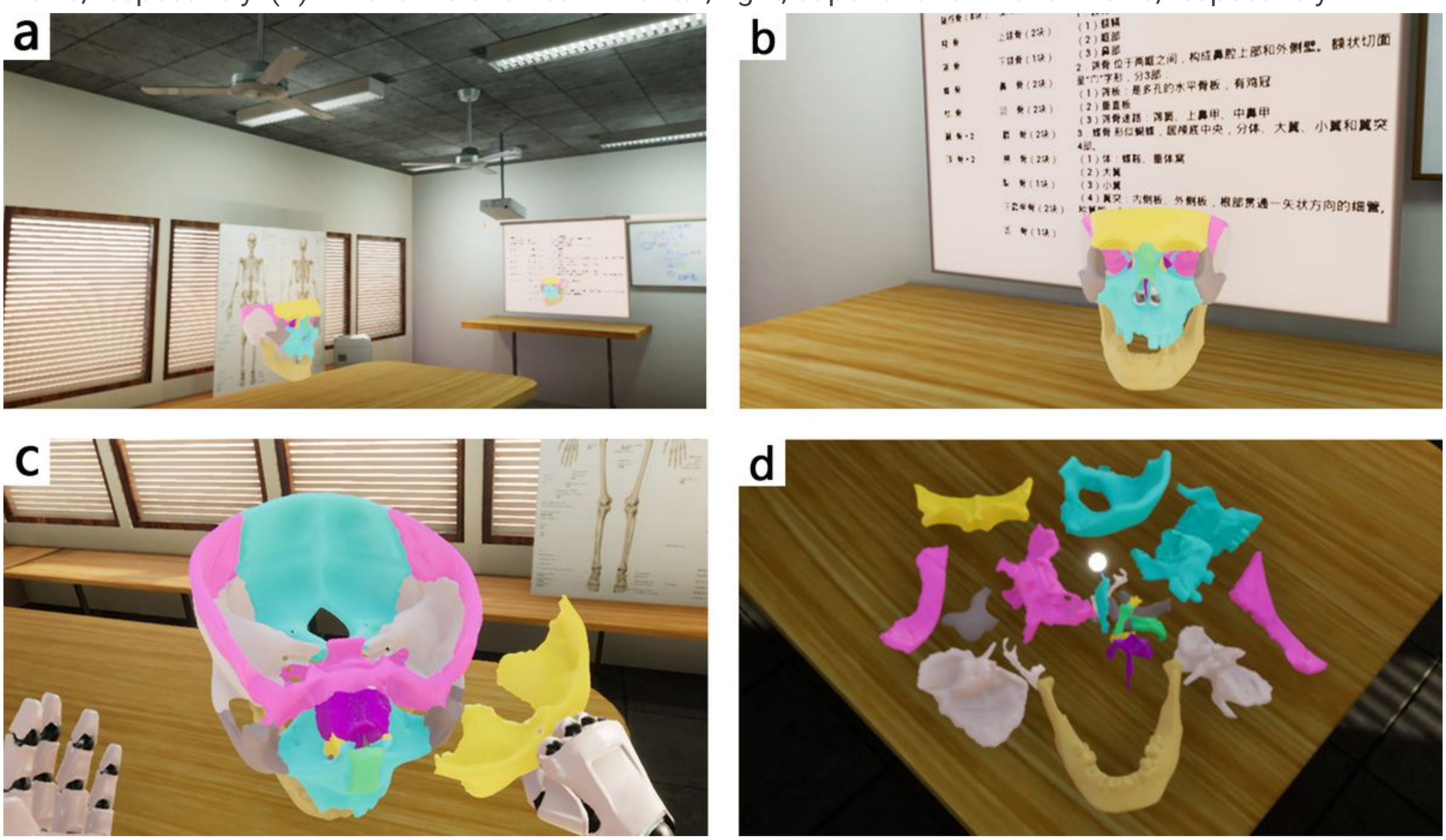

Figure 2

Photos of the simulation classroom and the VR skull model. (a) The whole scene of the classroom: one skull is placed on a table in the front of the classroom, the other is placed on a table in the middle of the classroom and pictures of human skeleton is placed in front of the window. (b) The VR skull and the projection screen. (c) Isolating frontal bone from the whole skull. (d) Each bone is isolated and the light ball represent the center of the original skull.

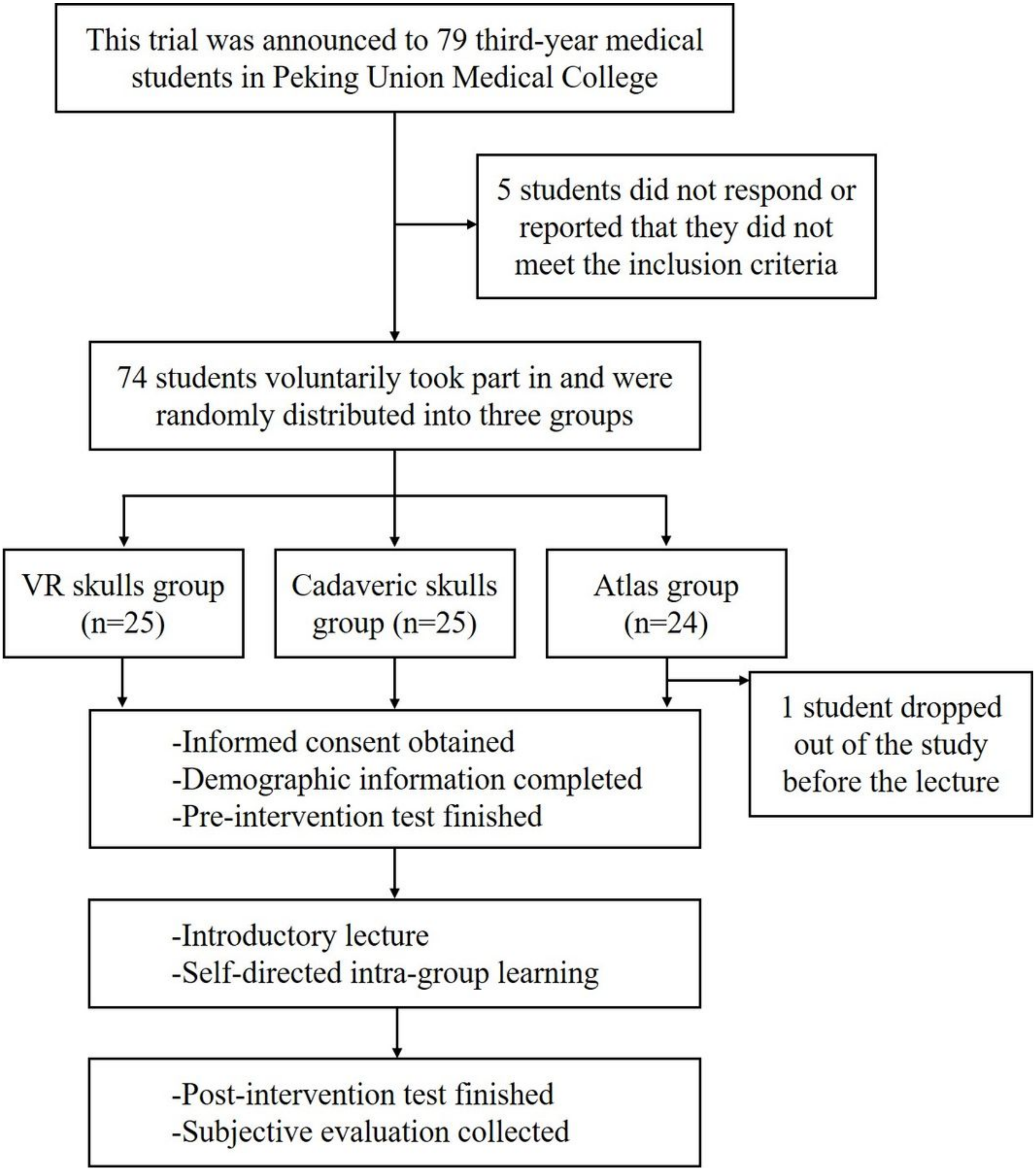

Figure 3

Flowchart of the study design.

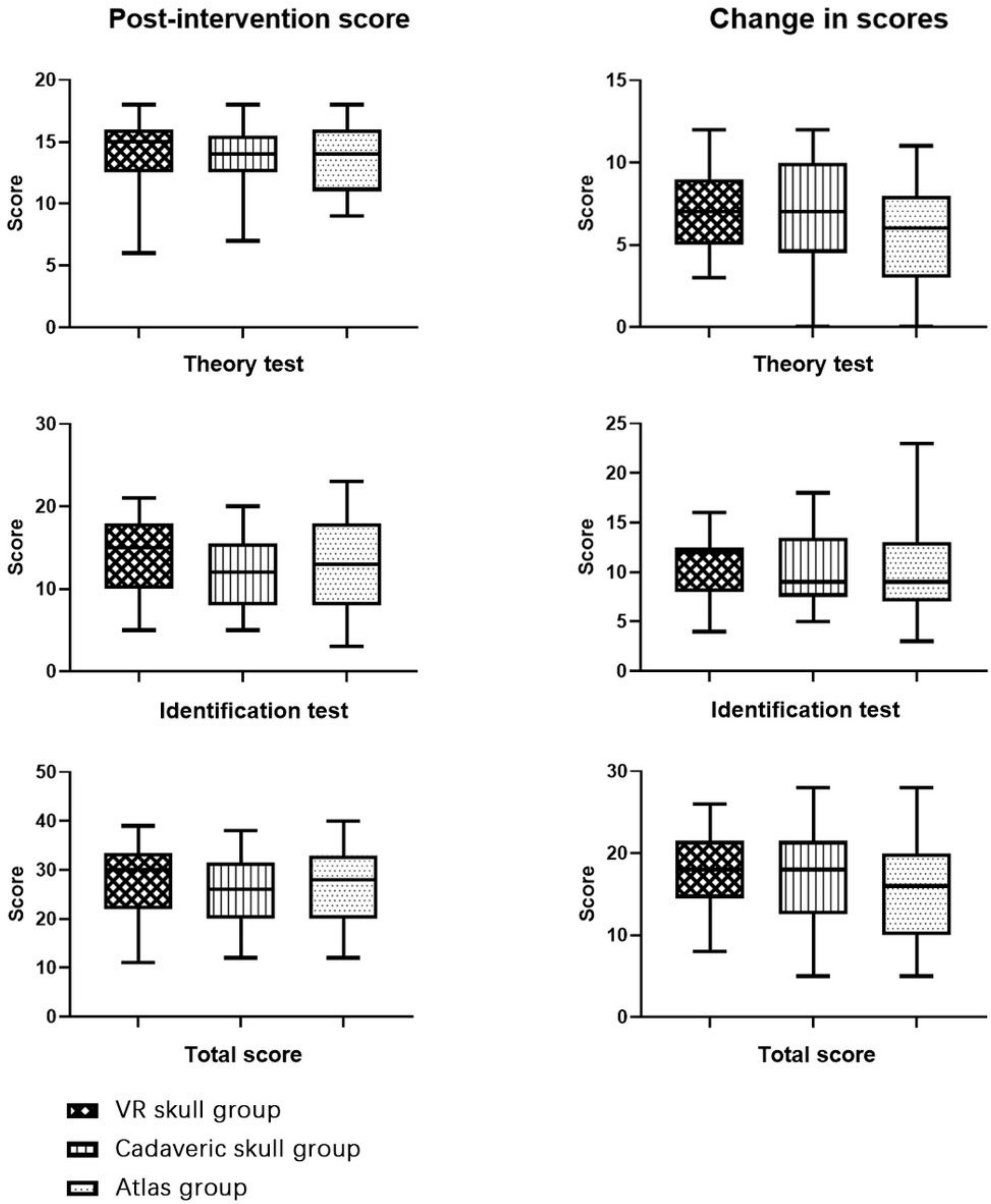

Figure 4

Comparison across the three groups in the post-intervention test scores and changes in scores. There were no statistically significant differences across the three groups in the post-intervention test scores and changes in scores.

Supplementary Files

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- supplementaryBMCmedicaleducation.docx