Collaborative VR Anatomy Atlas Investigating Multi-User Anatomy Learning

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Abstract. In medical education, anatomy is typically taught through lectures, cadaver dissection, and using replicas. Advances in VR technology facilitated the development of specialized VR tools for teaching, training, and other tasks. They can provide highly interactive and engaging learning environments where students can immersively and repeatedly inspect and interact with virtual 3D anatomical structures. Moreover, multi-user VR environments can be employed for collaborative learning, which may enhance the learning experience. Concrete applications are still rare, though, and the effect of collaborative learning in VR has not been adequately explored yet. Therefore, we conducted a user study with $n = 33$ participants to evaluate the effectiveness of virtual collaboration on the example of anatomy learning (and compared it to individual learning). For our study, we developed an UE4-based multi-user VR anatomy learning application. Our results show that our VR Anatomy Atlas provides an engaging learning experience and is very effective for anatomy learning, individually as well as collaboratively. However, interestingly, we could not find significant advantages for collaborative learning regarding learning effectiveness or motivation, even though the multi-user group spent more time in the learning environment. Although rather high for the single-user condition, the usability tended to be lower for the multi-user group. This may be due to the more complex environment and a higher cognitive load. Thus, more research in collaborative VR for anatomy education is needed to investigate, if and how it can be employed more effectively.

Keywords: Virtual Reality · Anatomy · Education · Anatomy Atlas · Collaborative Learning.

1 Introduction

The teaching of human anatomy is fundamental in medical education as it forms the basis for the development of clinical and surgical knowledge among professionals[30,17], and influences the design of the medical curriculum [14]. Classically, anatomy teaching is done using dissection, prosection, anatomical models, and lectures. Dissection offers a hands-on approach to examining anatomical specimens, enhancing students' understanding of anatomy [32], prosection reinforces students' comprehension of complex structures and relationships, and anatomical 3D models help to visualize anatomical structures. However, dissection is costly and time-consuming, prosection relies heavily on the anatomist's skill and expertise [9], and lectures may not be effective in promoting active learning and engagement compared to more interactive approaches. Also, the availability of human cadavers and animal specimens for dissection is limited [4].

Thus, virtual reality (VR) has become increasingly prevalent in recent years and is considered a valuable tool in education [23,27]. The technology offers several advantages, such as safe, controllable, immersive 3D environments and natural interaction, making the learning experience more intuitive and engaging [31,2]. However, most current VR-based learning applications are limited to single-user usage, and there is minimal research on the effectiveness of collaborative VR-based learning. Collaborative learning, in general, has been shown to have positive effects on learning outcomes [6,15,19] and to provide numerous other benefits, though. For instance, a higher problem-solving performance, a shared understanding of meanings and a shared sense of achievement [28], increased productivity, positive interpersonal relationships [24], better psychological health, higher social competence, and self-esteem [20].

To investigate if collaboration in VR (anatomy learning) also provides benefits and more positive outcomes than individual VR learning, we developed a multi-user VR anatomy learning application. We conducted a user study to evaluate its effectiveness. Concretely, we examined the participants' learning progress, usability, and motivation when using our VR learning environment, individually and in groups. With our results, we provide valuable insights into this sparsely-researched area.

2 Related Work

Virtual reality (VR) is a rapidly expanding field that holds promise for a variety of applications in healthcare, most importantly for education and training. Accordingly, the use of VR in medicine got much attention lately [25]. For example, Falah et al. [11] developed a VR and 3D visualization system for anatomy teaching that offers an interactive, real-time 3D representation of the human heart and various self-assessment tools. Similarly, Fairen et al. [10] developed and evaluated a VR anatomy teaching tool that provides real-time, interactive 3D representations of various anatomical structures that were augmented with additional information. An evaluation with anatomy students showed very positive results. Codd and Choudhury [7] evaluated the use of 3D virtual reality and compared it with traditional anatomy teaching methods (dissection and textbooks) on the example of a human forearm. Interestingly, they found no significant learning advantages using VR. In contrast, Kurul et al. [18] also conducted a study on anatomy training comparing immersive, interactive 3D VR with classical teaching methods and found the former to lead to significantly higher test scores. Another example highlighting the benefits of VR to anatomical education is the Immersive 3D Anatomy Atlas by Gloy et al. [13]. It provides a realistic 3D model of the human body in an immersive environment and allows users to explore individual anatomical structures interactively. An evaluation showed that the VR group took significantly less time to answer anatomical questions and had significantly better test results than students that learned using textbooks. The use of VR in the medical area is not limited to education, though. Other promising application domains are surgery planning and training. For instance, Reinschluessel et al. [26] developed a VR-based surgery planning tool that provides a 3D view of medical data. They found that planning in VR had many advantages, such as improving the surgeons' spatial understanding and identifying anatomical structures.

Most VR tools for medical education and training are limited to single-user usage only, though. Only a few works enable collaboration and even fewer investigate its effects and benefits. Works that do provide shared VR environments are, for example, the one by Kaluschke et al. [16], who presented a multi-user haptic VR system for dental surgical skill training, and the one by Fischer et al. [12], who presented a system for real-time volumetric medical image visualization with support for multi-user VR interactions. Boedecker et al. [3] also developed an immersive VR application for liver surgical planning that was later extended by Schott et al. [29] to allow for collaborative usage. It provides various teaching scenarios for collaborative and cooperative training in different group sizes. An exploratory study with medical students and surgery lecturers indicated positive outcomes for usability and presence. Another immersive VR learning environment that supports collaboration of multiple users was developed by De Back et al. [8,1]. Its effectiveness was shown through two empirical studies that revealed that collaborative learning provided greater learning gains compared to conventional textbook learning, particularly among participants with low spatial ability. For a more detailed overview and review of VR for anatomy education, we refer to the work by Lee et al. [21].

3 Our Collaborative VR Anatomy Atlas

For our work, we decided to use the Immersive Anatomy Atlas by Gloy et al. [13] as a basis. It already provided a good implementation of a VR anatomy learning application and was based on the modern Unreal Engine 4. The latter made it easy to extend for our purposes, mainly, multi-user functionality. Thus, our Collaborative VR Anatomy Atlas allows multiple users to meet, interact, and collaboratively learn within a shared environment, see Figure 1. The user interface is the same for the single- and multi-user condition and consists of the HMD and controllers for interaction and room-scale and teleportation for locomotion. Each user is represented by an avatar consisting of a virtual HMD and a pair of hands with which they are able to grab, move, rotate, and interact with the organs. When an organ is grabbed, it gets highlighted and its name is shown on a label. We decided on this avatar model, as it doesn't require complicated scanning setups, is computationally cheap, and is not prone to distracting or glitchy behavior. We use a client-server model based on the network functionality provided by the Unreal Engine 4, which allows for shared learning sessions between users in the same local network or over the internet. Our application can be started as either a listen or a dedicated server. The avatars, body parts, and other interactive objects, such as the operation table, instruments, and tablets, get replicated (synchronized) between users using RPCs. Specifically, when an object is moved (significantly) or its state is changed by a user (client), an RPC is sent to the server, which then executes a multi-cast RPC to all connected clients. In our implementation, we prevent updates on the client that initiated the change. Additionally, we optimized the replication process by employing struct replication, delta replication, caching, and careful selection of reliable/unreliable replication channels, reducing the data to be transmitted to a minimum. We also developed and integrated additional features such as a model of the human circulatory system that simulates the pulsatile blood flow, and extensive logging functionality to enable researchers to track user interaction and behavior within the virtual environment. Lastly, we developed a VR quiz (post-test) to evaluate participants' anatomy knowledge after their learning session. To access the quiz level, users can click on a 3D button located on an interactive tablet, which also provides access to other functions and controls.

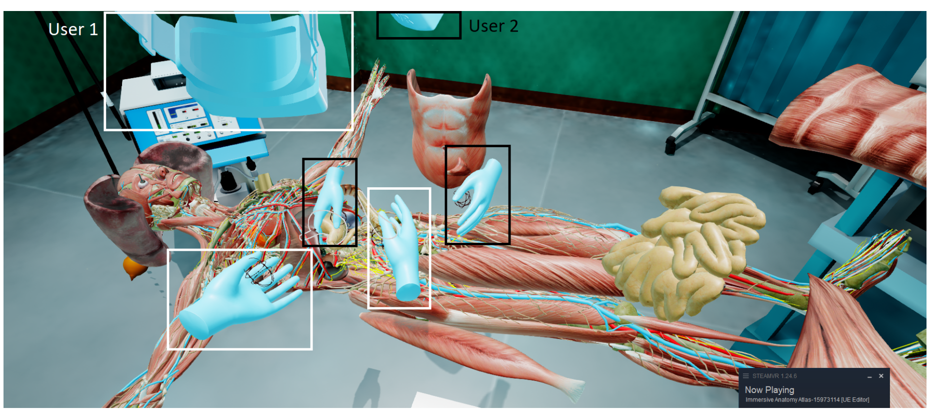

Fig. 1. Two users within our Collaborative VR Anatomy Atlas examining anatomy. Each user has an avatar consisting of a virtual HMD and one pair of hands (light blue, highlighted in black and white boxes).

4 User Study

4.1 Research Questions

The purpose of our study is to investigate the effectiveness of collaborative anatomy learning in VR, specifically, using our collaborative VR Anatomy Atlas, and to compare it to individual learning. Moreover, we are also interested in assessing its impact on learning motivation and its usability. Thus, we formulated the following research questions that we intend to answer with our study: (R_1) Is the Collaborative VR Anatomy Atlas effective for anatomy learning? Based on prior research that found benefits in collaborative learning [20,24], we want to investigate if (R_2) collaborative learning in VR also leads to better learning outcomes than individual VR learning. Additionally, we want to evaluate the usability (R_3) and user experience/motivation (R_4), in general, and especially if there are any differences between individual and collaborative learning.

4.2 Design and Setup

For our study we employed a between-subject design, hence, we divided the participants randomly into two groups: one group testing the single-user condition and the other group testing the multi-user condition. Multi-user sessions always consisted of two participants and each condition was performed an equal number of times, thus, the number of participants testing the multi-user learning condition was twice as large. We limited ourselves to groups of two, in order to still get meaningful results while having a manageable sample size. The study was conducted in our laboratory and, in the case of the multi-user condition, both participants were in the same room and could communicate verbally.

The learning sessions using our Collaborative VR Anatomy Atlas were conducted using HTC VIVE Pro HMDs including a pair of controllers. To provide a good user experience, we ensured that the frame rate was maintained at 90 frames per second. In the virtual environment, the participants were represented through avatars (see Chapter 3) and were able to freely move around using room-scale VR and teleportation. The virtual environment resembled an operating room and included a virtual anatomic 3D model that they were supposed to interact with and explore in order to learn about the anatomy.

To evaluate the learning effectiveness, we designed a multiple-choice test consisting of 8 anatomy questions. This test was conducted two times: one time before the learning session on paper (pre-test), and one time after the learning session directly in VR (post-test). For the latter, the participants transitioned to a quiz level. There, the correct answer is displayed in green and incorrect ones in red. The key presses for each answer were logged, but only the first answer entered was evaluated. Thus, the participants could learn the correct answer and improve their knowledge without affecting the validity of the study, even if they initially answered incorrectly. By comparing the results of the two tests, we calculate the learning progress. Additionally, we employed questionnaires on usability and motivation. Specifically, the System Usability Scale [5] and an adapted version of the questionnaire on motivation for cooperative and playful learning strategies (CMELAC) [22]. We customized the latter by removing the "Teamwork" factor as it was not applicable in the single-user condition and we wanted to ensure equivalence between both conditions. However, we believe it to be still valid and reliable. We also added a question to gauge the participants' interest in learning in a virtual reality environment. To analyze the participants' behavior, we tracked the time they spent in VR, video recorded the sessions, and employed extensive data logging using our custom implementation.

4.3 Procedure

The procedure of our study is depicted in Fig. 2. First, the participants were informed about the study and its goal, read and signed a consent form, and had time to ask questions. Then, the participants were asked to complete a demographical questionnaire about age, gender, previous experience with VR, etc. To determine the anatomical pre-knowledge, the participants were then asked to complete our pre-test questionnaire consisting of 8 anatomical questions (on paper). Following this, the Collaborative VR Anatomy Atlas application, its features, and its usage were briefly explained. Lastly, the participants were given up to three minutes to freely explore the VR environment and familiarize themselves with it.

Once the participants were ready, the learning session was started in which they had to explore the virtual anatomic model and complete various tasks with which we aimed to mimic classical non-VR learning. Specifically, the tasks were discovering the human anatomy, searching for specific organs (e.g. the spleen, pancreas, liver), and finding answers to the pre-test questions. The tasks were solvable individually as well as team-wise (in the multi-user condition), however, we expect the latter to be more effective, as in traditional learning. No assistance was given during task completion, but the tasks were repeatable. Figure 2 (left) shows an example of a multi-user learning session. Participants were given an unlimited amount of time.

Upon completion of the tasks, the participants were transitioned to the quiz level and took our anatomy post-test. There, they had to answer the shown questions by pressing the corresponding 3D buttons. After the post-test, and while their memories were still fresh, the participants had to complete the questionnaires about usability and motivation (on paper). They were also asked if they experienced any motion sickness and to provide subjective feedback. The procedure was identical for both conditions, with the exception that the participants of the multi-user group were explicitly instructed to work together on the anatomical tasks and to learn collaboratively. However, at the VR quiz level, they were required to complete the post-test independently.

5 Results

In this section, we present demographic data, the results of the anatomy pre-test and post-test as well as the results of the questionnaires on motivation

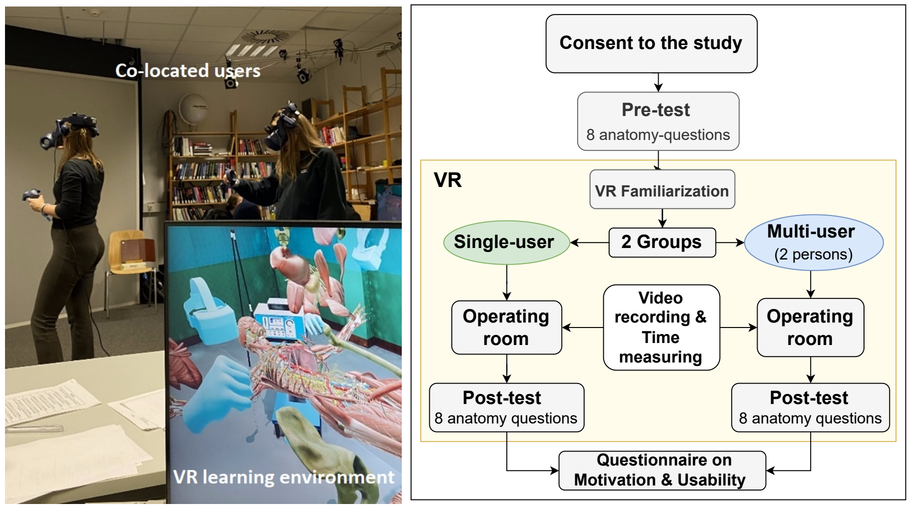

Fig. 2. Left: Multi-user learning session. In this case, both participants were in the same physical room. The virtual operating room with the anatomical model can be seen on the monitor in the foreground. Right: Flow diagram of the study procedure.

and usability. As the data was, as expected, normally distributed, we conducted independent samples t-tests to test for statistically significant differences between the single and multi-user groups.

5.1 Demography

The study was conducted with $n = 33$ participants who were randomly divided into two groups for the two different learning modalities: 11 participants experienced solo learning (single user) and 22 participants experienced shared learning (multi-user) in random pairs. We selected participants that were roughly in the same age group as typical medical students. However, as they were mostly university students form various subjects, they had no particular medical experience. The single-user group was made up of 2 female (18.2 %) participants and 9 male (81.8 %) participants while the multi-user group was made up of 14 men (63.6 %) and 8 women (36.4 %). Moreover, a substantial percentage of single users (54.5 %) and a smaller percentage of multi-users (22.7 %) reported having extensive experience with VR, a significant percentage of single users (36.4 %) and multi-users (31.8 %) reported having used VR before, while a minority of single users (9.1 %) and a substantial percentage of multi-users (45.5 %) had no experience with VR. We also asked about the preferred learning setting: By chance, a higher percentage of single users (45.5 %) preferred learning alone than in a group (9.1 %) while for the multi-user group, the ratio was more balanced (45.5 % each).

5.2 Anatomy Knowledge and Learning Progress

The results of the anatomy pre-test with 8 anatomical questions (conducted before the VR learning session) are depicted in Fig. 3 (left). The mean pre-test score for the single-user group was 2.091 (SD = 1.375) and the one for the multi-user group was 2.727 (SD = 1.518). Although the means are similar, there is a slight advantage for the multi-user group. However, the difference is not statistically significant ($t(31) = -1.170, p = 0.251$).

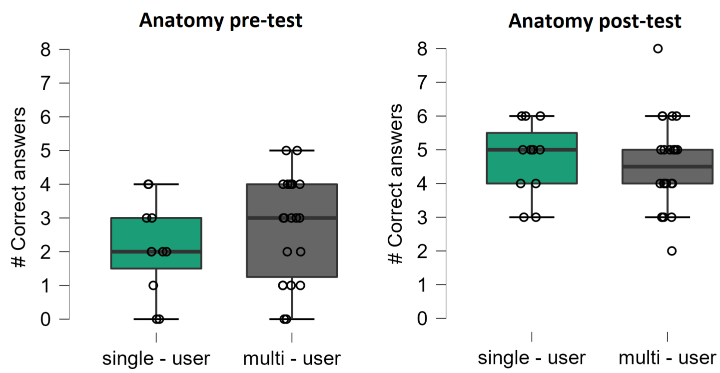

Fig. 3. Results of the anatomical knowledge pre-test conducted before the study (left) and the post-test conducted after the study (right). The multi-user participants had, on average, slightly more pre-knowledge. In the post-test, both groups scored better than before and fairly similar, with a slight advantage for the single-user group.

The results of the anatomy knowledge post-test (conducted after the study) are depicted in Fig. 3 (right). Both groups visibly improved compared to the pre-test and answered more questions correctly. Between the groups, the results are again similar, this time, with just a slight advantage for the single-user group. The mean score for the single-user group was 4.727 ($SD = 1.104$) and the mean score for the multi-user group was 4.545 (SD = 1.371). We, again found no significant differences between the groups ($t(31) = 0.381, p = 0.705$).

In order to better investigate the learning effectiveness, we compute the participants' learning progress as the difference (delta) between the pre- and post-test results, see Fig. 4 (left). The single-user group, on average, did have slightly higher learning progress: the mean score was 2.636 (SD = 1.859), whereas the multi-user group's mean score was 1.818 ($SD = 1.140$). The median, however, is more similar between the groups. A t-test resulted in: ($t(31) = 1.569, p = 0.127$). However, the result is still above the usual threshold of p $\leq$ 0.05 for statistical significance.

The time spent in the VR learning session, divided by single- and multi-user group, is depicted in Fig. 4 (right). The mean time for the single-user group was 22.130 minutes, whereas it was 33.774 minutes for the multi-user group.

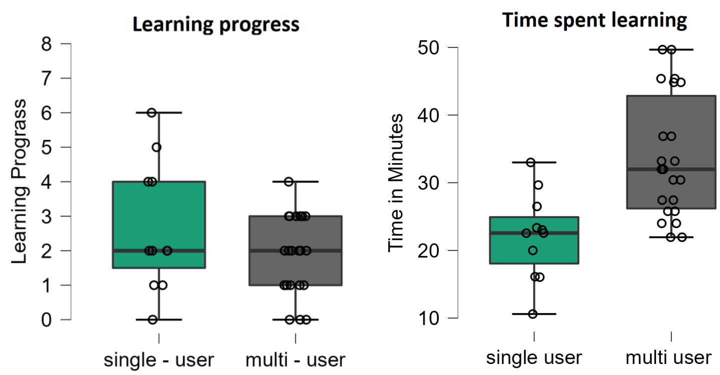

Fig. 4. Left: Learning progress (delta between pre- and post-test) for single- and multi-user groups. The single-user group learned, on average, slightly better. Right: Time spent learning in VR. The multi-user group spent, on average, more time in VR.

We found that the single-user group spent significantly less time in the VR environment than the multi-user group ($t = -3.783, p < 0.001$).

5.3 Questionnaires on Motivation and Usability

The results of the questionnaire on motivation for cooperative and playful learning strategies (measuring the factors of motivation, learning, and flow) are depicted in Fig. 5 (left). The average scores between the single- and multi-user groups are similar and both very positive. Concretely, on motivation, the means scores were 4.429 ($SD = 0.564$) (single user) and 4.253 ($SD = 0.612$) (multi-user), on learning 4.091 ($SD = 0.628$) (single user) and 4.164 ($SD = 0.564$) (multi-user), and on flow 3.97 ($SD = 0.69$) (single user) and 3.788 ($SD = 0.739$) (multi-user). The standard deviations indicate that the scores were relatively consistent within each group. We found no significant differences between the single-user and multi-user groups in terms of motivation ($t(31) = 0.795, p = 0.433$), learning ($t(31) = -0.336, p = 0.739$), or flow ($t(31) = 0.681, p = 0.501$).

The perceived usability of the Collaborative VR Anatomy Atlas was measured using the System Usability Scale. The SUS scores were calculated using the standard methodology and are depicted in Fig. 5 (right). Overall, the participants provided positive feedback and moderate to high ratings. The mean SUS score for the single-user group was 75.227 ($SD = 8.976$) and for the multi-user group 66.364 ($SD = 14.15$). The t-test revealed that there is a noticeable difference in means between the single-user and multi-user groups, although the usual threshold of $p = 0.005$ for statistical significance was just not reached ($t(31) = 1.887, p = 0.069$).

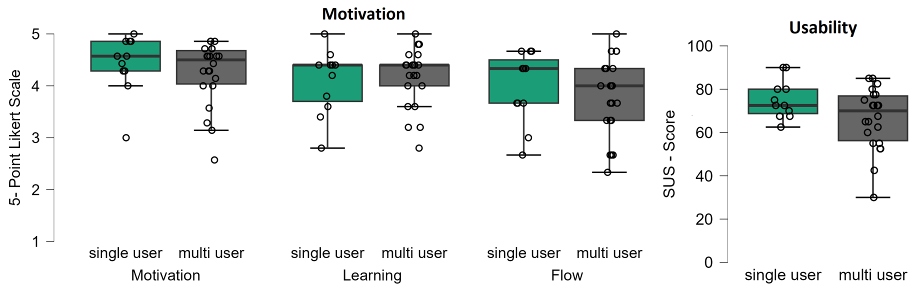

Fig. 5. Left: Results of the motivation questionnaire (factored into motivation, learning, and flow). The averages between the single- and multi-user groups are similar and both very high. Right: The System Usability Scale scores. The scores are generally high but the single-user group's feedback is more positive.

6 Discussion

Looking at the results, the post-test scores show a substantial improvement compared to the pre-test scores, for both groups, single-user and multi-user. Accordingly, on average, the participants had high learning progress. These positive results may come due to the VR learning environment allowing the participants to interact with the content in an immersive, engaging, and interactive way, which could have helped them better retain the information and recall it more easily during the post-test. The VR environment also allowed learners to visualize and explore anatomy in a three-dimensional way, which could have been helpful to understand the subject matter and the spatial relations between anatomical structures. With these results, we can answer our first research question R_1: our Collaborative VR Anatomy Atlas is, generally, effective in enhancing the knowledge and understanding of anatomy. This result is in line with prior research [23,27], that found learning using VR to be beneficial.

Interestingly, the learning progress and post-test scores are not higher for the collaborative learning condition. In fact, they tend to be slightly (but not statistically significant) lower than the ones for the single-user group. Thus, we could not find VR learning to be more effective in collaboration than individually, which answers our research question R_2. This result is interesting as we would have expected advantages for the multi-user group since collaborative learning is generally considered beneficial [6,15,19]. A potential explanation for the higher (or at least similarly high) single-user learning outcomes could be that the single-user group had on average slightly less prior knowledge about anatomy (see the pre-test scores). This means that the single-user group had more learning potential. Another possible reason for these results may be that the participants that learned individually could better focus on the task than the participants in the shared environment. The participants in the latter group were possibly more distracted by each other and the more complex multi-user environment, which provides additional social cues and requires communication and coordination between users. This may have increased their cognitive load and, therefore, reduced the learning outcomes. Furthermore, they may felt more competition during the learning session and the VR post-test. Additionally, our chosen avatar representation may have not provided a sufficient level of immersion, personalization, and embodiment, which possibly lead to a low feeling of social presence. Therefore, the potential benefits of collaboration may have not been fully exploited. The users' preferred learning setting could also have affected the learning experience and their resulting learning progress, since a substantially higher amount of participants in the single-user condition reported preferring learning alone than in a group, while the ratio was more similar in the multi-user group. This may have influenced the results in favor of the single-user group for this study. We also have to consider the option that the task of anatomy learning in VR may be one that is not benefiting from collaboration.

Our results regarding the time spent learning in VR show that the multi-user group stayed significantly longer in the learning sessions. On one hand, this could be an indicator of a more engaging, positive user and learning experience, which multiple participants suggested after the study. On the other hand, the increased time may indicate slower learning progress and reinforce the assumption of a more complex, distracting environment for the multi-user group.

Regarding our research question R_3, we found that the results of the usability questionnaire are generally positive, especially for the single-user group. This shows that our Collaborative VR Anatomy Atlas provides a good user experience. The score for the multi-user group is noticeably lower, though. This reinforces our assumption that participants in the multi-user condition perceived the environment as more complex and demanding, potentially leading to a higher cognitive load. Thus, the lower usability may be a central reason for the lower learning progress for the multi-user group. We also got very positive average scores in our motivation questionnaire for both the single-user and multi-user groups, which indicates high levels of motivation and engagement when using our Collaborative VR Anatomy Atlas. The scores for all three factors (motivation, learning, flow) were similar between the groups, which answers our research question R_4. This result is somewhat surprising, as, after analyzing the other results, we would have expected the multi-user group to fare slightly worse to be in line with the lower usability results and our theories about the more complex, distracting shared environment and increased cognitive load. The subjective feedback given by the participants during and after the learning session was generally very positive, too. They found the Collaborative VR Atlas to be an effective, useful, and enjoyable anatomy learning tool. Especially the collaborative scenario was often noted to provide an engaging, fun user and learning experience. Moreover, no participant experienced any signs of cybersickness.

7 Limitations

One limitation of this study is related to the adapted CMELAC questionnaire. Although we assume it to be still valid and reliable, we did not formally reassess it. In addition, the number of participants was relatively small and usability ratings were mediocre, so the study's power may be limited.

8 Conclusions and Future Work

In order to investigate the effectiveness of collaborative learning in VR, we developed the Collaborative VR Anatomy Atlas, a virtual reality system for anatomy education, and evaluated it by conducting a user study with $n = 33$ participants in which we compared individual learning to collaborative learning. Our application is based on the Unreal Engine 4 and provides an immersive multi-user learning environment in which users can interactively explore detailed anatomical structures including a model of the circulatory system. The results show that our Collaborative VR Anatomy Atlas was effective in anatomy learning for both single and multi-user scenarios. Moreover, the participants found the learning experience engaging and motivating and reported moderate to high usability scores. However, we could not find significant advantages (or differences) for the collaborative learning scenario, neither regarding learning effectiveness, nor motivation. The usability even tended to be slightly lower. We suspect this to be due to the more complex shared environment and a higher cognitive load. Other reasons could be that the used avatars were not immersive enough, leading to low social presence, or that learning anatomy in VR is a task that does not necessarily benefit from collaboration. Nonetheless, we believe that, like in real-world learning situations, collaborative VR settings can be effective and efficient for learning complex spatial knowledge. However, our results demonstrate that more work-needs to be done to determine the best 3D interaction techniques and forms of collaboration in VR to achieve these goals.

In the future, we plan to further enhance the usability and user experience, especially regarding multi-user usage, by developing improved interaction techniques and integrating more comfort features, such as different colors for each avatar's hands. It would also be important to normalize the learning progress based on pre-existing knowledge and formally revalidate the adapted CMELAC questionnaire. Moreover, we want to conduct further studies to compare the effectiveness of the Collaborative VR Anatomy Atlas to traditional (collaborative) anatomy education methods and examine the impact of presence, cognitive load, more immersive avatars, and co-located vs remote collaboration. Future research could also focus on exploring larger group sizes and potential correlations between learning progress and gender mix-up within groups/age ranges. Lastly, comparing traditional VR setups with Mixed Reality setups may be interesting.

9 Acknowledgment

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