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A VR/AR Environment for Multi-User Liver Anatomy Education

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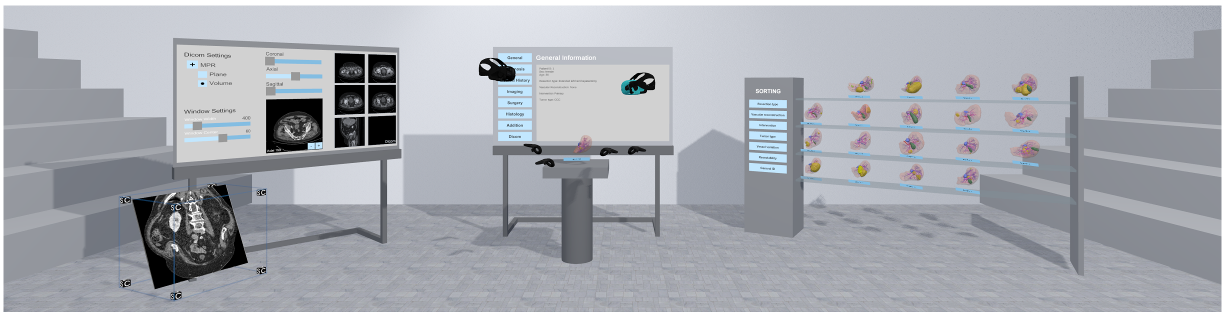

Figure 1: Overview of all stations in the VR environment. Left: 2D image data board with multiplanar reformated view and virtual light box; Center: two VR users interacting in front of an *Information Board* that displays the patient record for the selected 3D liver model on the virtual table; Right: virtual shelf containing 19 3D liver models based on CT data of patients who have undergone liver surgery.

Abstract

We present a Virtual and Augmented Reality multi-user prototype of a learning environment for liver anatomy education. Our system supports various training scenarios ranging from small learning groups to classroom-size education, where students and teachers can participate in virtual reality, augmented reality, or via desktop PCs. In an iterative development process with surgeons and teachers, a virtual organ library was created. Nineteen liver data sets were used comprising 3D surface models, 2D image data, pathology information, diagnosis and treatment decisions. These data sets can interactively be sorted and investigated individually regarding their volumetric and meta information. The three participation modes were evaluated within a user study with surgery lecturers (5) and medical students (5). We assessed the usability and presence using questionnaires. Additionally, we collected qualitative data with semi-structured interviews. A total of 435 individual statements were recorded and summarized to 49 statements. The results show that our prototype is usable, induces presence, and potentially support the teaching of liver anatomy and surgery in the future.

Index Terms: Human-centered computing—Human computer interaction (HCI); Human-centered computing—Interactive systems and tools; Human-centered computing—Collaborative and social computing systems and tools; Applied computing—Life and medical sciences; Applied computing—Interactive learning environments

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1 Introduction

Liver surgery is a highly complex subfield of surgery that is performed at specialised clinical centres. Medical training here is challenging due to the complex operations, but also the complex underlying disease patterns. It includes the surgical treatment of liver cancer, i.e. benign and malignant tumors in the liver and living-related liver transplants. It is particularly challenging since the liver is supplied by both the portal vein and the hepatic artery. Surgeons always consider effects of a resection on these vascular systems, i.e., surgeons have to decide carefully where to cut in these vascular trees. Determining the right access to a pathology and the appropriate amount of tissue to remove are further tasks in the planning process. In order to convey this information in medical education in an understandable way, new teaching modalities are needed that bring the different aspects of surgical decision-making together [17]. A spatial environment that combines 3D models, 2D image data and meta-information of curated cases can serve as a beneficial support for surgical education.

Virtual and Augmented Reality (VR/AR) has great potential to support training and learning complex spatial relations, such as those in intertwined vascular trees. In recent decades there has been a sharp increase in VR/AR applications for education and especially medical education [7, 19, 39, 40, 48]. Whereas conventional medical education methods include didactic, laboratory practice and textbook learning [20], VR/AR offers new possibilities for medical knowledge transfer [2, 26, 44]. Simulating medical education through VR/AR could even accelerate clinical education [37]. Besides advanced Virtual Reality (VR) simulators [3, 8] the use of VR for learning human anatomy has already been evaluated [10]. For instance, Weyhe et al. [46] have presented a virtual 3D anatomy atlas. Within a user study, it could be shown that their VR application leads to fast learning success, and higher satisfaction could be achieved compared to conventional learning. In general, these solutions are designed to support individual exploration of single users. Multi-user VR offers great potential here, as such environments allow the exploration of anatomy even in large learning groups over distance [35].

We present a multi-user learning environment for medical students as an introduction to liver surgery (Figure 1). The prototype serves to train students in the advanced (clinical) semester and potentially prepare them for surgery planning. Theoretical anatomical knowledge can be taught by a teacher or freely explored by a group of students. We enable problem-based learning through clinical cases in a virtual environment designed for seminar groups. The clinical cases used represent the most frequently occurring malignant tumors in the liver. These cases include the 3D surface models, volumetric data, medical background and treatment information. The teacher/instructor and students can select individual cases out of a virtual shelf. Similar to a real library, items are sorted and similar cases can be referenced. Implementing a VR/AR environment allows free interaction with large amounts of data, their dynamic sorting according to specific characteristics and the exploration of further medical background information. Our prototype can be used with various devices ranging from VR and AR headsets to desktop PCs. Additionally, students can participate in virtual lectures either co-located or remotely.

2 Related Work

A recent survey of Rashidian et al. [33] gives a comprehensive overview of different aspects of education in liver surgery. Within 53 articles, two main branches of education were distinguished, i.e. cognitive knowledge and psychomotor skill training. The latter, educated either by classical practicing in the operation room under proctorship or by simulation-based training [8, 28, 29, 43], is not the focus of our paper. Instead, our prototype supports the cognitive aspect, containing elements such as liver anatomy, tumor localization, diagnosis and surgical theory. In the field of anatomy education, this relates to *regional anatomy* that focuses on parts of the body and *surgical anatomy*, the application and study of anatomy to avoid complications and guide surgeons during interventions [31].

In 2012, Johnson et al. [17] argued in favor of a transition on medical education from a “passive, didactic, highly detailed anatomy course of the past, to a more interactive, as well as functionally and clinically relevant anatomy curriculum over a decade”. This is supported in studies that compare conventional anatomy training with VR approaches. Kurul et al. [21] could show that participants had higher test scores with a VR system. In the following, we describe learning solutions that vary in interactivity and immersion.

A passive way to convey medical information is videos. These represent an easy to access source of information, which can be used without any additional intrusive hardware even in the operating room [42]. Tailored to education, these can lead to positive learning outcomes. An interesting system was presented by Nobuoka et al. [27]. Their multi-layer three-dimensional liver anatomy atlas was created by filming a real dissection, layer by layer, with a camera in different anatomical views. Students can replicate steps in a surgical procedure by viewing the created images and videos in these layers. Fung et al. [11] combined real surgical videos with 3D animations. Their video atlas is available online for different procedures in the areas of the liver, pancreas and transplant surgery. This atlas was created with extension in mind and already used to visualize rare and complex cases [32].

More interactive applications are available as web-based applications. Furcea et al. [12] describe an e-learning platform that combines elements for pre-planning of the operation with the training of laparoscopic liver surgery. Similar to our work, their platform can be accessed remotely over the browser but does not offer a wide range of VR/AR devices and interaction possibilities. If real data sets are integrated into the application, they are often based on CT scans, i.e. 2D representations. These have to be mentally converted into 3D representation, which is challenging for inexperienced students. Crossingham et al. [9] offer an interactive website with 3D reconstructions of liver models. However, there is no possibility to connect these 3D models with their original 2D datasets. This was realized by Birr et al. [4] with the *LiverAnatomyExplorer*, again, as a web-based solution. This tool combines 2D images, 3D models, surgical videos and assessment tools. A similar application with added volumetric models and special interaction techniques to perform individual resections was presented by Mönch et al. [25]. In contrast to our work, these do not allow collaboration of multiple users and offer no VR and AR modes. An example of a collaborative education solution was presented by Richardson et al. [35]. However, they focus on gross anatomy. In their application, multiple students can participate in a shared *Second Life* environment.

There also exist VR/AR solutions for surgery training, planning and education. They can offer intuitive interaction, sense-of-physical imagination and the sense of presence and immersion, which are related to high motivation and learning [14, 31]. *IMHOTEP* is such a VR framework dedicated to surgical applications and aims to collect several data sources around surgery in one environment. The data comprises treatment data, multi-modal patient data, 2D images, 3D volumetric models and 3D surfaces and is organized in different workspaces. Similar, the *LiverPlanner* [34] allows the pre-operative planning of complex liver surgeries. This is done in a semi-immersive environment with a stereoscopic large-screen projection system. As an input device, a combination of a tablet and 6DOF controller is used. In contrast to our application, these aims to prepare and plan individual surgeries.

Semi-immersive and immersive anatomy education systems were surveyed by Hack et al. [13]. They list 38 systems that either uses shutter glasses, passive glasses or autostereoscopic displays. They could show several advantages of these systems related to spatial understanding. These were particularly large for complex vascular structures [1], which is highly relevant for liver anatomy.

HMD-based anatomy education systems in the form of a 3D puzzle were presented by Messier et al. [22] and Pohlandt et al. [30]. The former compared a 2D monitor, a stereo monitor and an Oculus Rift and report on positive initial results. The latter used an HTC Vive. Here, a student can choose between different anatomical structures (skull, foot, etc.) and scale them freely. The VR puzzle allows the disassembly of a solved puzzle in a specific order, which roughly resembles the dissection course of medical students.

Cooperative environments can either be co-located or remote, which has a significant influence on accessibility and possible communication. In general, it can have a positive educational effect if multiple users share one virtual environment [6, 15, 16, 23]. In both settings, small groups of students could explore complex anatomical structures together. One student leads the exploration and the others watch passively. The technical setup, however, is costly and not accessible in medical faculties. We allow collaboration with cheaper HMDs and desktop PC instead. An alternative to the group and classroom settings are one-on-one settings. Moorman [24] presented a one-on-one scenario where a teacher supports students via video conferencing. In a work from Saalfeld et al. [36], a one-on-one tutoring system is presented to educate the area of the human skull base. Here, a combination of different hardware is used. The tutor sits in front of a *zSpace* (stereoscopic display) which allows him to view the surroundings and gives him access to a keyboard. The student uses an HMD and is positioned in a scaled-up human skull.

3 Material

19 data sets of patients undergoing liver surgery due to liver tumors were selected. The selection represents the most common malignant tumors in the liver, i.e. hepatocellular carcinoma, cholangiocarcinoma and colorectal liver metastases. Furthermore, a wide range of different resection types is presented in the case collection, ranging

Table 1: Sorting types and corresponding parameters.

Sorting type	Sorting parameters
Resection types	Extended hemihepatectomy left, Hemihepatectomy (left/right), Left lateral resection, Atypical (simple/complex), mesohepatectomy, in situ split
Vascular Reconstruction	None, Cava, Hepatic Vene, Portal Vene
Intervention	Primary, Recurrence
Tumor type	Hepatocellular Carcinoma, Cholangiocellular Carcinoma, Metastasen Mamma-CA, Colrectal Liver Metastases, Mucinous cystic neoplasia, Metastases Gastrointestinal Stromal Tumor, Focal Nodular Hyperplasia, Echinococcus multilocularis, Gall Bladder CA
Vessel Variation	No, Yes
Resectability	Resectable, limit value

from small atypical resections or single segment resections to major surgery such as extended hemihepatectomies. The data sets are based on 3D images generated by CT scans. The necessary segmentation was carried out by a liver surgeon at the University Medical Center of the Johannes Gutenberg-University Mainz (Germany) with experience in reconstruction with Synapse 3D (*FUJIFILM Europe GmbH*). The resulting 3D STL files was converted into the OBJ file format and imported into the game engine Unity (*Unity Technologies*). Digital Imaging and Communications in Medicine (DICOM) is a standard for the storage, management and communication of medical image information. In this work, the term DICOM is used to describe all 2D and 3D image data, including associated clinical patient information.

4 The Multi-User VR/AR Environment

We propose a VR/AR multi-user prototype as an exploration and learning environment for liver surgery education. Various interaction possibilities have been developed, which are described in Section 4.5. We used a participatory design process for requirements elicitation. Our prototype was developed in an iterative process with experienced liver surgery lecturers from the department of General, Visceral and Transplant Surgery, University Medical Center of the Johannes Gutenberg-University Mainz, Germany. The prototype can be used in VR, AR or desktop PC mode. Furthermore, several VR and desktop users can use the application at the same time. Three core functionalities were integrated for data exploration: An interactive *Liver Shelf* (Figure 2), an *Information Board* (Figure 1) and a DICOM workstation consisting of a *DICOM Board* and a *DICOM Cube* (Figure 5).

4.1 Learning Objectives

Our VR/AR multi-user learning environment provides an entry point to liver surgery education by teaching theoretical content of liver surgery resection planning through a problem-based learning approach using clinical cases [14]. The focus here is on promoting symbolic knowledge [31]. The high degree of clarity of the complex three-dimensional structures of the liver should make it easier to memorize (anatomical) learning objects. The VR mode, in particular, is designed as a safe, closed and controlled learning environment.

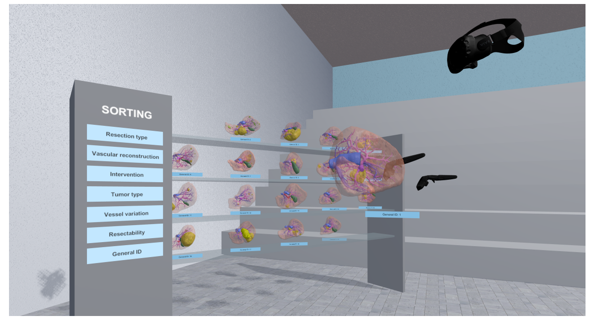

Figure 2: Interactive *Liver Shelf* with 19 medical 3D data sets.

Ambient noise and fast animations were deliberately avoided in order to keep distractions to a minimum.

Nevertheless, our prototype is intended as an experimental environment in which users can discover medical data independently. Our prototype enables collaborative learning by allowing students to acquire intricate knowledge through self-exploration in collectives. It is possible to participate actively in virtual reality and observe passively when, e.g., teachers impart knowledge. Our environment complements existing materials and methods for liver surgery educators because real patient cases are vividly presented, can be discussed interactively, and data are easily accessible to students.

4.2 Liver Shelf

We chose to offer an overview visualization of all data sets inspired by shelves in a library. Different 3D liver models are arranged in several compartments that are stacked over each other. This includes the liver surface, blood vessels, gall bladder and different kinds of tumors or cysts. The 3D models can be grabbed, translated and rotated with the *Virtual Hand* technique, and scaled via bimanual interaction. The liver surface is visualized transparently to reveal internal structures. The coloring of the structures is based on common illustrations in medical textbooks (e.g. tumor yellow; gall bladder green; vena cava blue; artery red; hepatic veins). Figure 2 shows the *Liver Shelf* in a VR representation with a user inspecting a 3D surface model. The shelf can be extended with additional data sets so that several shelves up to a whole library are also feasible. Further functionalities have been added, which are not possible in a classical library. Our data sets can be automatically sorted according to different criteria (see Table 1).

4.3 Information Board

More detailed, anonymous information can be displayed on boards. This information includes: age, sex, diagnosis, medical history, imaging, surgical history, histology and various 2D image data. This information come from treatment notes and medical reports. If the user is interested in details of a liver data set, he can teleport or walk to the *Information Board*. In order to activate them, a selected 3D data set needs to be placed on a platform in front of the *Information Board* (Figure 1). After that, the meta information is organized with different categories. The user can choose a category via selecting a button. This is realized via ray-based interaction, i.e. the user activates an interaction ray originating from their controller and confirms the selection by pressing a controller's button. Furthermore, the ray can be used as a pointer to refer to text passages.

4.4 DICOM Board

DICOM data sets can be selected in our prototype via the *Information Board* and displayed on a *DICOM Board* (Figure 5). The *DICOM Board* contains a 2D image viewer and also the possibility to activate a multiplanar reformation view (*DICOM Cube*). For this

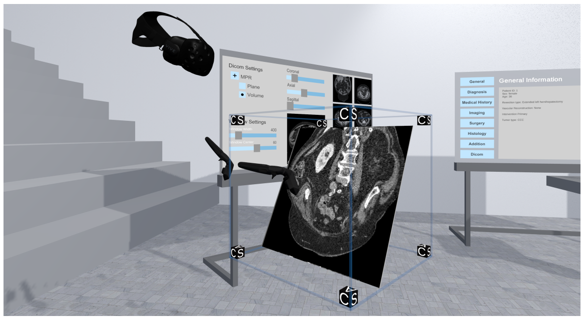

Figure 3: 3D *DICOM Cube* with interactive plane in front of the 2D *DICOM Board* with CT data from different slice images.

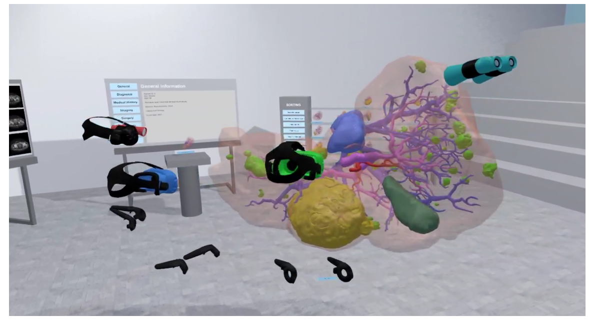

Figure 4: Multi-user scene view with three VR users (represented by Vive headsets + controller) and multiple spectators (represented by binoculars).

purpose, basic tools have been created with which users can work with the data set based on traditional slicing. This includes changing the range of gray values depicted or changing the slice direction in the three anatomical planes. These planes are used to describe directions or positions of structures and oranges in the human body: sagittal = left and right; coronal = back and front; axial = head and tail. This is implemented using a slider and the ray-based interaction described above. In addition to classic slicing, it is possible to interact with data sets using multiplanar reformation (MPR). With this *DICOM Cube*, a user can freely place a plane in the 3D data set and view the resulting slice (Figure 3). This allows to select a plane where the anatomical target structure can be assessed quite well. Besides the plane, the *DICOM Cube* itself can also be moved freely. For additional orientation, the hull of the dataset is depicted with lines. The orientation of the data set is shown with the help of small cubes in the corners. The cube is labeled with the alignment (sagittal, coronal, axial).

4.5 Multimodal Enviroment

Our prototype can be used in different ways, namely a VR, an AR and a spectator mode. The spectator mode allows users to join the VR scene using a desktop PC. Furthermore, the prototype can be used with several users in a multi-user mode. These scenarios use the same or very similar interaction types and environment structure. The differences are described below.

4.5.1 Virtual Reality Mode

To increase immersion, a simplified lecture hall was created in addition to the interaction elements described above. The simplified presentation should also be less distracting and reduce the cognitive load. Besides a real-world movement, which is limited by the hardware (e.g., cable length, tracking space), the users have the opportunity to teleport through the environment with the help of their controller. Range-limited teleportation was deliberately chosen to strengthen the sense of security. It is not possible to walk through walls or change elementary objects in the VR environment. A blend between the two locations is also intended to reduce the cognitive load and avoid disorientation of the users [45]. In comparison to the AR concept, rooms of any size are possible. Especially in the VR scenario, a direct representation of other users is missing. As a remedy, other VR users are presented with a basic avatar comprising a VR headset and two controllers. In order to distinguish users from each other, the VR headsets have different colors. This is defined automatically by the application when a user joins.

Furthermore, users can display a name of their choice above the headset. Head and hand movements are always transmitted in real-time so that actions such as head shaking, nodding, or waving can be recognized by other participants. The ray that originates from the user's controller can be used as a pointer and has the same color as the VR headset. Figure 4 shows multiple users in the VR scene, examining a scaled-up 3D model of a liver.

4.5.2 Spectator Mode

If a VR scenario is used, but no VR hardware is connected, the prototype is executed as a desktop application. This allows users to participate without the need for VR hardware. In contrast to the VR users, they are displayed as binoculars. These are also colored and can display a custom name. Desktop users cannot actively manipulate objects and are passive in a so-called *Spectator Mode*. The interaction in this mode is realized by mouse and keyboard input. Using the arrow keys (alternatively the WASD keys) the position can be changed and the space bar offers the possibility to activate a pointer ray. The mouse is used to change the orientation and the user's vertical position can be adjusted with the mouse wheel. With the *Spectator Mode*, the user can also access the view of a VR user and can exactly see what a VR user can see. Thus, a lecturer can supervise a group of students to provide feedback to them. In the AR scenario, it is not possible to participate as a spectator.

4.5.3 Augmented Reality Mode

In preliminary consultation with medical experts, it was considered that complete isolation from the real world could cause discomfort for the lecturer. It was also noted that collisions could occur in the real room, and the user can feel uncomfortable not knowing what is happening due to students' lack of physical presence. To mitigate this, an AR environment was created. In comparison to the VR mode, environmental objects such as the lecture hall were removed. Furthermore, the area in which objects were positioned was reduced. This is necessary because no free teleportation is possible in AR and objects cannot be positioned at will due to real-world space, headset cable length and tracking space.

Furthermore, teleportation is the quickest way to cover longer distances so that a VR environment can be designed more generously. Figure 5 shows a user's perspective in the AR environment, examining a 3D model of a liver in front of our *DICOM board*. Real-world structures, such as walls or tables, are visible in contrast to the VR solution. The interactions with the individual stations (via controller), including the user interface itself, are identical to those of the VR mode.

4.6 System Architecture & Technical Details

An overview of our system architecture in combination with the VR/AR Modes described in Section 4.5 can be seen in Figure 6. The development was realized with Unity 2019.1.2f1. For data exchange (e.g. position/rotation of objects/users), our prototype is connected via a network and we use the Photon Unity Networking 2 package (*Exit Games Inc.*) for network communication. Several HTC Vive (*High Tech Computer Corporation*) HMD devices were

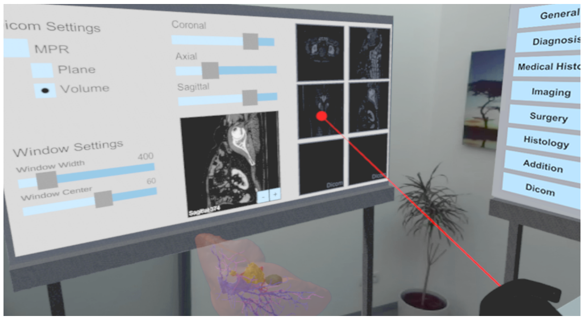

Figure 5: Perspective of a user in the AR environment examining a 3D model of a liver and the *DICOM Board*.

used to run our VR scenario. However, it is not necessary to use this particular headset. The headsets were operated using Steam VR (*Valve Corporation*). The user interaction possibilities were realized with the HTC Vive Controller.

For the AR implementation, the HTC Vive was also used in combination with the ZED mini (*Stereolabs Inc.*). Thus, it is possible to realize video see-through AR in combination with a VR HMD. Microsoft HoloLens (*Microsoft Corporation*), which is currently widely used in research, could not meet our requirements for the level of detail and number of models to be displayed.

In comparison to a VR setup where participants can move freely through space with the help of teleportation, sharing of real-world registration among users is not mandatory. This is different in the AR setup, where all participants have to be in the same real-world coordinate system. Usually, a separate registration is performed for each system, but in this case it is necessary that each system can use the same room registration. To address this, we developed a small tool which automatically transfers and replaces the required registration files from one VR setup to all others via network. These are primarily the “lighthouse settings” and the “chaperone files” created during the Steam VR room setup, which are located in the Steam VR config folder. To use the Spectator Mode, only common desktop peripherals (e.g. keyboard, mouse, monitor) are needed.

5 Evaluation

An explorative study format was chosen, in which the focus was on the collection of qualitative statements. The feedback of the potential users should help to refine usage scenarios of our different modes more precisely. Particular emphasis was placed on individual aspects regarding the quality, quantity and presentation of the medical data, including the usability of the interactions. We focused on the suitability of the application for multiple users, especially concerning the VR mode and the corresponding desktop application.

5.1 Study Design

The evaluation procedure was based on the think aloud protocol [41], in which the users should permanently express their thoughts while experimenting. Participants were able to move freely throughout the environment and were repeatedly encouraged to interact with it in an explorative way. The entire interview was conducted with the help of a semi-structured questionnaire. For this purpose, audio recordings were made for later analysis. Only the VR prototype was additionally evaluated with usability and presence questionnaires. It was evaluated using the Standardised Usability Scale (SUS) [5]. In addition, we used the Igroup Presence Questionnaire (IPQ) [38], which offers the measurement of the feeling of experienced presence in a virtual environment. The IPQ offers three sub-scales (spatial presence, involvement, experienced realism) and an additional general element (general presence), which can be regarded as independent

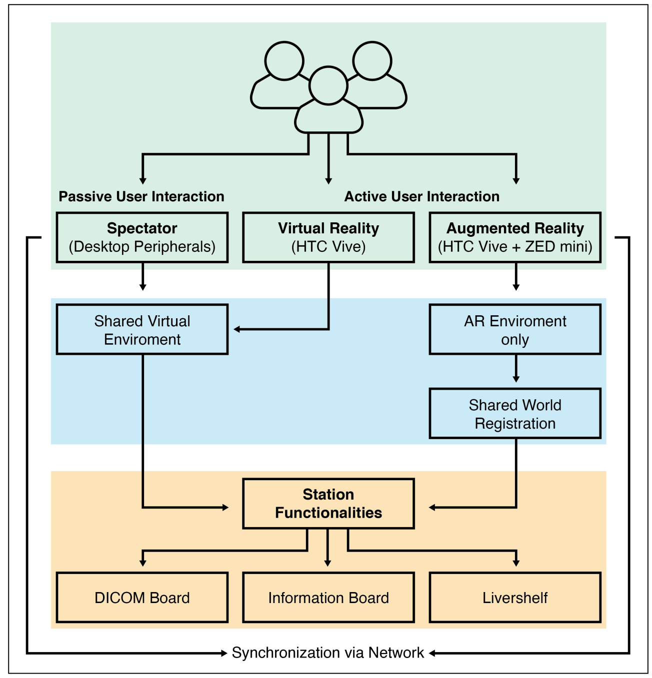

Figure 6: Overview of the system architecture.

factors. The IPQ is based on 14 questions and is carried out using a 7-point Likert scale.

5.2 Participants

The VR/AR modes were demonstrated to a test group of ten participants aged between 23 — 34 (M = 27.4) who had a medical background. To gain independent insights from student and expert needs, we divided our test group into two subgroups:

The first subgroup was formed by five non-paid experienced surgeons (three male, two female) from University Medical Center of the Johannes Gutenberg-University Mainz, Germany. All of this subgroup, except one person, had teaching experience(Tutorials for courses in ophthalmology, surgical suturing, ultrasound and anatomy). Two participants have more than five years of professional experience as a doctor. In this subgroup, all of them had previous experience with VR. Two participants stated that they had no experience with AR. There were no participants in the study who were involved in the development of the system.

The second subgroup consisted of five medical students (three male, one female, one not specified) from our university who were paid 20 Euro for their participation. One participant had experience as a teaching assistant. Four participants had passed the fifth academic semester. All of them had previously used a VR application. Two participants stated that they had no experience with AR.

5.3 Setup

Both test groups completed the experiment in a VR lab within a 3×3 meter tracking space. The study for instructors (medical experts) was conducted via video call. At the participant end, there was a technical assistant, who was located in the same room as the test person and only had to take care of the technical equipment and the well-being of the test person. The test person received instructions from the investigator exclusively via loudspeaker. During the experiment with the test group of medical students, the investigator was in the same room as the test subject. In both cases, the investigator was supported by an assistant who was physically located in a separate room and joined the session as a VR user. The investigator conducted the interview and was in spectator mode during the VR application.

To test the load limit of the multi-user VR application, a technical test with three participants in VR Mode (wearing VR headset) and 15 participants in spectator mode was conducted. No latency problems were detected for 20 minutes. Due to the limited tracking space and in compliance with hygiene regulations due to the COVID 19 pandemic, the AR mode was not tested with multiple users.

5.4 Procedure

The study lasted about one hour, with step-by-step presentations of the different modes: first VR Mode, second Spectator Mode, and third AR Mode. After explaining the process to the participant and obtaining written informed consent as well as demographic data, the experiment started in the virtual world, initially demonstrating user-to-user interaction by waving hands and shaking the head. If the participants stated to be ready, the three different stations were visited one after the other, starting with the *Liver Shelf*. The participants were regularly encouraged to say what they thought and saw, what their expectations were and why they took which action.

During the tour of the first station, the focus was on the interaction with the 3D representation. The test persons were asked to explore the interaction techniques as independently as possible. As soon as they reached their limits, the study assistant demonstrated the techniques. Different 3D models were handed over to each other and structures were examined together. Following this, the sorting functions listed in table 1 were presented in the virtual environment. The sorting of the *Liver Shelf* had to be changed at least once.

The participants should now choose a 3D representation and place it on the platform of the *Information Board* (2nd station). There the participants could explore medical background information on the selected data set. At the third station, the *DICOM Board* was presented. After a short introduction, there was a free interaction period where the participants could slice through a dataset and create photocopies. At least one randomly chosen slice had to be selected, a copy had to be created and passed on to the assistant. The participants were then asked to test the *DICOM Cube* with the help of the slice plane at the last station. At the end, each participant was asked if they felt unwell during the experiment in VR mode.

After the main routine was finished, the participant has to leave the VR mode and join again as a spectator. After the controls were cleared using the keyboard, the user had the opportunity to explore the virtual environment. Inside was the study assistant, which interacted with the environment in VR mode.

During the setup of the AR mode, the questionnaires on usability and presence of the VR mode were filled out. Due to hygiene and travel restrictions, it was not possible to present the AR mode in a multi-user setup. We presented the AR mode via a live video stream from the perspective of the study assistant. The assistant performed interactions and the study participant could comment on them.

5.5 Data analysis

After completion of the study, we transferred the recorded individual statements into a table. In the first step, the statements were labelled to assign them to the individual stations and participant. Subsequently, the statements were assigned to specific categories, which included input methods and devices, visual processing and contextual awareness. Thereupon, overlaps were identified and clusters were formed that contained at least duplicate statements. Finally, a summarizing statement was developed for these clusters.

6 Results

A total of 435 individual statements were recorded. Forty-nine statements could be summarized and assigned to ten categories presented in Table 2. The categories include statements about the virtual organ model or the *DICOM Cube* ("3D Representation"), the placement of

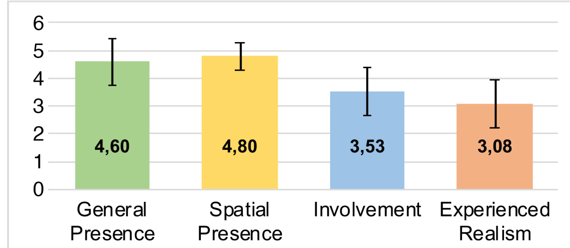

Figure 7: Results of the individual items of the Presence Questionnaire. G = General Presence, S = Spatial Presence, I = Involvement, R = Experienced Realism.

these models ("Spatial Arrangement") and the direct interaction with models and the cube ("3D Interaction"). Interactions that explicitly refer to the graphical user interface (GUI) are classified as "2D Interfaces". There were also categories for statements concerning the application with several users ("Multi-user"), the input device used ("Input Device"), "Locomotion" and perception ("Virtual Environment") of the virtual world emerged. One participant stated that they felt uncomfortable in the virtual environment for a short time at the beginning. All other test persons did not feel uncomfortable. It was not possible to demonstrate the AR Mode to two people. The usability of the VR mode received a score of 79 (max. = 100; SD = 7.8). The results of the IPQ are shown in Figure 7. Spatial presence was rated best (M = 4.8s; SD = 0.5) and experienced realism lowest (M = 3.08; SD = 0.87).

7 Discussion

Overall, our prototype was well received by the participants. According to the SUS, our VR mode achieved good usability (Recap: Score = 79). This positive value can be explained by the fact that the control was explained mostly in advance. However, most of the interactions were explored by the users themselves; some were described as intuitive (e.g., enlarging 3D objects). Users positively perceived the direct grasping of the organs. Nevertheless, the mixing of direct and indirect interaction (ray) often led to confusion and restrictions on the action. The presentation of additional information would be beneficial for students. The preparation of the data and presentation of the 3D model is particularly highlighted, as they provide a realistic insight into the anatomies of the liver (see Table 2; 3D Representation, 3D Interaction).

Separate functions for showing and hiding individual structures and highlighting would contribute to a better understanding of the context. Occasionally, participants could not understand some terms as well as the hierarchy, which may occur due to their early phase of medical education (see Table 2; 2D Interface). The presentation in the form of a shelf has the disadvantage that objects in the lower area attract less attention and are difficult to reach (see Table 2; Spatial Arrangement). Thus, users often had to bend down when manually putting a model back, because only direct grabbing was possible.

7.1 Information Board

Since the *Information Board* contains all case data and its preparation is similar to a classic medical report, it was positively received. However, the interaction between the 3D model and displayed text should be intensified. According to our participants, it would be desirable to highlight structures selected on the model in the continuous text. Marking text passages could also lead to the highlighting of specific structures (see Table 2; Information Board).

7.2 DICOM Board

The interface of the *DICOM board* is based on familiar desktop interaction from the real world, which helped participants to find

Table 2: Summary of the collected statements of the respective stations under allocation of different categories. The identifier (ID) represents the respective test person and serves for contextualization. ID = 1-5 experts; 6-10 students.

Category	Statements	ID
Liver Shelf		
3D Representation	Color scheme of the structures is appropriate More detailed exploration of individual pathologies desired Pathologies are clearly visible and adequately presented When enlarging the model more information should appear When rotating the model the context to the position in the body is missing	1,2,7,8,9,10 2,9,10 1,2,6,7,9 7,8 8,10
Spatial Arrangement	3D models were placed too low Arrangement of 3D representation is suitable Hierarchy of 3D models is not obvious	1,5,7 5,8 7,9,10
3D Interaction	Direct 3D interaction (scaling, translation, rotation) with Organs feels natural Exploration methods are easy to understand Mix of direct and ray interaction leads to confusion Object removal is expected with ray instead of gripping it directly Possibility to hide specific structures, change transparency and brightness Ray should hit internal structures Unused models should automatically sort themselves into shelves	1-7,9,10 2,4,5,9 6,7,9 3,5,7,10 1,2,3 5,6,7,9 1,3,5,8
2D Interface	Extension of the sorting function by adding more sub parameters Labeling is poorly readable Sorting option of patient ID is not helpful Sort function is useful	1,3 4,5 7,8 1,5,6
Information Board		
3D Interaction	Individual structures should be selectable and point to information board details	4,8,9
2D Interface	Scope and presentation of the information appropriate Text is too small and contrast is too weak	3,6,8 1,4,5
Multi-user	Presence of several information boards for parallel interaction and exploration	7,8
DICOM Board		
3D Representation	*DICOM Cube* needs further orientation hints Registration between 3D model and *DICOM Cube*	3,4,6,8 2,4
3D Interaction	Board functionalities should be available on preview image and photocopies *DICOM Cube* is a helpful addition because it promotes spatial understanding *DICOM Cube* and plane should be scalable, because visible areas are wasted Interactive photocopies are a useful addition to the static view Ray should better hit the plane directly instead of ending at the *DICOM Cube*	3,5,8 2,4,6,7,8 2,3,4 1,2,4,5,9 3,7
2D Interface	Data set should start centered for better orientation Preview image should be scalable Ray interaction leads to confusion while using Sliders Step by step slicing by using +/- symbol was interpreted as zoom function	1,3,4,8 4,5 7,8 2,5,8
Input Device	Ray interaction (slider movement) via controller is too inaccurate to slice data	1,4
Miscellaneous	Insufficient resolution of CT data in *DICOM Cube* Terms such as DICOM unknown Uncertainties during initialization of the *DICOM board*	1,5,6,8,9 6,10 1,2,3,5,6,9
General		
Multi-user	Adopting the VR user view is helpful for better understanding No more than 5 people should be in AR mode at the same time Spectator does not disturb the immersion Spectator mode is suitable for passive participation in larger groups Teacher is in spectator mode and can passively support students in VR mode VR mode is especially suitable for small learning groups	5,9,10 2,3,5,9 6,7 1,2,3,6 8,10 1,3,8,10
Virtual Environment	AR mode looks more familiar, because participants and environment are in view Spatial conditions limit movement in AR mode The distraction from the environment is greater in AR mode	2,6,8 6,7 7,9,10
Locomotion	Preference for walking instead of teleporting in VR mode	6,10
Miscellaneous	Implementation of AR mode seems unstable	4,8

their way around quickly. However, the initial relationship between patient data (3D liver model) and DICOM CT display was not understandable to users. There was a lack of understanding to activate the *DICOM board* because the CT slices had to be adjusted at the sliders first. The creation of photocopies and free interaction with them were especially helpful. Thus, views from different sectional planes could be created and discussed in parallel. In order to improve performance, the image resolution was reduced, but this was rated negatively by users because structures were hard to see. Almost all participants noted that the three-dimensional preparation of the data set as a cube is beneficial. Especially VR offers the possibility to create an interactive relationship to the body position. In the beginning, some student users had difficulties in getting the orientation concerning the human body and noticed that a hint about the body position would be helpful at this point. There was also the desire to display the liver directly in the cube and thus enable hybrid rendering (see Table 2; DICOM Board).

7.3 Interaction

Regarding the 3D interaction with the organ models or the *DICOM Cube*, the ray interaction should be improved so that direct manipulation and pointing on surfaces (structures) is possible. The adaptation of the 2D interface from the real world may be intuitive to use, but some elements are too hard to reach (small buttons) or too fine or even too coarse in the controls (e.g. sliders). This limitation is due to the choice of hardware (Vive Controller) and its implementation. The fact that some users complain about poor readability or too small text size can be associated with incorrect headset placement and missing lens correction.

7.4 AR Mode

AR technologies provide a sense of presence, enabling cooperative and situational learning, which can be beneficial for learning [47]. Users can see each other, which will increase the social feeling in contrast to VR. Our AR application could not be tested with several participants so far, but the participants also expressed possible spatial restrictions and the increased space requirements in AR mode. The teacher would rather have the impression of being seen and heard. In the teaching context, the focus might be lost for the students because of increased distractions. The participants also complained about the lower representation of structures. Although the interactions regarding the system's operation are identical to those in the VR environment, the usability, in this case, is only slightly comparable because the effect on the presence is different.

7.5 VR Mode

The IPQ measurement shows that the VR mode induces presence. Especially the high scores for the subscales "Spatial Presence" and "General Presence" show that the users in our sample had the feeling of being present in the VR environment and acting independently and freely. This indicates a decent suitability of this environment as an explorative learning environment. As expected, the subscale "Experienced Realism" has low values because our virtual environment has low realism in its abstract representation. Especially the first item of this subscale "How real did the virtual world seem to you?" underlines this with an average value of 2.2 (SD = 1.14). The second item of this subscale "How much did your experience in the virtual environment seem consistent with your real world experience?" achieved the best rating (M = 3.9; SD = 1.52), which underlines the intuitive nature of the interactions as well as the real-time communication. With an average value of 4.8 (SD = 0.63) on the subscale "Involvement", the last item "I was completely captivated by the virtual world", which indicates a good suitability for a learning environment that requires concentration. Here the third item "I still paid attention to the real environment" got a low value, which corresponds to the low degree of reality of our environment.

7.6 Learning Environment

A high level of presence increases motivation, which in turn is essential for achieving learning objectives. Our VR/AR environment promotes active learning by allowing users to explore anatomical structures through natural interactions, enabling embodied cognition and reducing cognitive load [31]. Our multi-user approach enables collective learning groups, which promotes communication and social interaction [14].

Our evaluation opens up different learning scenarios: If there is the possibility that all students are in virtual reality, this concept is particularly suitable for small learning groups. Students could benefit from interactivity, exchange of knowledge and discussing together. However, this scenario requires a more dynamic structure, so that it should be possible for each participant or group to receive individual information through specially accessible boards. The placement presented in our concept is much more suitable for a classical teacher-student scenario in which the teacher provides information. The idea behind the observation mode was initially to enable the participation of many users without special hardware.

Given the increasing presence of virtual teaching due to the COVID-19 pandemic, this kind of virtual environment could have a positive effect on the learning behavior of students. However, it turned out that the interaction possibilities are too limited, which could have adverse effects on motivation. For a teaching concept in this area, we suggest that the teacher is in a passive role, supporting students, giving instructions and hints.

Furthermore, a single observer does not seem to influence the presence of VR users, but this would have to be evaluated with a larger number of users because many observers could cause distraction. A fade-out and mute function seem to be a useful addition here. Furthermore, the perception of the participants among themselves must be improved. The use of avatars allows the inclusion of facial expressions and gestures, which in turn would promote communication among the users.

8 Conclusion and Future Work

We presented a multi-user, VR/AR learning environment to support students in liver surgery education using clinical cases. Different teaching scenarios were demonstrated that allow collaborative and cooperative learning in different group constellations. We presented different modes that can be individually selected by the user depending on the application case, thus enabling distance learning for all. Due to current hygiene regulations, we were only able to present the AR environment as a video demonstration, which is why we hope for meaningful results in future evaluations under study-friendly conditions. We see the implementation of user feedback and the resulting improvements as the next working steps for this. The concepts should then be integrated into a real training session and validated in that setting. At the same time, our prototype remains expandable in terms of the number of participants and the amount and type of medical data (e.g. by integrating concepts like the Bento Box [18]). Our setup may be adapted to training in further surgical disciplines. Our work offers a promising outlook to complementing complex practical and theoretical teaching content in surgical education with technologies like VR and AR.

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