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A VR neurointerventional setup for catheter-based interventions focusing on visualizing the risk of radiation

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ABSTRACT

Interventional neuroradiologists carry out their minimally-invasive procedure by using X-rays within the setup of a Bi-plane Digital Subtraction Angiography. This work provides an immersive virtual reality (VR) environment where the physicians can perform an simulated catheter-based intervention. Since radiation is invisible, the risk of radiation exposure can be enhanced virtually.

Our goal is to see whether radiation visualization influences medical professionals such that they take a more mindful approach towards interactions on the operating table then without one. We tested our scenario within an expert study where ten neuroradiologists participated and solved intervention-related tasks.

Our expert study found that while visualization does not affect the placement of the radiation shield by the physician, the overall radiation exposure using visualization does decrease as users standing very close move to a greater distance from the table. Furthermore, our System Usability Scale evaluation revealed a high score for this approach's usability.

1. Introduction

Interventional radiologists and neuroradiologists may get in contact with radiation quite frequently during a minimally-invasive intervention. With the radiation being invisible and its spread due to scatter effects being hard to grasp, it can be difficult to stay mindful of the current exposure and the ways to mitigate it. Thus, proper teaching becomes necessary for a safe work with radiation [1].

With no visual feedback, teaching a safe placement of shielding or a safe position to work from can be quite abstract, with no tangible way to communicate if a proper level of correctness or safety has been reached. At the same time, experimentations with the radiation protection during training can only be done within a restricted manner due to the associated health risks [2]. Meanwhile, improper radiation protection can also lead to serious long term health issues [3–5]. One method to reduce or at least measure the health risk posed by radiation during interventional neuroradiology is the use of personal dosimeters [6,7], allowing to keep track of the doctor's exposure. However, this will only provide insights into the current risks that have been already taken, and not into ways to prevent or alleviate these risks.

To help with this issue, a virtual training program could be utilized, allowing medical students and novices to safely train operations and radiation protection measures without any real exposure to radiation. Such a training program also opens up opportunities to visualize otherwise abstract and intangible features of the operating room, like the spread of the radiation within the room and the effectiveness of the used shielding. Different means to visualize volumetric data like the radiation intensity within a room have already been explored in related works [8], however, its usability and effect during medical training are so far unexplored.

This work investigates the usability of an immersive virtual reality (VR) environment for neurointerventional radiology and the effects of seeing a visualization of the radiation while working on a C-Arm within an Angiosuite.

2. Related work

There have already been multiple works comparing VR medical training to classical methods.

One such application is covered in Sultan et al. [9], where a VR application playing 360° medical briefings and debriefings was used in a study with medical students. The students using the VR application were reported to perform significantly better in a multiple choice questionnaire used for the evaluation.

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Issleib et al. [10] evaluated a VR simulation of resuscitation training. In a study with undergraduate students, they found that a classic life support training was superior in teaching technical skills, however, the VR counterpart for the training resulted in a higher learning gain being reported through a questionnaire. The inferior learning of technical skills in VR may never be feasibly avoidable, due to the inherit lack or reduction of physical haptic feedback of patient and tools when working in VR.

Another relevant aspect is the motivation to learn, which was studied in Sattar et al. [11] where a 360° VR video of a surgery was compared to text based learning as well as regular video based learning for final year medical students. The study found that students learning with VR were more motivated and rated their own competency higher than with the other two methods.

Anatomy training also benefits from VR, as shown in a study conducted by Kurul et al. [12], where a VR application that allows the user to explore an anatomical model of neck and head was compared with a classical training showing anatomy slides in a presentation. While both groups improved their test score after the training, the VR group performed significantly better.

While all these works found benefits for VR medical training, they just aimed to recreate the classical training as true to practice as possible. However, virtual environments offer more opportunities, opening the door for allowing users to see or do things that would not be possible within the narrow restrictions of classical training.

One application that takes use of this is covered in Zikas et al. [13], where a virtual simulation of a Covid-19 swab test was implemented. In addition to mirroring classical training, they also have a type of see-through vision, allowing the user to see the swap through a window in the patient's skin inside the patient's nose. They report that trainees trained with their VR application performed significantly better in swab tests then those who were trained traditionally.

Another application that uses the opportunity of a virtual world to introduce additional information to the user is presented by Barenthien et al. [14]. Here a VR medical education application was created and evaluated. This application creates a virtual laboratory with a radiation visualization at a C-Arm. The visualization depicts radiation rays as colored lines flying through the world, with the color at a point on the ray representing the intensity. Their work aimed at evaluating the suitability of their VR application, focusing on technical correctness of the radiation dose and the user's ability to answer general questions about radiation protection. While the application created and showed a visualization of the radiation, the evaluation for the use of it was only in form of a subjective question about its usefulness each user had to answer. The results were that the majority found it useful, while a minority had a neutral position and no user was against the visualization. However, a study analyzing the influence of actually seeing a radiation visualization while performing an intervention at a C-arm has not been done.

While both works [13,14] still have similar results as the previous mentioned works, where VR recreations of classical training have shown to be beneficial, neither investigate the effect of displaying this type of additional information beyond a subjective question about the general sentiment towards it.

Though VR does not only give the opportunity to introduce otherwise intangible information, it also allows to train procedures that have otherwise little reliable trainings opportunity due to being tied to risks or rare circumstances.

One of these examples is explored in Chheang et al. [15] where a VR liver surgery is implemented and tested. This application allows the user to cut into a liver and simulate the bleeding caused by cutting through blood vessels within it.

Gout et al. presented a VR trainings environment for medical disaster response for first responders [16]. They focused on such an application as with real-life drills being too costly and disasters too infrequent a lot of students graduated without ever participating in a medical disaster response drill [16].

For the visualization of volumetric data, like the spatially distributed radiation, there have also been several prior works. Some include particle visualizations, where objects are placed in space and visualize data through color, density or position [17]. Such an approach has a light performance impact [18], can be easily balanced for performance and data size [19] and has already proven useful for VR [20].

This approach may run into issues with occlusion, as many objects floating in space may obstruct the users view on relevant parts of the world. To aid with this issue, one can attempt to limit the visualization to relevant portions. One of these approaches would be the use of a clipping plane, allowing only data on behind a plane to be displayed [21]. This can be combined with a particle system, effectively cutting the space in which the visualization is displayed and moving this cute to a position of the user choice [17]. Though due to needing some form of user control to define this clipping plane to be at a beneficial position for a given task, this may add additional technical complexity to a medical training application, as the user would require more cognitive effort and needs to learn to control the app

Another approach to limit the volumetric visualization to relevant parts would be to tie it to object surfaces within the virtual world, like the doctor's or patient's body or the operating table [8,22,23]. Although this eliminates all masking problems, some information is also lost, as data points that are in the open are no longer displayed. However, for a radiation visualization on a C-Arm this may not be the most suitable, as a main point of interest for the radiation safety being the head and body of the doctors, which will be primarily be in the open air without a visible surface to the user, such it is data that would be lost.

Lastly, as discussed previously, Barenthien et al. [14] visualize radiation as rays moving through the air. This visualization does well to depict at which locations radiation is being scattered, but does not communicate the shadow or the effective area of a shielding. There are also some struggles with depth perception when the user is not standing inside the radiation ray, due to the nature of 3D lines on a 2D screen looking the same as 2D lines, losing a degree of freedom in information and not conveying their depth direction.

3. Materials and methods

In the following, we introduce the immersive VR environment and its components. Afterwards, the System Usability Scale which was employed for our evaluation study, is explained.

3.1. Laboratory setup

In this section, details about the virtual laboratory setup are explained, as well as the ways a user can interact in the immersive VR environment.

For the application we used the Unity Engine v2020.3.12f1 and a MetaQuest 3 connected to a computer through a link cable. The models for the shields, patient, catheter and lighting arm as well as the control panel were created in Blender v3.5. The C-Arm and patient table were created in a previous work [24], and modified in Blender to meet our requirements. For the control panel, the overhead shield and lighting arms and the shield table sliders, we measured and recorded the real counter parts in the STIMULATE[1] Angio lab. Then functionality of the control panel was implemented to mimic the one in the Angio lab as well with the blue and orange lever in Fig. 1 controlling one of each of the two C-Arms in rotation and position. We also consulted with experts to have the shield arm behave as expected, with elastic lattices that can match the form of the patient below. Same applies to the catheter that was designed to function as realistic as feasible.

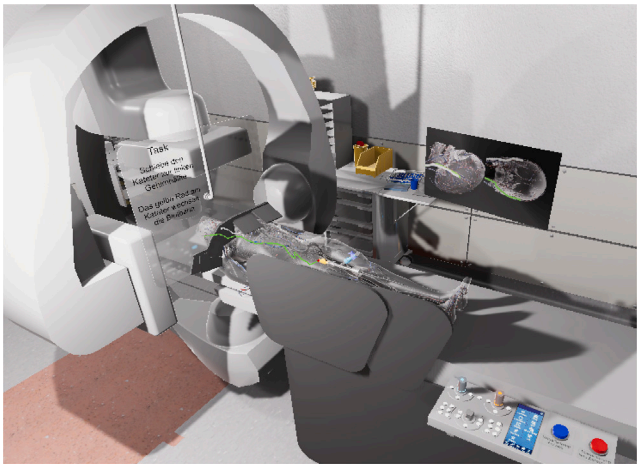

Fig. 1. The virtual laboratory showing a patient on a table, a double C-Arm, one movable and one unmovable shield, a control panel for the arm movement and a display showing the expected imaging result for each arm.

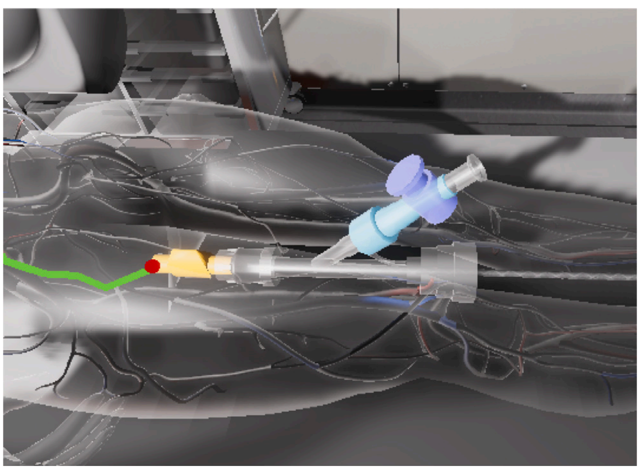

Fig. 2. A catheter at the patient's leg within the virtual environment.

In Fig. 2 the virtual catheter the user is interacting with can be seen. By grabbing the yellow wheel at the front of the catheter and rotating it, the expected path through the blood vessels changes. For the evaluation there are two possible predefined paths, which can be seen in Fig. 3, with one path leading to the left brain hemisphere while the other is leading to the right side. The current expected path is highlighted in green, so the user can adjust the wheel until they see the desired path. The wire coming out at the back of the catheter can be grabbed by the user and moved into the patient in order to simulate a neurointerventional catheter-based therapy. The red dot near the yellow wheel in Fig. 2 indicates the tip of the catheter inside the patient. This can also be seen on the display that shows the expected radioimaging for each of the C-Arms, as can be seen in Fig. 1 behind the table to the right. The patient is depicted in a transparent manner, revealing the blood vessels below and allowing the user to have an understanding of the blood vessel and depth of the catheter wire and the path ahead within the otherwise occluded volume of the patient's body. With this, the user recognizes when the catheter wire has reached the desired location in the brain.

[1] Research Campus STIMULATE: https://archiv.forschungscampus-stimulate.de/en/start/index.html.

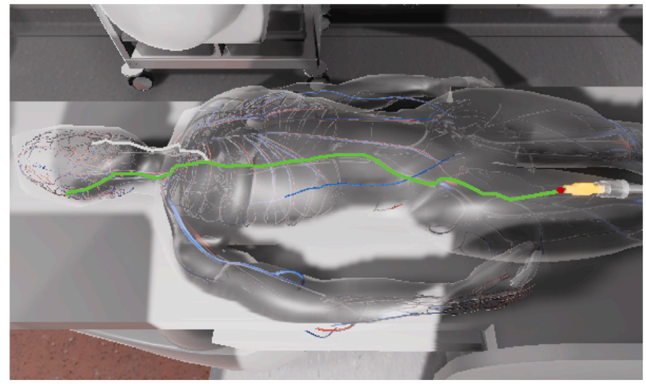

Fig. 3. A semi-transparent patient within the virtual environment. Two possible paths for the catheter are highlighted, one to the patient's right side of the brain (green) and one to the left side (white).

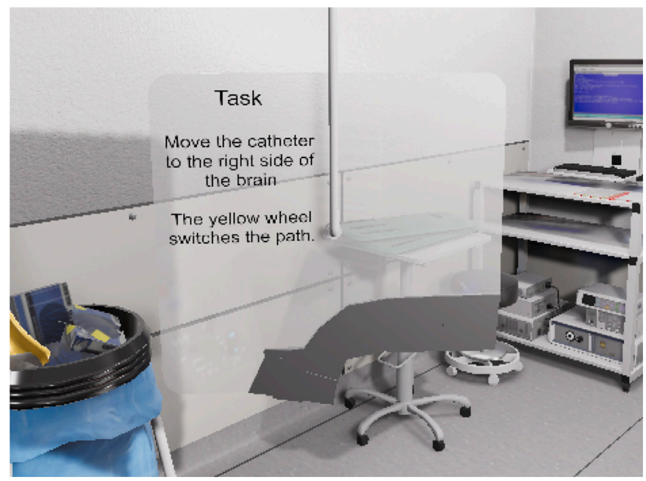

Fig. 4. A movable lead shielding hanging from a dynamic arm on the ceiling. The darker lattice at the bottom is elastic and will adjust itself to the surface below.

To protect themselves from radiation, the users have a movable shield (Fig. 4) that can be grabbed and placed wherever the users want. This shield is suspended in air by a dynamic arm on the ceiling, so the user cannot only modify the shield's rotation and position but also its height. Using the elastic lattices at the bottom of the shield, it can be placed directly onto the patient's body, as can be seen on the left side of Fig. 1.

In addition to this shield, a secondary shielding can be seen in Fig. 1 as large dark plates in front of the control panel.

Lastly, the lab has a control panel to control the movement of the two C-Arms, as can be seen in Fig. 5. Each arm has a lever that by default rotates the arm around one of two axes depending on whether the lever is moved vertically or horizontally. The levers have a secondary function, which is used if the trigger button is pressed while moving the lever. In reality, this can be imagined as a button on the back of the lever. The secondary function is the movement along the table when the lever is moved horizontally or the simultaneous rotation of both arms at the same time if moved vertically.

3.2. Radiation visualization

For the visualization of the radiation intensity, the visual effects graph in the Unity Engine was used. This visual effect creates round particles that represent the radiation intensity at a point by color and the average direction of rays at a point through movement. This effect can be seen in Fig. 6. In Section 2, we described several approaches for a

Fig. 5. The control panel for both C-Arms. The orange and blue control stick are used to rotate and move the Arms. The display is used to select specific position presets. The blue and red button are used to start and recalculate the radiation visualization.

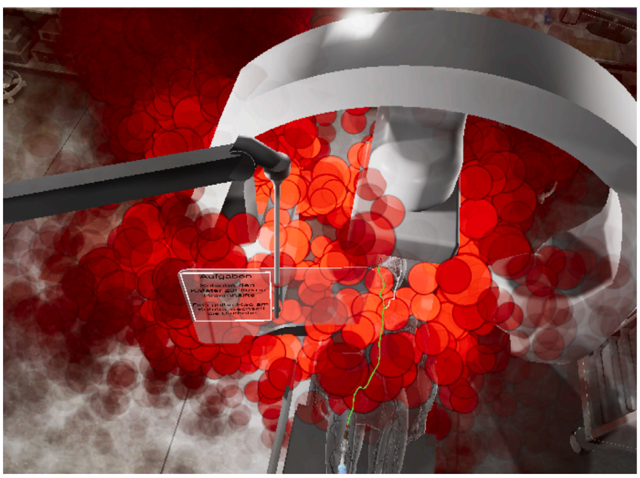

Fig. 6. The visualization of the radiation. Brighter red means higher intensity.

volumetric visualization. The choice for a particle system was made due to the need of displaying data in the open air to sufficiently illustrate the effect of a shield in regards to the radiation that reaches the users head and hands.

3.3. Radiation simulation

To simulate the scatter of the radiation, a Monte Carlo simulation was implemented. While the main body of the radiation can reasonably be approximated without simulating each individual ray, the scatter of the radiation on objects like the patient cannot, as the radiation can be redirected in an unpredictable direction due to the Compton effect [25]. As with this it is not feasible to statistically predict the path or intensity of the radiation, a Monte Carlo simulation was chosen to implement the unpredictability of each ray through randomness. The source within the C-Arm emits rays that each get their scattering on and in objects individually simulated. This method takes some time, so for the study, we could not recalculate the radiation continuously throughout the runtime. Instead, we added a button to recalculate the simulation and asked the user to press this button after they performed a change in the VR environment. The calculation takes about ten seconds and results in a 3D radiation intensity map, where the world is divided into cubes, and for each cube the average amount of rays that passed through is memorized.

Such an intensity map can be seen in Fig. 7 where a higher redness indicates that more radiation rays went through the cube. To hide distracting artifacts for the application, a bilinear filtering is applied on this 3D map, which smooths over hard lines between the cubes. The higher the resolution of the cube grid for the intensity map, the more accurate but also the more performance-intensive it becomes. We decided on a resolution of $32 \times 11 \times 32$ with each cube being 23 cm wide to balance performance and accuracy. However, this means that radiation may leak through very close to a shielding surface, as the shield may cut through the middle of such a 23 cm wide cube.

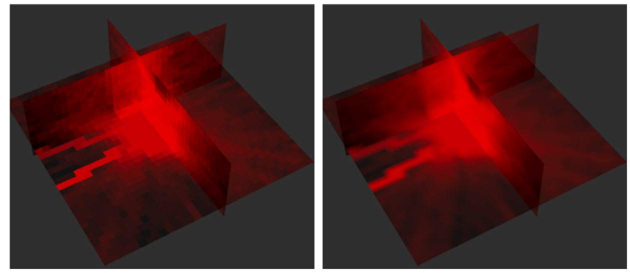

Fig. 7. A 3D radiation intensity map with (right) and without (left) bilinear filtering.

3.4. System usability scale

For the evaluation of the usability of a software application, the System Usability Scale (SUS) can be used [26]. Here, the user of an application is asked ten statements on a 7-Likert-Scale from strongly disagree to strongly agree, where a 4 represents a neutral choice. The sentiment behind the questions alternates with each odd statement being positively phrased and each even statement being negative. In the following is a summary of these ten statements:

1. I think that I would like to use this system frequently
2. I found the system unnecessarily complex
3. I thought the system was easy to use
4. I think that I would need the support of a technical person to be able to use this system
5. I found the various functions in this system were well integrated
6. I thought there was too much inconsistency in this system
7. I would imagine that most people would learn to use this system very quickly
8. I found the system very cumbersome to use
9. I felt very confident using the system
10. I needed to learn a lot of things before I could get going with this system

For the evaluation of the VR system, each study participant was asked to answer the SUS with pen and paper, right after they carried out the VR tasks.

4. Evaluation and results

The effect of the radiation visualization was evaluated in a user study. This study was designed to investigate whether there is a change in the behavior of the neuroradiologists when a visual representation of the radiation is enabled. For this, we allowed the user to freely move in the immersive VR environment. Initially, we placed the shield and the user start position further away from the patient forcing an initial movement and placement on the user side.

4.1. Hypotheses

We hypothesize the expectation that while seeing the visualization of radiation, the medical doctors will be more aware of their exposure, resulting in a more mindful placement of the shield and a more careful positioning of themselves. This would serve as an indication that a tool like this can be used to improve radiation safety.

H1 Users take a significantly higher distance to the radiation when interacting with the catheter with a radiation visualization.
H2 There is a significant difference in shield positioning when comparing the catheter interaction with and without visualization of radiation.
H3 The average radiation exposure while using the catheter without a radiation visualization is higher than the average exposure with the visualization active.

4.2. User study

When the participant enters the virtual Angiosuite, the user starts a few meters away from the C-arm table with the movable shield nearby. This starting distance to the operating table is chosen to allow us to better observe the users' own choice of positioning, as they are forced to walk up to the table themselves.

As an introduction to the application, the user has to move around in the VR environment and is taught how to grab and move objects by an instructor who was part of the project team and is standing in the same physical room as the participant. In addition to free movement in the real world, continuous movement is also allowed through a thumbstick on the left Oculus-Controller. This is needed as the real-world space might be smaller than the virtual environment. The confinements of the real world space become visible in VR if the user gets too close to a predefined boundary through the default Oculus Play-Area grid.

To help with both grabbing objects and teleportation, there are lasers going from the users hands to the location a hand is pointing at. If the pointed location can be teleported to, or the object the user is pointing at can be grabbed, these lasers turn from red to white.

After bringing the shield to a desired position using a controllers Grip-Button and moving while the shield is grabbed, the main tasks begin. These tasks are labeled with an ID to help keeping track of when and for what purpose data is being recorded, and the application automatically determines when a task is completed and moves forward updating the instruction text as well as some scene preparations. The user is asked to move the catheter wire first to the left brain hemisphere and second, to the right brain side, with a text printed on the shield keeping track of the current task as seen in Fig. 4. To change the path the catheter wire takes, the user is instructed to grab and turn the yellow wheel at the front of the catheter in order to navigate, i.e., to virtually perform the intervention.

After finishing the first two catheter interactions, the visualization needs to be turned on using a blue button on the control panel as seen in Fig. 5. This will move the shield back to its original position, forcing the user to place it again, now while being able to see the radiation visualization in the immersive VR environment. After setting up the shield, the radiation simulation needs to be recalculated using the red button on the control panel, which takes around 10 s to simulate the scatter for four thousand rays. Using the newly calculated visualization with the adjusted shield position, the user is then tasked with moving the catheter to the right and left brain hemisphere again.

4.3. Measurements

Throughout the use of the application, several pieces of information are automatically recorded every other second, which was implemented in our prototype. These include the current location and rotation of the shield, the users head and hands as well as the current task ID. While the radiation intensity at all points of interest is also being recorded, for the part where the visualization of radiation is disabled, these values are calculated from the recorded setup as the user is not being asked to recalculate the simulation as they have not yet been introduced to this mechanic. As described in Section 3.3, the result of our radiation simulation is a 3D map of cubes, where each cube holds a record of the amount of radiation ray that passed through it with four thousand rays being simulated. For the current radiation exposure at a time step we record the ray number of the cubes that represent the current user head and hand positions. To allow us to compare different users' exposure on the shield and position effectiveness rather than the time spend on a task, we then average this ray count over the time steps. Only time steps during the catheter interaction tasks are considered. In addition to these automatic records, the user is filling out a System Usability Scale (SUS) after completing all tasks. The questionnaire sheet for the SUS also inquires if the user had prior experience in VR and in neurointerventional work on a C-Arm.

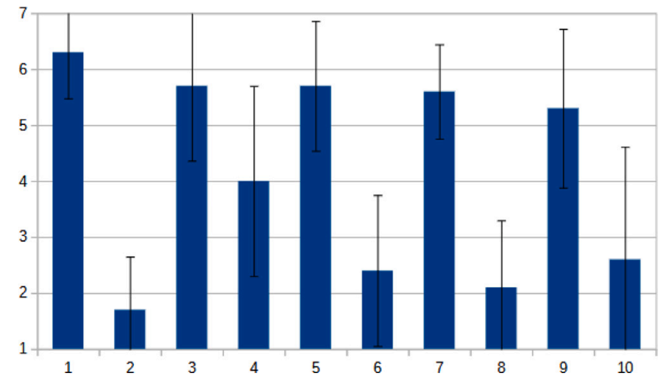

Fig. 8. The System Usability Scale results of the preliminary study. The ten bars refer to the ten statements of the sus as can be found in Section 3.4. A low score means the user strongly disagreed with the given statement.

4.4. Preliminary study

A preliminary study with five medical experts (2 male, 3 female, ages 35–42) working in the Neuroradiologic Clinic of the University Hospital Magdeburg was conducted. Four out of the five said they had experience with the interventional work on a C-Arm, while only one had used VR before.

The teleport function seemed counterproductive to our attempts at investigating a potential shift in the participants positioning. This is due to the movement becoming a precision aiming test, with the participants aiming at the position they want to go. Depending on how precise the aim is, they may or may not end up at the desired location. Participants would also rarely readjust their position after a teleport, and seem to avoid the continuous movement with the thumbstick when given the option to teleport as well. They almost seemed frightened to accidentally move in the wrong direction.

This is why the decision was made to remove teleportation from the main study, forcing participants to engage in continuous movement methods.

Another issue was the control of the yellow wheel to change the catheter path, as we expected this wheel to be grabbed with the hand pointing forward to the front of the catheter, however this is not how it is being handled by medical experts. With the expected grip, it made sense to define the rotation of the wheel around the participants wrist rotation, but it turned out that this is not how medical experts use the catheter. Instead, all the participants want to grab the wheel from the side with the hand pointing orthogonally to the catheter, rotating the wheel upwards and back or inwards and down, eliminating any rotation around the wrist, causing the participants to be unable to rotate the wheel. This behavior was then adjusted for the main study as well.

All in all, the participants liked the application, expressed a subjective learning success, and gave the application a decent SUS score of 72.67. As can be seen in Fig. 8, the main problem with the application was statement number 4. This statement is about needing a technical support person to use the application. As we revised the movement and wheel rotation controls for the main study, the score for this statement is expected to improve.

The final statement number 10, which is about needing to learn a lot before being able to use an application also scored mediocre. This can be expected as most participants had never used VR before and needed to understand the controls first.

4.5. Study

After improving the initial prototype, we had to re-evaluate the immersive VR setting. Our main study was conducted with 10 medical experts (6 male, 4 female, ages 35–49) of which 6 had prior experience with working with a C-Arm and 5 had experience with VR. Hereby was the number of participants highly limited as we are focusing on medical experts working in the given field, who are limited in number and have limited availability. The main differences to the preliminary study is that teleportation was removed and the rotation mechanic of the catheter wheel was adjusted. The real-world room in which the main study was conducted was also more spacious and allowed participants greater freedom of movement in the real world than in the preliminary study.

4.6. Results

In this section, the SUS is being evaluated as well as the participant behavior with the recorded technical data during system usage.

The recorded data includes (1) the users' positions, (2) the shields' positions' and (3) the radiation exposure.

Based on the recorded user's position, we extracted an average position for each user while doing the neuro-interventional related tasks, as illustrated in Fig. 9. While some participants can be seen taking more distance (e.g., see the pink, purple, light yellow or sky-blue primitives in Fig. 9), others are going closer to both the operating table and the radiation source with the visualization turned on (see the cyan and orange users). By far the biggest change in position was done by the yellow and sky blue participant, who took an additional 26.3 cm and 29.0 cm distance to radiation source. Those two were also the ones that interacted closest to the operating table without the visualization, with yellow being on average only 12 cm away from the table while sky blue was actually leaning 7 cm over into the table behind the tables shielding. Similar can be observed for pink, purple and teal who took an additional distance of 17.8 cm, 22.3 cm and 26.0 cm when the visualization was turned on. While red and cyan were at a similar distance to the operating table as purple and teal, they reduced their distance to the radiation source by 1.5 cm and 4.6 cm when the visualization was turned on. The biggest step forward was done by the second furthest away user with orange 32.1 cm closer to the radiation source. It seems like participants that were closer to the operating table without visualization also took a larger step back with the visualization, while the only user that went vastly closer was also one that was very far away before.

On average the users end up 9.97 cm further away from the radiation source when the visualization is turned on, as can be seen in Fig. 10.

Almost all the participants place the shield in nearly the same position for both with and without radiation visualization. In general, it seemed like the participants already knew exactly where they wanted the shield and placed it out of habit. Some users even placed the shield before they were asked to do so, during the phase in which they are getting the Grab-Controls explained. Quite a few participants placed their shields almost identical to each other, as can be seen in Fig. 11, where on the left side image, there are four shield placements overlapping closest to the detector side of the C-Arm.

Even though the shield position stayed almost the same, and quite a few participants came closer to the operating table, the average radiation exposure of the initial four thousand rays went down by 58.5% from 20.78 to 12.15 rays. As mentioned in Section 4.3, this radiation exposure are all the scattered rays that went through the

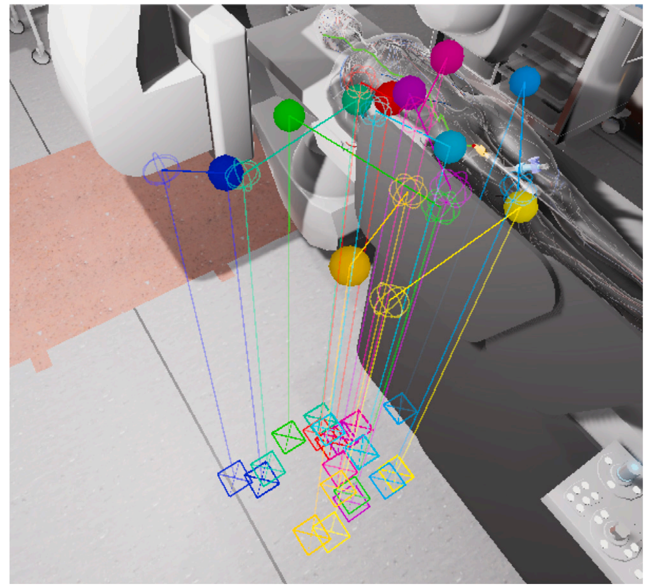

Fig. 9. The average position of each of the ten main study participants while doing the catheter-related tasks. Each person has a different color assigned. The full spheres represent the head position without radiation visualization. The wire-spheres represent the head position with radiation visualization. The squares on the ground are where the user would be standing.

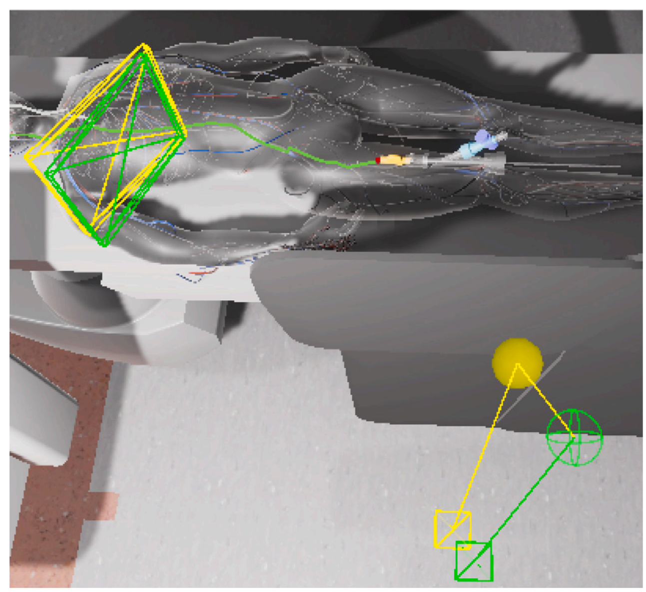

Fig. 10. The average positions over all players. Green is with radiation visualization turned on. The floating quads are the average shield position. The full sphere is the average head position without radiation visualization. The wire sphere is the average head position with radiation visualization enabled. On average, the user is about 10 cm further away from both the radiation source as well as the place shield.

cube the head and hands are in a time step, summed up and averaged over the amount of time steps recorded. This reduction in the radiation exposure was especially caused by users who were very close to the table (without radiation visualization) and that took a step back once the radiation visualization is enabled, as can be seen in Fig. 9. Also, one of the participants that got closer to the patient when radiation visualization was turned on, did not place the shield correctly at the C-Arm for the first tasks (without the radiation visualization), causing a significantly higher radiation dose without visualization then the other users. This refers to the orange user in Fig. 9 who has no corresponding

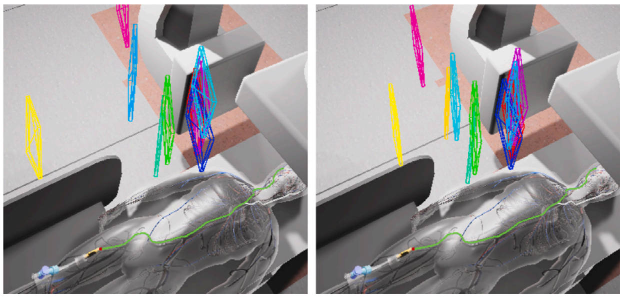

Fig. 11. The shield position for each user. On the left, the results without radiation visualization are depicted, on the right with radiation visualization turned on. The study participants placed the shields almost in exactly the same position when they had to redo it with the visualization turned on.

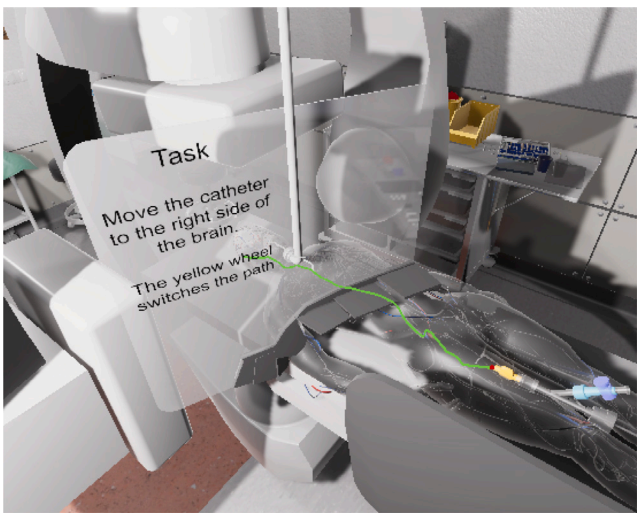

Fig. 12. Expected shield position, used as a reference point for the user placed shields.

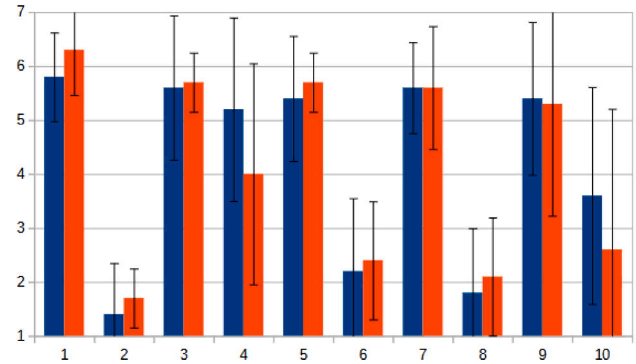

Fig. 13. The System Usability Scale results of the main study (orange) compared to the preliminary study (blue). The ten bars refer to the ten statements of the SUS as can be found in Section 3.4. A low score means the user strongly disagreed with the given statement.

Table 1
Summary of the ANOVA's results of the users positioning and Question 4 of the SUS.

Variable	df	F	p	Sig
Effect of visualization				
Player distance to source	1	2.606	0.123	No
Shield distance to expectation	1	1.444	0.245	No
Radiation exposure	1	4.769	0.042	Yes
Preliminary and Main study				
SUS4 needing technical support	1	1.457	0.249	No

orange shield in the left side of Fig. 11 which depicts the shield positions for the first two tasks, as the orange shield was placed further down the room. The immersive VR environment also allowed users to interact with the catheter from afar, by pointing at it and grabbing it virtually even though the catheter was out of arms reach. This allowed for the varied average positions of each user in Fig. 9, where certain positions would not allow the neuroradiologist to access the catheter in reality.

4.6.1. *Questionnaire results*

The overall consensus of our participant group is that they would like to use our application frequently, found it easy to use and found its functions well integrated, as seen by the strong agreement for entry 1, 3 and 5 in Section 3.4. The participants did not find our application too complex (2) but they were unsure about the level of support needed by a technical person (4). This improved from the preliminary study where the consensus was that technical support was needed. Furthermore, the participants found little inconsistencies (6) and found that they need to learn a little before using the system (10), while the system was not perceived as cumbersome (8). In the end the consensus between the participants is that using our application can quickly be learned by anyone (7) and felt confident in using the system (9) (see Fig. 13).

4.6.2. *Statistical analysis*

In addition to the described hypothesis in Section 4.1, we also expect that after the adjustments made with the feedback of the preliminary study, the SUS score will improve, especially for the technical support-related statements. For the statistical evaluation, we conducted single factor ANOVA tests between usage and non-usage of the visualization for the distance of the user to radiation source and the distance of the shield position to the expected shield position (Fig. 12). This ANOVA test was conducted in the spread sheet software LibreOffice. As the preliminary study had technical issues that were fixed for the main study, and the result for the SUS technical support question between preliminary and main study is quite different as seen in Fig. 13 and Section 3.4, we also conducted an ANOVA test between preliminary and main study for the SUS statement number 4. The statistical results are presented in Table 1.

There was no statistical significance in the average user distance to the radiation source or shield distance to the expected placement. The users placed the shields almost identically with and without radiation visualization. Meanwhile, for the user position, some took more distance while others got closer to the operating table when comparing the effects of the visualization. However, the users who got closer tend to have already had a secure distance while the ones that stepped back were too close before. This resulted in a statistically significant reduction of average radiation intensity while using the catheter, lowering the overall average intensity to 58.5% of what it was without the visualization. This reduction in radiation is mostly due to two reasons, users that were close to the operation table took a step back into the radiation shadow of the shield and users that were close to the shield took a step away from the shielding.

General feedback. The application received very positive feedback in general with the participants enjoying using it. One user mentioned that at the start they needed technical support, but once the controls were understood it became easy to use. This may be in part due to the controls not being listed anywhere in the application, instead, they were verbally communicated during the study. Some of the users who were already familiar with VR were surprised they felt no motion sickness. In general, there was no participant that complaint about any vision or motion sickness related issues. This may be in part due to the main studies room being so large, most of the tasks could be done without in-application movement, by simply moving around in the real world.

Even though some of the participants had little to no experience in VR, everyone found it easy to learn and intuitive to use.

4.7. Discussion

The first two hypotheses from Section 4.1 must be rejected. The overall user position is not further away from the radiation, instead participants that were far away without the visualization would now come closer to the operating table, while those who were close now take a little bit more distance. Shield positioning also did not behave as expected. The users knew exactly where they wanted the shield, no matter whether a visualization is turned on or not. This might be an indication that it was part of their training in order to become a neuroradiologist. However, even though the first two hypotheses have to be rejected, the third one is accepted. Even though the overall distance to the radiation did not increase with the visualization enabled and the shields were not placed any different, the overall average radiation exposure, calculated as detailed in Section 4.3, still decreased significantly. The reason behind this is that the specific participants that were too close to the operating table ended up taking a step back, and that was exactly what was required to make a significant difference.

5. Conclusion

We presented an immersive VR environment, where neuroradiologists could perform simulated minimally invasive interventions and turn the visualization of X-ray radiation, emitted from the C-Arm in the virtual Angiosuite, on and off. Even though our study had a low number of participants, due to our focus on medical experts, we still found statistically significant results. The user study reveals that for medical experts using a radiation visualization in VR does not have a significant impact on their placement of radiation protection measures like shields, as they seem to already know where to place it and do it out of habit. However, the use of the radiation visualization during the VR training caused a lesser overall exposure to the radiation, as those who were too close without the visualization, would take more distance when seeing the radiation in the VR environment. For participants who already were positioned decently, it had the contrary effect, they would come closer though still being within a safe distance. This indicates that the medical experts learned a better positioning within our VR environment, with lesser radiation exposure, even though this positioning may not be fully realistic for a real-world setting, given the additional reach possible in our virtual laboratory.

Furthermore, all participants found the application very usable. Even participants who never used VR before quickly learned the controls and were perfectly capable of using the application. This means a VR application like this can be very suitable for medical training, as unlike desktop PC controls, VR poses less of an accessibility limitation with its more intuitive controls.

For future work, our application could nicely be paired with a blood flow visualization akin to the works of Sprengel et al. [27], allowing the user to analyze blood flow within the brain and conduct minimal invasive procedures while seeing the alteration in the blood flow. Another possible way to extend this application would be gamification, adding a score board and replayable scenarios to keep the motivation and learning engagement of medical students using the application high. Furthermore, while C-Arm controls were already implemented, allowing to move and rotate the C-Arms, these were not evaluated within the scope of the study, and thus were not considered in the SUS questionnaire. A further study into the applications usability with a focus on the full use of all its features instead of focusing on repeated catheter interactions may be appropriate. With a broader participant group, it would also be valuable to compare the user performance between user groups with different levels of VR experience or visual impairments in a future study Potential cybersickness effects when using the VR training program could also be studied using the simulation sickness questionnaire [28] in a future study, especially when combined with a walk-behavior study in a multi-user setup.

CRediT authorship contribution statement

Marcus Streuber: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Mareen Allgaier:** Writing – review & editing. **Roland Schwab:** Writing – original draft, Resources, Conceptualization. **Daniel Behme:** Writing – original draft, Resources, Conceptualization. **Sylvia Saalfeld:** Writing – original draft, Supervision, Resources, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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