A Gesture-Controlled Projection Display for CT-Guided Interventions

A. Mewes[1], P. Saalfeld[2,1], O. Riabikin[3], M. Skalej[3], C. Hansen[1]

[1] *Computer-Assisted Surgery Group, Faculty of Computer Science, University of Magdeburg, Germany*
[2] *Visualization Group, Faculty of Computer Science, University of Magdeburg, Germany*
[3] *Clinic of Neuroradiology, University Hospital Magdeburg, Germany*

Abstract

Purpose The interaction with interventional imaging systems within a sterile environment is a challenging task for physicians. Direct physician-machine interaction during an intervention is rather limited because of sterility and workspace restrictions.

Methods We present a gesture-controlled projection display that enables a direct and natural physician-machine interaction during computed tomography (CT)-based interventions. Therefore, a graphical user interface is projected on a radiation shield located in front of the physician. Hand gestures in front of this display are captured and classified using a Leap Motion Controller (LMC). We propose a gesture set to control basic functions of intervention software such as gestures for 2D image exploration, 3D object manipulation and selection. Our methods were evaluated in a clinically oriented user study with 12 participants.

Results The results of the performed user study confirm that the display and the underlying interaction concept are accepted by clinical users. The recognition of the gestures is robust, although there is potential for improvements. The gesture training times are less than 10 minutes, but vary heavily between the participants of the study. The developed gestures are connected logically to the intervention software and intuitive to use.

Conclusion The proposed gesture-controlled projection display counters current thinking, namely, it gives the radiologist complete control of the intervention software. It opens new possibilities for direct physician-machine interaction during CT-based interventions and is well suited to become an integral part of future interventional suites.

Keywords Human-Computer Interaction, Computer-Assisted Surgery, Gesture Control, Intraoperative Visualization

Introduction

Interventional imaging devices, such as multi detector (MDCT) and cone beam (CBCT) computed tomography scanners, provide a wide range of functions. The direct interaction with these devices within a sterile environment is a challenging task for radiologists. Therefore, many functions are usually controlled indirectly by a radiology technician in a non-sterile control room. The technician interprets voice commands and hand gestures of the radiologists and operates the interventional software using conventional interaction devices such as keyboard and mouse. A direct usage of computer keyboards by the physician is no option because of the increased risk of infection due to contamination with bacteria

[1, 2]. The indirect interaction is time-consuming, error-prone [3] and requires additional specialized personnel, which, e.g., causes higher treatment costs.
Nowadays, direct control of intervention software is only possible to a limited extent. Available interfaces usually consist of a control panel with buttons and joysticks, touch displays, and foot pedals. Using this setup, users of these systems perform different tasks, such as controlling the position of a C-arm or the operating table, setting of acquisition parameters or triggering of scans. However, recent studies show that the use of those interfaces can disturb the workflow. According to Hübler et al. [3] radiologists may have to leave the sterile area in order to retrieve additional patient data on a separate workstation outside of the intervention room. Even the controller of the C-Arm and table is sometimes out of reach or blocked by another user, so that he cannot use it immediately.

To overcome the complexity of current interfaces available for the intervention software, we present a projector system with a Natural User Interface (NUI) based on visual gesture recognition, which enables radiologists to directly interact with the medical software on the radiation shield of the diagnostic device, which is usually straight next to or in front of them.

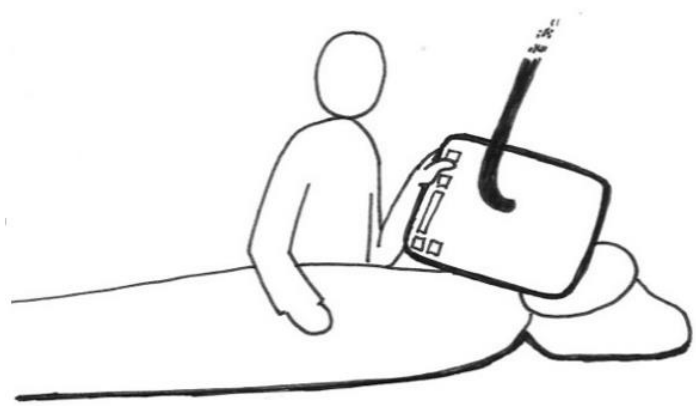

Figure 1: Concept of a projection display on a radiation shield directly controlled by the physician.

Related Work

Methods for physician-computer interaction have been investigated for many years [4]. However, only a few groups address visualization and interaction within sterile environments. Wachs et al. [5] and Ritter et al. [6] presented a camera-based system featuring hand gesture control for the exploration of medical images. However, these systems offer only a small set of gestures and lack in accuracy and robustness.

Gesture control is an element of NUIs. As stated in [7], the term *natural* means that the user's behaviour and feeling during the interaction is close to real world interaction. A special case of NUIs are 3D UIs, which enable direct interaction with, e.g., a 3D model through special input or output devices. In our paper we focus on the input device. This can be physical, like a stylus for the planning of a surgery [8] or a method such as gesture input. For example, Soutschek et al. [9] and Kollorz et al. [10] recognized gestures with a time-of-flight camera to interact with 3D image data for intra-operative applications.

The introduction of affordable 3D interaction devices and robust depth cameras created new possibilities for touch-free interaction in the OR. Ebert et al. [11] introduced a system to control a medical image viewer by simple hand gestures and voice commands using the Microsoft Kinect. They propose a training of 10 min to get familiar with their system. Due to a recommended working distance of 1.2 m a large display is required for many tasks, which might cause space problems. Gallo et al. [12] and

Hötker et al. [13] proposed similar approaches using the Kinect. Gallo et al. additionally implemented filters to reduce signal noise and improve accuracy, Hötker et al. used supplementary voice commands for less ambiguity. A more sophisticated gesture recognition algorithm for the Kinect was presented and evaluated by Jacob et al. [14].

Bizzotto et al. [15] conclude that the Leap Motion Controller (LMC) is a useful device for interacting with medical software, i.e. OsiriX, in a sterile environment. The LMC is an affordable consumer product and specialized in interpreting arm, hand and finger movements as gestures. Bizzotto et al. point out the advantage of a better working distance and accuracy than a Kinect-based system. The training time for three gestures in usability tests was approximately 5 min. Mauser et al. [16] presented a concept for LMC-based gesture control that is utilized for radiologic image slicing, 3D model rotation and other functionalities with simple hand positioning and orientation gestures being mapped onto mouse events. The authors emphasize the high potential for the use of an LMC in intra-operative situations, but also the need for a careful use case analysis and appropriate gesture selection. Because their gestures were ambiguous, they believe that a lock/unlock gesture is mandatory. The approach seems promising, however, they did not evaluate their system in a user study. Another touchless image navigation system has been introduced by Rosa et al. [17] in the field of dental surgery. The authors compare the LMC interaction with a Kinect-based system and resume that the Kinect system leads to faster fatigue due to unnecessarily wider movements of the body and needs a larger distance to the screen.

Weichert et al. [18] performed accuracy measurements using the LMC by determining the deviation between the desired 3D position of a reference pen and the 3D position obtained by an LMC. In static test cases, the deviation was lower than 0.2 mm, in dynamic cases it was below 0.7 mm. The diameter of the reference pen used as tracked tool had no impact on the error. Similar results were found by Guna et al. [19], where the standard deviation was less than 0.5 mm in static test cases, but a significant drop in accuracy was recognized when samples were taken more than 250 mm above the LMC. However, to the knowledge of the authors, no group investigated the convenience of natural gesture interaction with a medical software using the LMC regarding usability aspects.

Materials and Methods

We present a gesture-controlled projection display that enables a direct and natural physician-machine interaction during CT-based interventions. First, requirements for the system based on a workflow analysis are described. Second, the setup of our projection display is presented in detail. Third, the choice of supported 3D interaction tasks for our prototype is described. Finally, a gesture set to control basic functions of intervention software is proposed.

Requirement Analysis

An analysis and evaluation of the workflow in interventional radiology, in particular neuroradiological interventions, was performed within previous work of our group [3]. Therefore, a top view camera recorded the control panel of the CT scanner. A back view camera recorded the operators in total view. These cameras were equipped with microphones that recorded system sounds or discussions between users. In sum, 25 treatments were recorded. Among other things, the following observations were made:

- Users had to leave the sterile area in order to retrieve additional patient data (medical imaging data and diagnostic report) from a workstation outside of the sterile area
- Users tried to interact with an interaction device (touch panel, joystick, foot pedal) that is out of reach or blocked by another user

Based on discussions with two interventional radiologists and a usability specialist the following requirements for physician-computer interaction during CT-based interventions were defined:

- *Clinical applicability*: The interaction should be possible within a sterile environment with limited space. It should not influence the workflow of interventions.
- *Accessibility*: The interaction device for the intervention software should always be reachable for the physician.
- *Usability*: The interaction task should be fast, convenient, not tiring and require a small amount of training.

The results of our workflow analysis and the subsequent discussions with our clinical partners lead to the development of a gesture-controlled projection display that is described in the following.

Setup of Gesture-Controlled Projection Display

For interaction with the medical software, we propose a set of natural gestures, which are recognized by a LMC. This depth sensor consists of two infrared cameras and three infrared LEDs inside an 80 mm x 30 mm x 11 mm casing and is attached to a PC. It has an interaction volume of approximately 0.5 m x 0.5 m x 0.5 m. By using the developer API of the LMC it is possible to detect a predefined set of four hand gestures, and it is also possible to define own gesture sets. The LMC is placed at the bottom of an acrylic glass screen and observes the user's hands from the bottom.

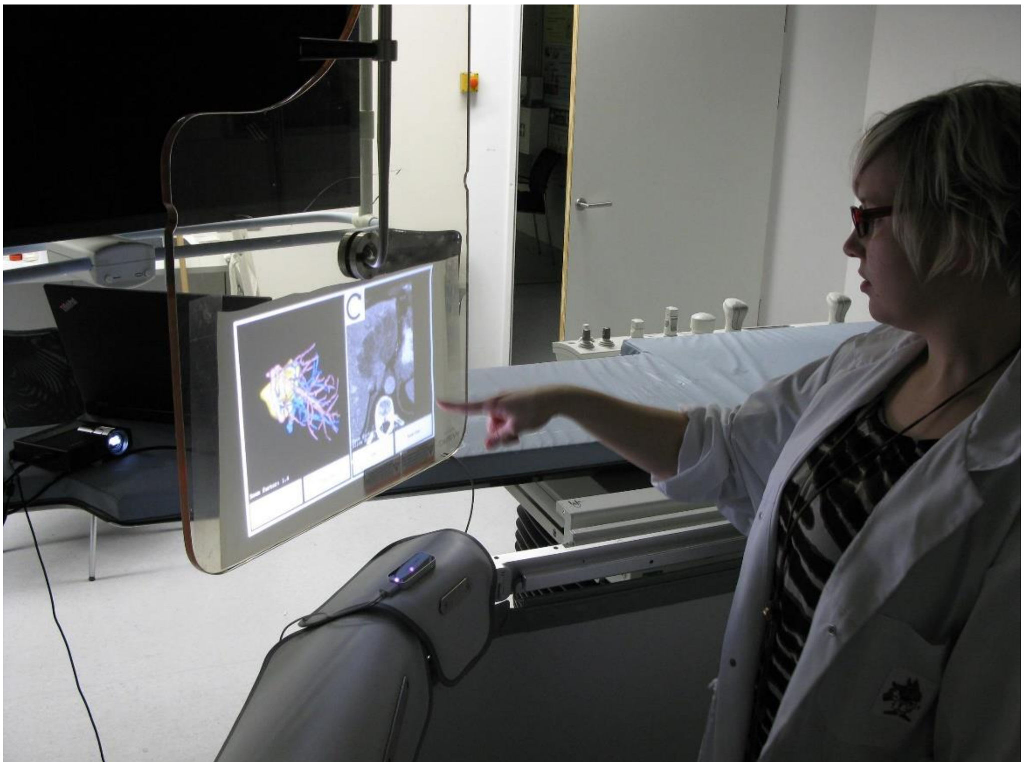

Figure 2: Setup of our prototype. The projector on the left is projecting the viewer software onto the radiation shield in the middle. Below the acrylic glass, the LMC is placed to recognize hand and finger gestures for the interaction.

The viewport of the intervention software is projected onto the screen by an ASUS P1-DLP pico projector with a resolution of 1280x800 px. The acrylic glass screen is covered with a transparent projection foil (Modulor Opera) in order to provide good contrast. The resulting diagonal of the projection is approximately 0.5 m, which fits exactly inside the interaction volume of the LMC.

To map hand and finger positions directly on the correct viewport coordinate of the display, we implemented a point-based calibration method that aligns the interaction volume of the LMC to the viewport. Therefore, the corners of the viewport are selected by the user and used as calibration landmarks.

Choice of supported 3D Interaction Tasks

Gestures for natural user interfaces have to be chosen very carefully depending on the use case. In this work, we propose natural gestures to control basic functions of intervention software. More specifically, we decided to limit the supported interaction tasks to the following basic functions of intervention software:

- Navigation within a stack of radiologic images, including slicing, zooming and panning of 2D slices
- Manipulation of 3D planning models, including rotation, zooming and panning
- Selection of virtual objects such as buttons

3D and 2D viewers are separated and arranged side by side on the screen, as shown in **Figure 3**. The software provides visual feedback on which interaction zone the gesture is focused. This might help to prevent confusion due to the fact that there should be no unlock gesture, which implicates potentially misinterpreted gestures.

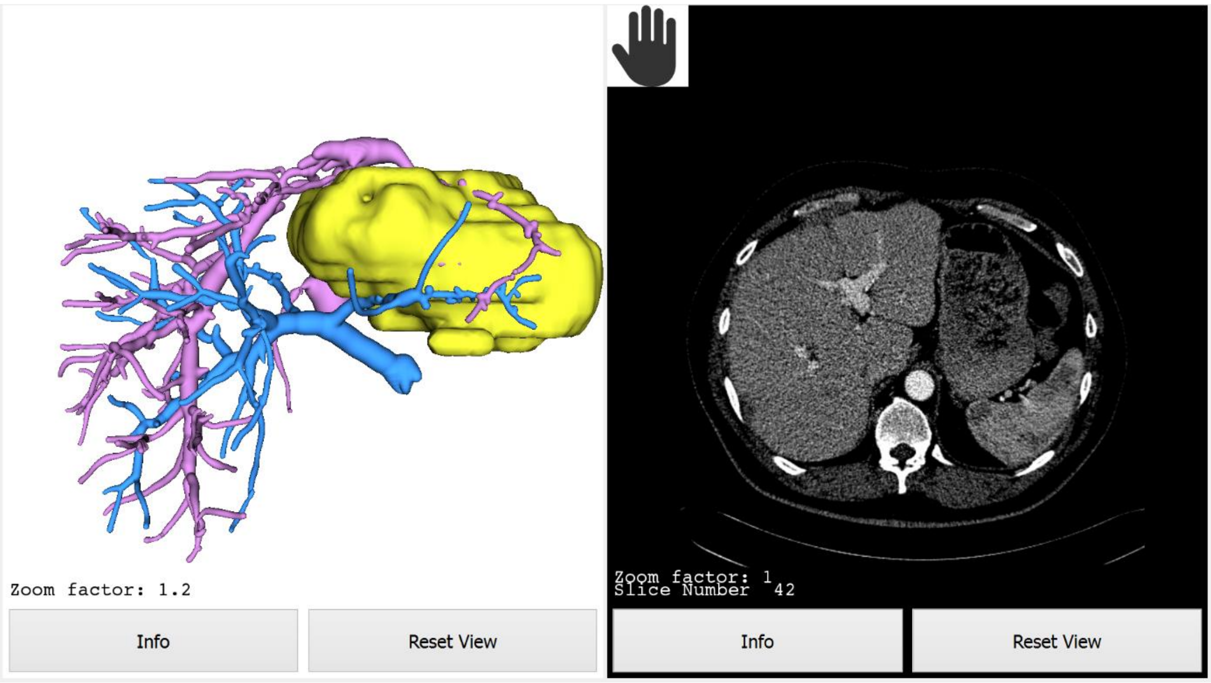

Figure 3: Screenshot of the intervention software that is used in the user study. The left interaction zone shows a 3D model of the liver vasculature (portal vein and hepatic vein), and a primary liver tumor in the left liver lobe. The right interaction zone shows a corresponding CT slice that was selected by a user and an icon that indicates the active interaction zone.

Defining a Set of Natural Gestures

We aim to create a natural user interface based on hand gestures. Therefore, we defined our gestures with the assistance of an expert working in the medical application domain. For this, we presented the desired basic functions of intervention software and discussed several possibilities to realize them with gestures. The expert was asked to perform the gestures accompanied by questions regarding aspects of Nielsen et al. [20], who propose that gestures for human-computer interaction should be, amongst other things, metaphoric. They should be not stressing to the user, logically connected to the software

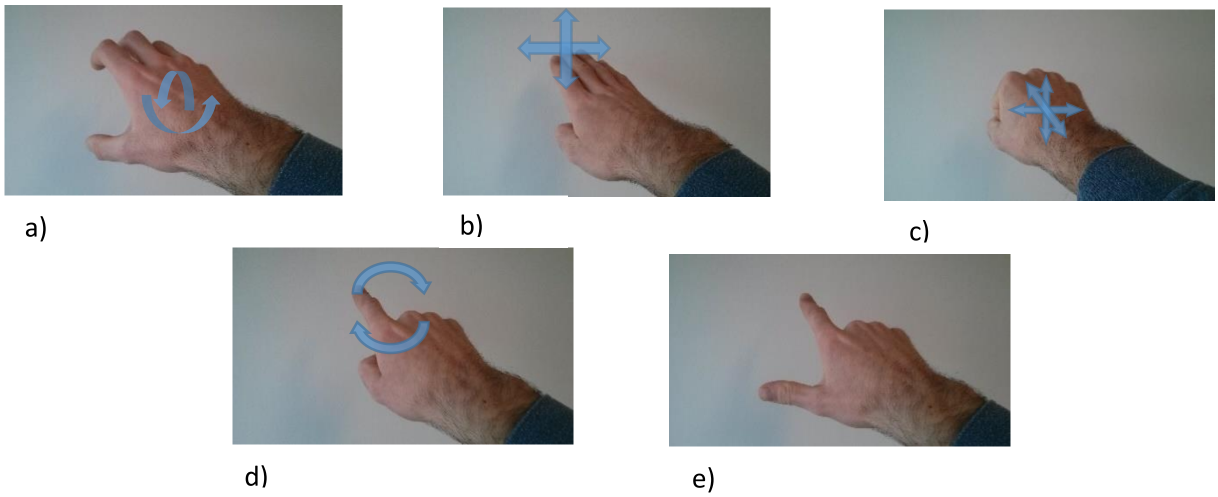

Figure 4: Gesture set: a) continuous 3D rotation - freely rotating hand while grabbing; b) discrete 3D rotation - swiping up, down, left, right; c) zooming and panning - translating fist up, down, left right, forward, backwards; d) slicing - drawing circle with index finger clockwise or counter clockwise; e) point and click.

functions, easy to remember, and self-descriptive. Our gesture set is therefore inspired by the interaction with real objects. This way, it is easy to remember and the level of intuitiveness is high. To rotate a 3D object continuously, the user has to perform a *grab gesture* with half a closed fist, as if he or she was grabbing it in reality, and rotate the hand **(Figure 4a)**. A discrete 45° rotation gesture is a *swipe gesture* in up/down or left/right direction **(Figure 4b).** This is inspired by a globe rotation, but in two dimensions. Zooming is done equally in the 3D and 2D view by virtually grabbing the 3D object or the slice, respectively, with a fully closed fist and pulling it out or pushing it towards the screen (*fist gesture*, **Figure 4c)**. Slices can be moved vertically and horizontally with this gesture as well. The user can change the slices by drawing circles with his index finger clockwise or counter clockwise (*circle gesture,* **Figure 4d**). This is analogous to turning/rotating a large control knob. The radiuses of the circles are mapped onto a step size while cycling through the images. For selection tasks, the user has to perform a *pointing gesture* with the index finger extended towards the object, and by hitting the non-extended middle finger with the thumb a single click is executed (**Figure 4e)**.

Evaluation

We conducted a user study to evaluate the applicability of our gesture set for the described functions. The study was divided into two parts, a pilot study and a main study.

Pilot Study
The pilot study was conducted with two medical students and a usability specialist. Participants were asked to execute tasks which correspond to each gesture. During the execution they should comment about the intuitiveness and usability of the gestures using the Think Aloud protocol [21]. Despite mostly positive feedback, the pilot study revealed problems regarding the *grab gesture*. On the one hand, the participants stated that the recognition of the gesture was not reliable, which lead to frustration. On the other hand, they noted that continuous rotation is not absolutely necessary. Hence, the *swipe gesture* for discrete 3D object rotation is introduced in the main study. Both gestures were tested and are compared in the result section. The training time was not extraordinarily long (< 10 min), thus it was not further investigated.

Experimental Design
To determine the intuitiveness of the gesture set, an approach similar to Nielsen et al. [20] was followed. The different functions of the software as well as the available gestures were shown to the participants. Subsequently, each participant was asked to assign the gestures to the functions. The errors of the assignments were counted to get a measurement for the self-descriptiveness.

The applicability of the gestures was evaluated using eight tasks, which were modeled by scenarios from the workflow of CT-based interventions. These scenarios were obtained together with an expert in the medical application domain, and based on observations and results of our previously conducted workflow study [3]. The tasks were stated in a within-subjects manner. To prevent influences through learning effects, tasks were presented in a randomized order. This was also necessary because the tasks varied in difficulty. For example, the participants were asked to set a specific slice in the 2D viewer or to find out the range of slices in which a liver tumor can be found. In addition, the tasks varied in the amount of successive gestures, which had to be performed to solve it. Examples are the continuous rotation of the 3D model to a given orientation (one gesture) or the usage of the *swipe gesture* to rotate the object to a given orientation and, after that, to show additional information by using the *point gesture* to click a button (two gestures). In addition, all experiments were video-recorded to measure the time of each individual gesture and to collect verbal comments.

We created a questionnaire to collect qualitative information about the users' professional experience, especially with gesture interaction or radiological images. In addition, two questionnaires with a five-point Likert scale (--, -, 0, +, ++) were used. The first states gesture-specific questions inspired by [20] regarding usability aspects mentioned in the requirement analysis. For each gesture, the participants had the possibility to leave a comment in the questionnaire.

The second questionnaire is based on the short version of the usability questionnaire ISONORM 9241/10 [22]. This questionnaire contains questions regarding aspects of usability, e.g., *suitability for the task*, *self-descriptiveness* and *error tolerance*. The questionnaire was adjusted to be applicable to our prototype. For example, our software has no features regarding *individualization* and therefore these questions were removed. Finally, the participants who were physicians could state if they could imagine using the gesture-controlled projection display in the operation room.

The experiment was performed as follows: First, the setup of the gesture-controlled projection display was described to the participant. Thereby, the different functions of the 2D and 3D viewer were explained. Second, the gestures were shown on a piece of paper (similar to **Figure 4**) and the assigned control of each gesture was explained. Third, in the unlimited training phase, the subjects practiced the gestures one at a time with advice from the test supervisor until they felt comfortable with the usage of the software. After the training phase, which lasted 10 min maximum, the participants were asked to solve eight interaction tasks such as shown in **Figure 2**. Finally, the questionnaires were handed out to the participants.

Results

So far, software for CT-based interventions is of limited value during the intervention because a wide range of functions could only be controlled indirectly by a radiologic technician in the control room. In this work, we analyzed the workflow of CT-based interventions, developed a prototype for a gesture-controlled projection display, defined an appropriate gesture set for basic functions of medical intervention software, and evaluated our methods in a clinically-oriented user study.

The pilot study showed that the robustness of both 3D rotation gestures was insufficient for untrained users. Hence, we decided to improve the recognition algorithm for the main study. Our subject pool for the main study consisted of 12 participants with an age ranging from 21 to 41 years (Ø 26.4), eight were male and four female, nine participants were right-handed, three left handed. Six participants had a technical background in the field of medical engineering, four were medical students and two were radiologists. One radiologist had two, the other sixteen years of clinical experience. 42% (5 of 12) of the participants stated that they have many years of experience with medical software, 92% (11 of 12) with two-dimensional medical datasets, and 75% (9 of 12) with 3D models.

The gesture assignment tasks to quantify the self-descriptiveness of the gesture set resulted in Ø 2,6 (min 0, max 6) errors. Almost all participants (10) assigned the *point gesture* correctly. Most errors were made with the *swipe gesture*. Here, only one participant assigned the gesture correctly.

The duration of each task was analyzed to get the time for each gesture. **Table 1** provides an overview of mean, shortest, and longest time, and the standard deviation from all participants.

Table 1: An overview of the measured times. The tasks were analyzed to get the times for each gesture. The mean value, min, max, and standard deviation are illustrated.

	circle gesture	*fist gesture*	*grab gesture*	*pointing gesture*	*swipe gesture*
Mean value	32s	37s	92s	6s	72s
Min	4s	2s	5s	1s	14s
Max	160s	146s	245s	52s	145s
Standard deviation	32s	33s	60s	9s	49s

The standard deviation is high, especially with the *grab* and *swipe gesture*. This is presumably because the participants have varying experience with gesture interaction. This argument is supported by the different training times the participants needed.

For an analysis of the answers of both questionnaires, the five-point Likert scales were substituted with numerical values from -2 to 2. The individual questions for each gesture are summarized to obtain a gesture-specific rating. An overview of the ratings of each individual gesture is shown in **Figure 5**.

The different aspects of usability in the second questionnaire are evaluated in a similar way. The questions regarding the same aspect are summarized. The results are shown in **Figure 6**.

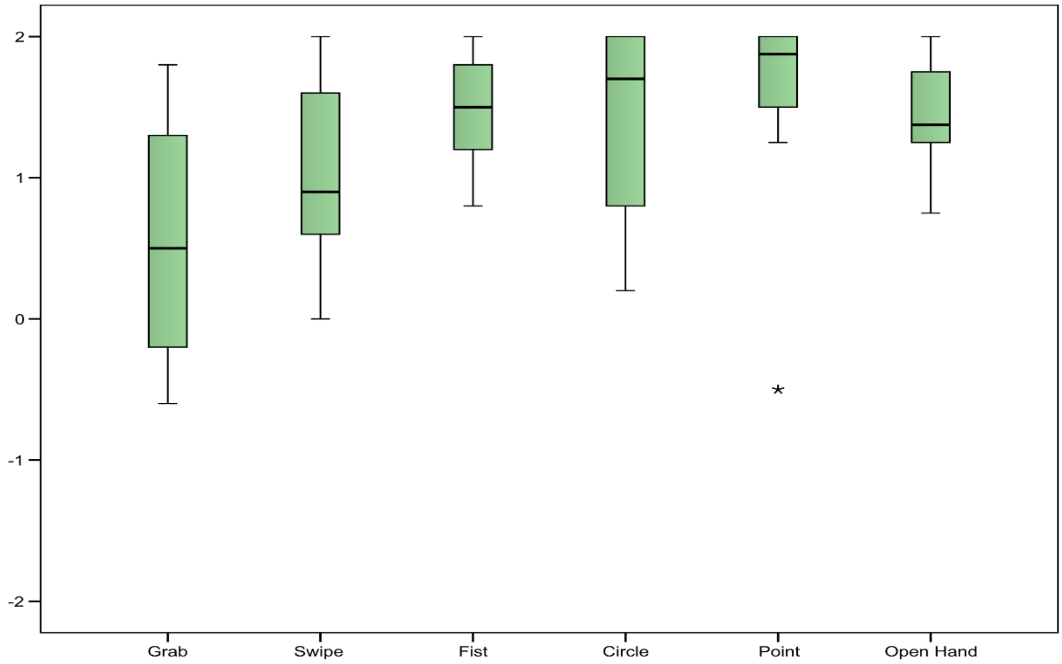

Figure 6: The boxplots give an overview about five-point Likert scale feedback from the participants for each gesture. The Likert values (--, -, 0, +, ++) were replaced with numerical values from -2 to 2.

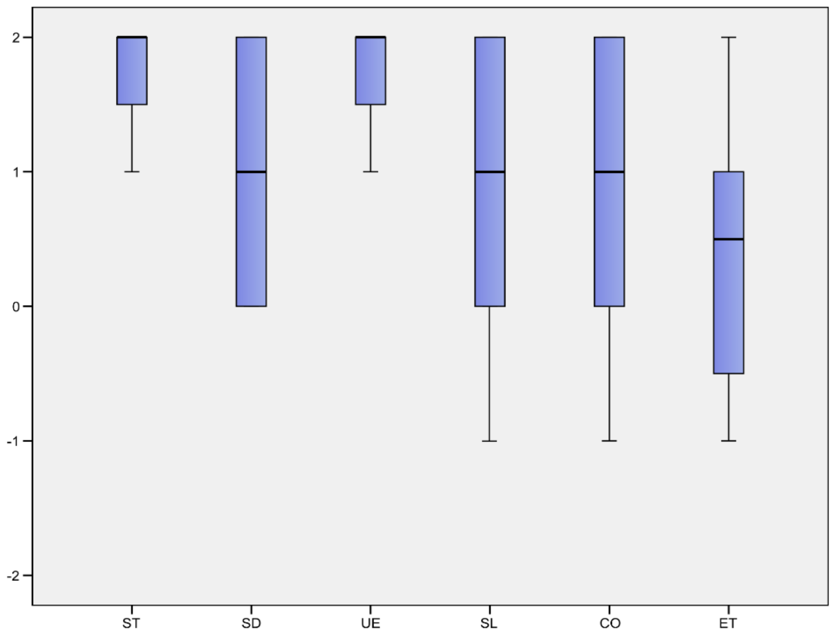

Figure 5: Overview of the results of the usability questionnaire (based on [1]). The boxplots for the usability aspects *suitability for the task* (ST), *self-descriptiveness* (SD), *conformity with user expectations* (UE), *suitability for learning* (SL), *controllability* (CO) and *error tolerance* (ET) are shown. The Likert values (--, -, 0, +, ++) were replaced with numerical values from -2 to 2.

The two physicians stated that they could imagine using the gesture-controlled projection display in the operation room. Other comments to the gestures are summarized in **Table 2**.

Table 2: Pros and cons based on the comments of participants.

grab gesture	+ simple and logical + principle of grabbing is intuitive + continuous rotation in real time - tiring after a while - robustness of the gesture
swipe gesture	+ similar to touchpad, hence, easy to use, easy to learn, not as many degrees of freedom as the grab gesture but better in practice - finger position is too important, fixed rotation degree is problematic, maybe a possibility to adjust it
fist gesture	+ easy to use and predictable, works well with the LMC - start and endpoint not clear, problematic during zooming
point gesture	+ easy, simple and reliable - some participants had problems with the click motion, because the LMC could not identify it
circle gesture	+ easy, precise, robust + the mapping of the circling radius to the slicing steps is very useful + one participant stated that this gesture works best

Discussion

An interesting result of the main study is that the mean times of the grab and the swipe gesture differed by 20 seconds. Additionally, the standard deviation of the grab gesture is higher, which supports the results of our pilot study. The difficulties of the *grab gesture* are also shown in the results of the gesture-specific questionnaire (**Figure 5**). Further, the participants stated that, even if the grab gesture is intuitive and logical, they had problems with the continuous 3D rotation. In the case that the rotation was restricted by their hand joints, they had to release the object, place the hand to a new position, grab again and rotate further. Then, it occurred that the object was not released correctly and a false-positive *grab gesture* was performed, which lead to frustration. The swipe gesture, however, is well known from handheld devices and therefore easy to use and natural for most users. For this reason, we recommend to use the swipe gesture for 3D object rotation if a discrete rotation is sufficient.

Another interesting aspect is that the motor coordination of some participants did not seem to be adequate to perform all gestures correctly. Especially the continuous 3D rotation was problematic, although it was inspired by grabbing and rotating a real object. Because some users could adapt to the restrictions of the *grab gesture* more quickly than others, the training times differed noticeably. Thus, we conclude that the gesture for the continuous 3D rotation must be further improved to be more robust and less tiring. Therefore the requirement “Usability” is partly not met, but will be addressed in the next iteration cycle.

During CT-guided interventions, ergonomic aspects are vitally important. In particular, the interaction between radiologist and intervention software plays a major role for the implementation of complex interventions. The use of the presented gesture-controlled interaction display would be highly advantageous for the improvement of surgical and radiological workflows through a central user interface. In addition, our concept could lead to improved hygiene in the intervention room because radiologists use a touchless interaction tool and thus do not need to touch any additional interaction devices (such as touch-screen or keyboard) whose sterility can only be ensured through extensive cleaning or sterile protective foils.

The technical setup of our projection display is a concept, which will be better integrated in the future. A compact mounting of the projector onto the radiation shield is required to minimize the effort when repositioning. This will further increase the clinical applicability. Anyway, the projection on the shield is always accessible for the radiologist (see requirements).

The results of our work have the potential to optimize the ergonomic conditions for interventional radiologists and possibly increase the safety of interventions. However, the integration into a standardized visualization and interaction concept is an important challenge for the applicability in the intervention room. User interface elements and gestures must be consistent and clear. A standardization for gesture-controlled systems in the OR is of utmost importance; it would require the involvement and cooperation of usability engineers, medical software developers and clinical users from different disciplines.

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