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Gamification and virtual reality for teaching mobile x-ray imaging

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***Abstract*— Mobile x-ray devices like C-arms are routinely used in the operating room to assist in surgical interventions. C-arms need to be adequately operated to avoid unnecessary radiation exposure and intraoperative delays. We present a simulation-based training system to support training of operating room personnel in a virtual environment. To make learning more efficient and enjoyable we integrated aspects of gamification. In a game-like setting, the user has to generate specific radiographs of a virtual patient. Game points are awarded with regard to image accuracy, time needed and overall radiation exposure. To learn basics of C-arm handling and x-ray imaging, non-medical objects can be examined as a first step. A virtual reality interface is provided to allow the user to interact with the C-arm in a more realistic way. User evaluations show that this approach is widely appreciated as providing a user-friendly and sufficiently realistic training tool with a high educational value for intraoperative C-arm imaging.**

Keywords*— *Mobile x-ray device; C-arm; intraoperative imaging; simulation-based training; medical education; gamification; serious game; virtual reality

I. Introduction

In this paper, we present a novel application of gamification and virtual reality technology to medical imaging training. A new concept is implemented and evaluated that contributes to the field of computer-based healthcare professional training, specifically to the training of operating room personnel with regard to intraoperative imaging procedures.

A. Motivation and Goal

For intraoperative imaging, mobile x-ray devices, especially C-arm systems, are routinely used to assist in surgical interventions. The exposure to radiation that is associated with these imaging procedures is undesirable for patients and potentially dangerous for operating room personnel [1]. A recent study showed that surgeons' awareness of radiation risks was unsatisfying, calling for more adequate training [2]. To address this lack of medical education, simulation-based training appears indispensable [3] and is deemed beneficial to the safety of patient and operating room personnel [4]. For education and training in intraoperative x-ray imaging (radiography), a computer-based C-arm simulation is therefore desirable.

The concept of "Serious Games", initially introduced by Clark Abt in 1987 [6] and formed by James Gee as "(Digital) Game-based Learning" [7], is designed to improve the motivation of the learner through game mechanics. In a recent study, Wang et al. show that implementing a serious game for an existing course module creates an effective learning environment and enhances the students' concentration and enjoyment of the given task [8].

Here, a virtual reality (VR) approach is presented that incorporates gamification aspects for the task of intraoperative radiography with C-arms. VR can enhance the overall user experience [9]. It can also provide a more natural interaction without the constraints of a user interface based on mouse and keyboard and without the need of laborious and expensive training systems that use mock-ups or phantoms.

B. Related Work

An evaluation of a commercially available desktop-based x-ray simulation system showed that computer based training (CBT) can improve radiographic skills of novice radiology students. Device-operating performance and radiographic vocabulary were tested with a CBT group and a real x-ray room control group [10].

Aiming at clinicians, Gong et al. created a training environment consisting of an x-ray fluoroscopy machine mock-up, a virtual patient and simulated x-ray imaging. The goal was to reduce radiation exposure through simulation-based training, as trainees were observed causing above-average radiation exposure to patients [11].

The computer-based training system virtX (*virtual x*-ray) simulates C-arm operation and radiograph generation in a desktop mode and a mode linked with a mockup of a C-arm and a patient phantom. Through attached motion sensors both the device and the patient phantom are tracked. The virtX system includes a feature to simulate and visualize radiation exposure of patient and operating room personnel as well as the radiation propagation in the operating room [5].

II. Methods and Materials

Based on the basic features of the virtX system [5] and with the help of the game engine Unity [12], a software has been developed that presents the user with a 3D scene that represents a virtual operating room. With a virtual C-arm, simulated radiographic images can be produced. In the game mode, the user has to reproduce given radiographic images under the constraints of minimizing handling time and patient dosage. These tasks need to be fulfilled either with simple, non-medical objects (to focus on the basic imaging technique) or in a medical context with real patient data. To allow for a more natural and immersive interaction with the C-arm, a virtual reality interface was implemented.

A. *Basic functionality*

The 3D scene shows the inside of an operating room consisting of an operating table, a C-arm, a virtual patient and an x-ray display (Fig.1). The radiographic images are simulated based on computed tomography (CT) data sets that are commonly produced in clinical practice. For this simulation, an extension for the game engine Unity has been developed that utilizes average intensity projection volume rendering [13]. For importing CT data sets, the software toolkit DCMTK [14] has been used.

The virtual C-arm can be oriented along its different degrees of freedom. Virtual radiographs can be taken either in single shot, pulsed or fluoroscopic mode and are modifiable through collimator adjustments, mirroring and rotating. The C-arm can be moved in the operating room and over a virtual patient lying on an operating table. The patient model is linked to an animation rig with movable body joints. The overall position and orientation of the patient and the body joints can be controlled through the user interface. The operating table can be moved and its height can be adjusted. These options reflect the most important parameters with regard to the non-trivial C-arm positioning during radiograph generation.

The tasks are presented to the user through textual instructions, sketches and the target radiographs that need to be replicated (Fig. 2). The task solving performance of the trainee is evaluated with regard to three aspects: correctness of the radiographic image (image section, orientation), time needed to achieve the image and the accumulated patient dosage (Fig. 3). An additional authoring mode allows for modification and creation of tasks by an expert.

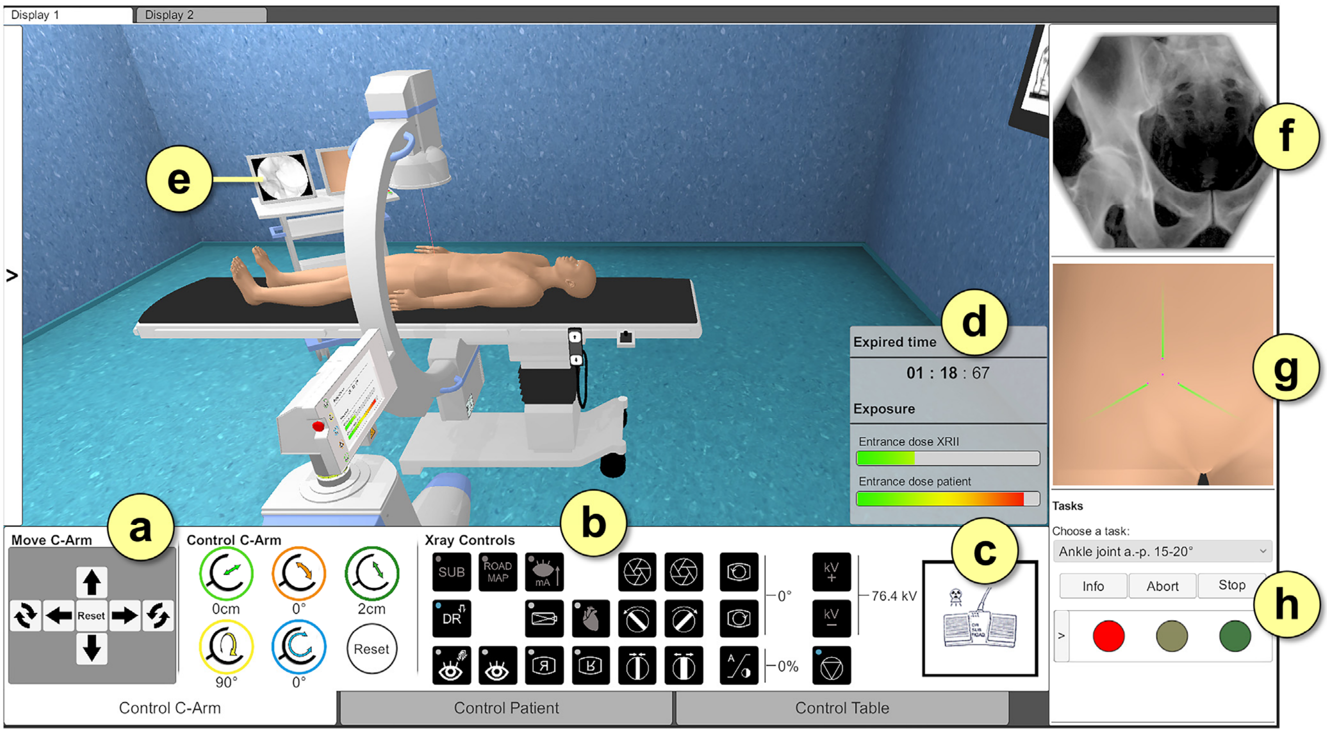

Fig. 1. Desktop user interface. a. Movement and rotation of the C-arm. b. X-ray controls. c. Pedal button. d. Task time and dosage feedback. e. Virtual radiograph in the scene. f. Virtual radiograph in the desktop user interface. g. View from image intensifier to patient including laser cross-hairs. h. Task selection panel with radiograph evaluation indicating C-arm positioning: failure (red), an acceptable image (yellow) or a very good image (green).

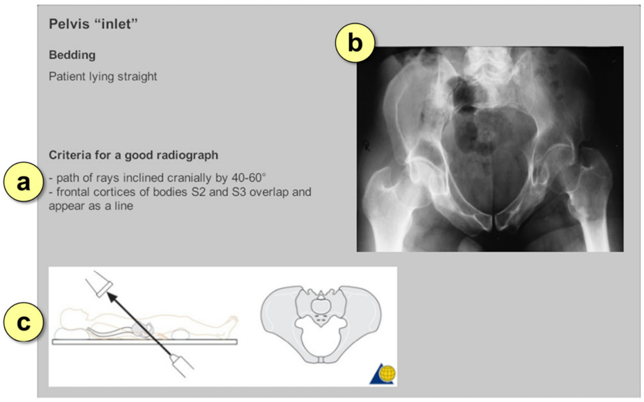

Fig. 2. Task description display. a. Patient bedding instructions and criteria for a good radiograph. b. Target radiograph to be reproduced by the user. c. Sketches illustrate required C-arm positioning.

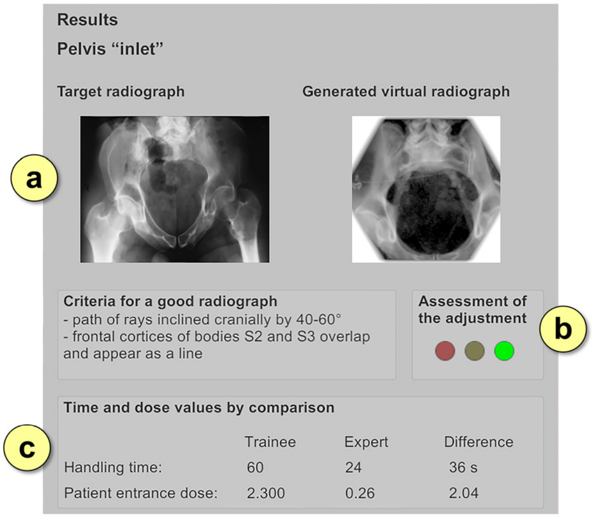

Fig. 3. The task evaluation dialog shows the user generated radiograph side-by-side with the target radiograph (a), task criteria and color scale assessment (b) and performance difference to an expert in handling time and radiation exposure (c).

B. Gamification

The main objective of the game is the creation of a good radiograph. The gaming experience consists of a sequence of multiple tasks with an increasing level of difficulty. In a typical game-like fashion, the trainee is rewarded with points based on image accuracy, time needed and overall radiation exposure.

To enhance the gamification aspect with focus on spatial understanding, specific non-medical tasks are available to the user. In these tasks, a treasure chest needs to be examined (Fig. 4). Wood and metal materials are combined in the chest to let the basic structure of the chest appear in the radiograph while not obfuscating the objects inside too much. In an entrance level, a cylindrical pipe is hidden inside the chest and the trainee is requested to make the cylindrical pipe appear like a perfect circle in the radiograph. Fig. 5 shows the task description for this non-medical task.

In a more advanced level, the trainee needs to find and image a collection of coins inside the chest (Fig. 6). The coins appear as very short cylindrical pipes, which makes finding the correct viewing angle more difficult as more different imaging angles produce similar images. For both tasks, Fig 7 shows exemplary radiographs that are not (yet) correctly oriented by the trainee.

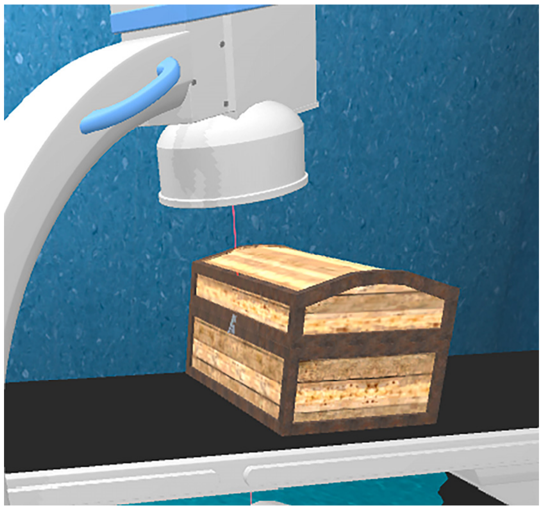

Fig. 4. In the non-medical tasks, objects have to be examined that are hidden inside a treasure chest.

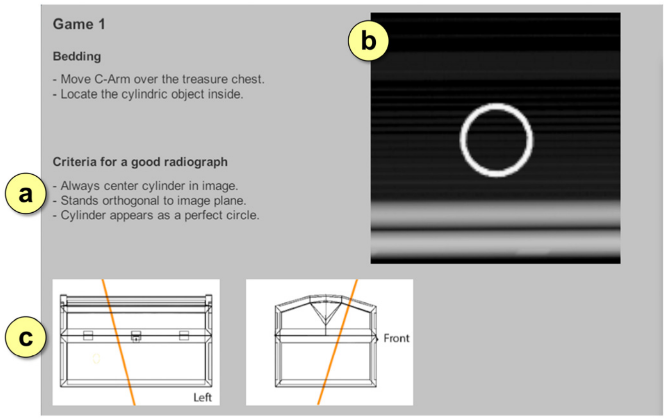

Fig. 5. Description of a non-medical task. Criteria for a good radiograph (a). Target radiograph shows the cylinder as circle (b). Two sketches show beam alignment with regard to the chest hiding the cylinder (c).

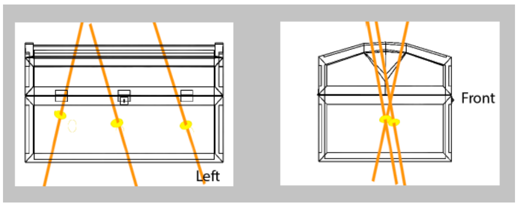

Fig. 6. Sketches for the coin task. Three coins have to be found and imaged.

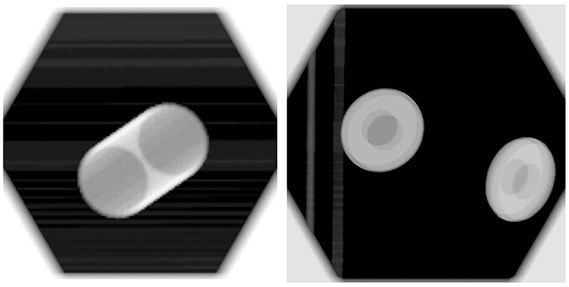

Fig. 7. Virtual radiographs of the non-oriented cylindrical pipe (left) and the non-oriented coin objects (right).

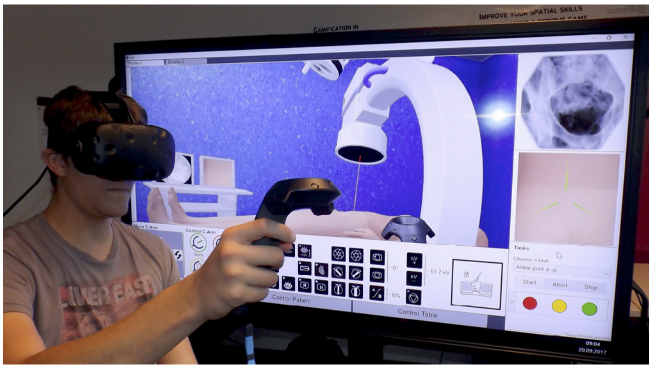

Fig. 8. User wearing the head-mounted display while interacting with the C-arm in virtual reality.

C. Virtual Reality Mode

In the virtual reality mode, the HTC Vive [15] head-mounted display (HMD) is used (Fig. 8). An optical tracking system keeps track of the HMD and hand-held controllers in a user-defined working area. HMD and controllers provide full motion tracking with six degrees of freedom (three for position and three for orientation). Fig. 9 illustrates the general functionality of a controller in our system.

The objects in the 3D scene can be virtually touched with the controllers. The C-arm is operated through interacting with its handles. There are two handles on the back to move the whole device on the floor. Furthermore, four handles are located at the bow of the C-arm to control rotation and position of the image intensifier.

To rotate or move the bow of the C-arm one of five joint axes has to be unlocked before movement is allowed. After unlocking, the user can move the C-arm on the selected axis. Fig. 10 shows an example of such user interaction. To take an x-ray image the user can push a button marked with a radiation symbol on the hand-held controller.

The operating table can be moved on the floor with a virtual joystick. The user has to grab the joystick and pull it in the desired direction. The height of the table can be adjusted with another control that provides one button to elevate and one button to lower the table.

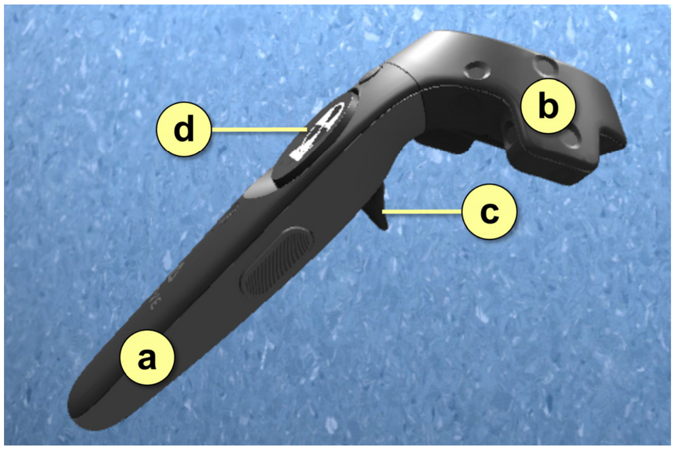

Fig. 9. Position and orientation of the physical hand controller is mapped to a VR representation of the controller. The user holds the controller at its handle (a). The controller head (b) contains optical sensors which locate the controller in physical space. The user's index finger may operate a trigger button (c). The user's thumb generates a radiograph by pressing on the cursor pad (d) that bears a radiation symbol in VR.

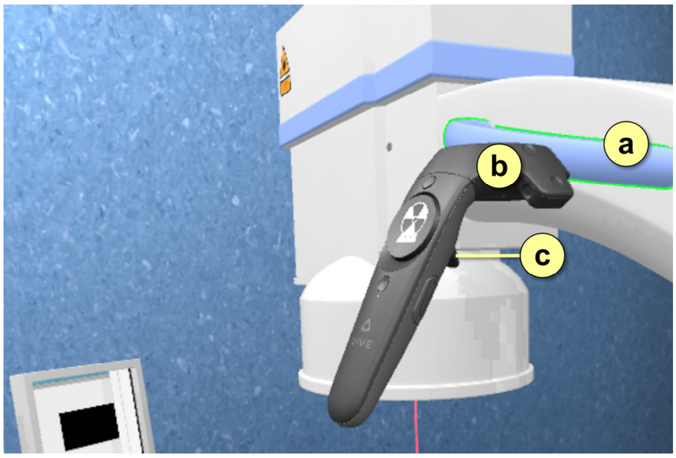

Fig. 10. When coming near an interactable scene element like the upper blue C-arm handle (a) with the controller head (b), the possibility of interaction is indicated through a green outline and a haptic controller vibration. In this example, the user can now move the C-arm bow while pressing the trigger button (c).

Fig. 11. Task selection pedastal shown in VR

To choose particular tasks or to switch to game mode, the user interacts with a pedestal (Fig. 11). There is one switch button to toggle the game mode, two arrow buttons to navigate through the task list and a colored start/continue/stop button with changing color and context-specific text label depending on the current task state. To avoid non-natural head-up display user interface elements, a big screen is embedded into the 3D scene that shows the current task description and evaluation similar to the user interface element that is used in the desktop mode.

III. Evaluation

Both the desktop and the VR mode were tested in an initial evaluation by non-medical users to evaluate the overall usability of the system (A). The VR mode was well received and subsequently tested in a second evaluation with operating room personnel (B).

A. Evaluation of overall usability with laypersons

Nine novice users without medical background tested the system in the desktop and the VR mode in sessions that lasted approximately one hour each. The users received a brief introduction to the utilization of mobile image intensifiers in the operating room. While using the system the users were told 1) to acquaint themselves with the user interface (desktop), or the interaction possibilities (VR) while focusing mainly on C-arm operation, 2) to take a radiograph of the left knee, 3) to take a radiograph of the head, 4) to choose and solve a task of their own choice and 5) to solve a task in game mode.

As feedback form for the whole session the standard User Experience Questionnaire (UEQ) [16] was given to users. With a second feedback form the users were asked how they liked respectively judge the user interface for the desktop and the VR mode on a scale from 1 (best) to 6 (worst). They were also asked if they enjoyed the game mode.

Fig. 12. User test with operating room personnel.

B. Evaluation of utility with healthcare professionals

The VR mode was evaluated as part of a training course for operating room personnel. The course attendees showed up in groups of four persons, which then used the system one after the other. An area of 2 x 3 meters was available as VR interaction space. For the attendees not currently wearing the headset a projection was used to show the current view of the person in VR (Fig. 12). Before each session with four persons, two moderators explained the controller usage with one moderator showing interactions in VR while wearing the headset himself. Each person could use the system for approximately 5 minutes. Each user was told to move the C-arm to a particular body part (e.g. right knee, left ankle, hip or pelvis) and to take a radiograph, potentially adjust it and potentially move on to another body part. The users were subsequently given a feedback form in which they were asked whether the presented VR system is useful for medical education, on a scale from "disagree" (1) to "fully agree" (5). In addition, textual feedback was requested about what they liked most and disliked most, about their years of experience with mobile x-ray devices, and about general comments they had.

IV. Results

A. Initial evaluation (overall usability with laypersons)

The UEQ showed near or above neutral results for efficiency and perspicuity and good results for attractiveness, stimulation and novelty (Fig. 13). The numeric UEQ results are generally in a range from -3 to +3. Results below -0.8 are considered bad, results from -0.8 to +0.8 neutral, results above +0.8 good.

For the user interface of desktop mode and VR mode above-average grades were given (Fig. 14), with the VR interface being considered slightly better in average than the desktop interface (1.9 vs 2.2). The qualitative feedback showed that difficulties with understanding the desktop or the VR user interface did not impair interest in solving tasks or playing the game. Eight out of nine participants answered with yes to the question whether they enjoyed the game part.

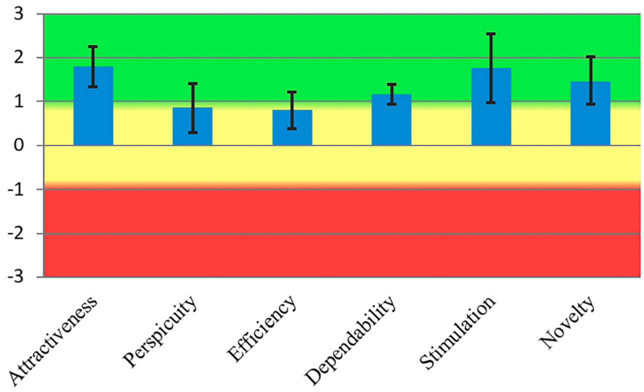

Fig. 13. User experience feedback measured on the six UEQ scales for the whole application with both desktop and VR mode showed above-average results for novelty, attractiveness and stimulation (n=9).

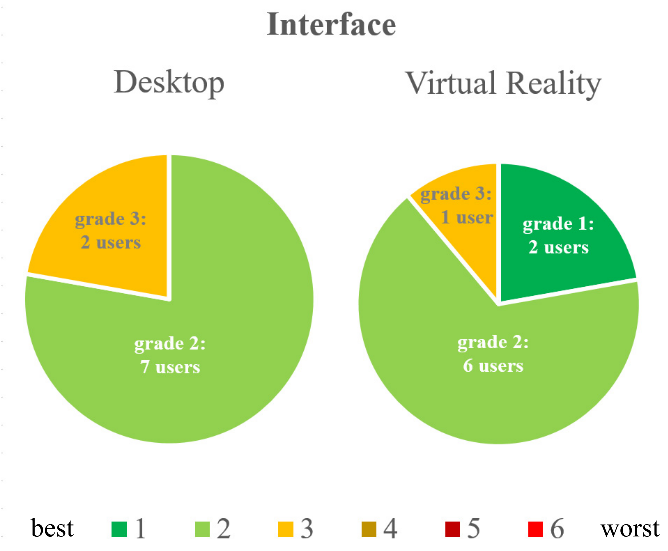

Fig. 14. Non-medical user's rankings for application interface from grade 1 (best) to 6 (worst) showed a trend towards favouring the VR interface (n=9).

B. Second evaluation (utility with healthcare professionals)

All course attendees work as operating room personnel. Of 68 course attendees, 41 gave written feedback after having tested the system. Prior experience with mobile x-ray devices ranged from 0.5 to 35 years with a mean of 8.7 years, and a standard deviation of 8.4 years.

Regarding the utility for medical education, 39 of 41 persons chose the best option ("agree fully"). Among these 39 persons, 27 persons emphasized their choice with positive-only additional comments, and 12 persons provided positive and negative comments (Fig. 15). This was matched by the observation that some participants displayed quite enthusiastic emotions during their session.

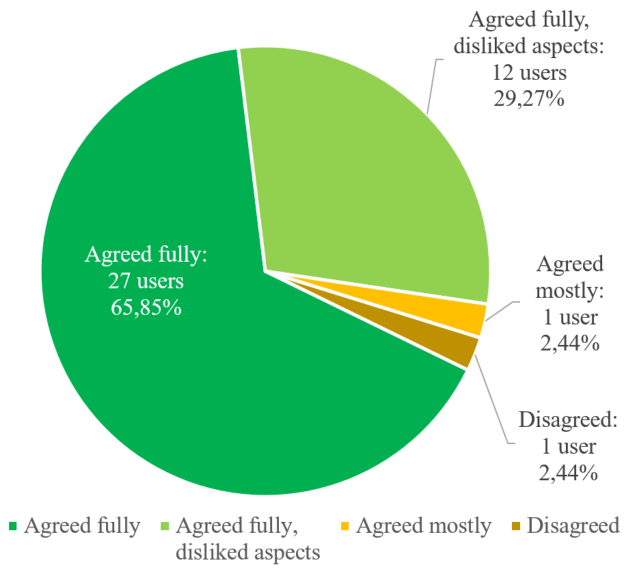

Fig. 15. Evaluation of the VR system by operating room personnel (n=41): Answers to the question "Do you the think the system is useful for medical education?", ranging from "disagree" (1) to "agree fully" (5).

TABLE I. MOST LIKED ASPECTS OF THE VR MODE

Aspect	Indications
Practice and learning	21
Radiation-freeness	15
Realism	15
Novelty	5
Spatial thinking	4
Less time constraints	2
X-ray image	2

TABLE II. MOST DISLIKED ASPECTS OF THE VR MODE

Aspect	Indications
C-arm handling problems	3
Quality of radiograph	3
C-arm handling realism	1
C-arm angle scales	1
First impression	1
Usability for persons of small stature	1

In positive written feedback a high level of "realism" was cited, aspects like "practice", "three-dimensional thinking" or the lack of radiation were mentioned. A summary is shown in Table 1. Negative textual feedback focused mainly on implementation aspects like better x-ray image quality and further improvement of the virtual handling of the C-arm (see Table 2).

V. Conclusion

An approach has been presented to incorporate new aspects of gamification and virtual reality into simulation-based training of intraoperative imaging. An evaluation with operating room personnel showed that users were motivated and stimulated by the introduction of game features and by the utilization of virtual reality technologies. Results from the initial evaluation with an UEQ questionnaire support this observation. It is particularly noteworthy that the virtual reality mode was considered to provide a realistic simulation by many users with substantial experience in an operating room.

The non-medical tasks can be useful to learn about basic operations of the C-arm and the characteristics of x-ray imaging without requiring any medical knowledge. In particular, the cylindrical pipe radiograph to be produced by the trainee allowed for the more direct visibility of C-arm interaction effects upon a simple, well-known geometric object.

VI. Acknowledgment

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