A virtual reality game to support visuospatial understanding of medical X-ray imaging

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***Abstract*—Visuospatial aspects of medical X-ray imaging can be difficult to understand. *xRayWorld* is a serious game built as a virtual reality application that is designed to introduce players to the X-ray imaging process. *xRayWorld* is equally suitable for beginners and advanced players thanks to different levels of difficulty and different game modes. In various minigames, users have to solve tasks by X-raying sealed boxes that contain non-anatomical objects. In addition, a virtual *practice lab* is included which allows users to freely experiment with X-ray imaging without a given task. The usability and game design of *xRayWorld* were rated positively by test users. The application can be considered a safe and cost-effective solution to teach relevant basics of X-ray imaging.**

Keywords—medical imaging, educational game, serious game, virtual reality, safe learning environment, X-ray imaging

I. Introduction

A. Motivation

X-ray imaging is widely used in healthcare as a diagnostic and intraoperative tool. The appropriate acquisition and interpretation of X-ray images require visuospatial understanding with regard to the underlying projectional imaging technique [1–3]. To train this visuospatial understanding in a flexible and safe environment, the virtual reality (VR) game *xRayWorld* has been developed as part of an academic research project. The goal of *xRayWorld* is to teach the basics of the X-ray imaging process by focusing on the understanding of how objects in a three-dimensional space are displayed on a two-dimensional X-ray image. Beginners are guided through an illustrative *story mode*. For advanced players, the application offers a *challenge mode* as well as a *practice lab* where experiments can be freely conducted.

B. Related Work

The idea of using VR for teaching medical X-ray imaging has been adopted in several contexts. For instance, [4] and [5] describe a VR application that teaches intraoperative C-arm imaging. [6] describes the evaluation of a commercially available VR simulator [7] used for several X-ray imaging procedures. [8] is another example of a commercial system that uses VR to teach X-ray imaging. These approaches focus on the realistic simulation of clinical situations. In contrast, *xRayWorld* focuses on basic visuospatial understanding, particularly for beginners, abstracting from specific X-ray devices and their detailed operation, and eliminating the need of anatomical knowledge. Thus, the use of *xRayWorld* could be the first step to teaching X-ray imaging. In addition, the aspect of gamification is central to *xRayWorld*, since learning with games has shown to be a motivating and effective method [9]. The major goal of this work is for trainees to have fun while learning about the X-ray imaging technique.

C. VR as a medium

The *xRayWorld* application was developed as a VR application for the HTC Vive system (https://www.vive.com/) but may also be used with other VR systems via Steam VR (https://www.steamvr.com/). In virtual reality, players can get to know and try out X-ray technology as an imaging procedure without any radiation risk. In addition, a VR application is potentially accessible to a wider audience, in contrast to medical X-ray equipment that is usually only accessible to medical institutions.

xRayWorld has been developed in an iterative way with regular user tests. The virtual setting and the interaction concepts have been specifically designed for VR. For example, it was ensured that players would have to change position as little as possible during playing and could enjoy the room-filling VR experience.

II. Methods and Material

A. Basic idea

The basic idea of the application is to give players an understanding of the visuospatial aspects of X-ray imaging with the help of several minigames. In each minigame, the players are presented with boxes containing geometric shapes that they can X-ray. Depending on the selected mode, the players are given a task, such as identifying a certain content, which they can only solve by X-raying the given boxes. In total, 18 minigames are available, that can be divided into three categories: *object games*, *template games* and *calculation games*.

B. Learning objectives

In all three minigame categories, the player can learn about the representation of three-dimensional objects in an X-ray image. The category *object games* is particularly designed to teach recognition of various objects in an X-ray image, considering variations in the objects' density, size, and shape.

Minigames of the category *template games* are supposed to generally improve three-dimensional thinking and to explain the relevance of the distance between an object and the X-ray image sensor for the representation of the object in the created projection image. In particular, the player is supposed to accurately recreate various templates in the form of given X-ray images. In the category *calculation games*, object recognition is supposed to be practiced through an additional game element (calculation task) in a presumably less conscious way. Here, for example, different object shapes represent different numeric values and the player needs to calculate the overall value of boxes that contain different objects.

An overview of the tasks can be found in Table 1. An example of a minigame is illustrated with in-game screenshots in Fig. 1. Here, the player is presented with a certain number of sealed boxes and an X-ray image. The task of the player is to identify the box that the given X-ray image was taken from by X-raying the given boxes.

After completing a minigame, the player receives feedback on how many X-ray images were created to solve the given task, how much time was needed, and how many wrong answers were given. In addition, an overall score is calculated from these values and zero to five stars are awarded accordingly (see Fig. 1, C). In each minigame, there is the possibility to receive hints should the player get stuck without help.

Overall, four game modes are available (Fig. 2). In the *story mode*, all available minigames are played in a specific order defined by a story. In the *challenge mode*, a selection of minigames is presented to the player in a random order with a time limit. In the *single game mode*, the player can freely choose a single minigame. In the *practice lab mode*, the player can experiment on his/her own and assemble individual boxes, independent of the minigames.

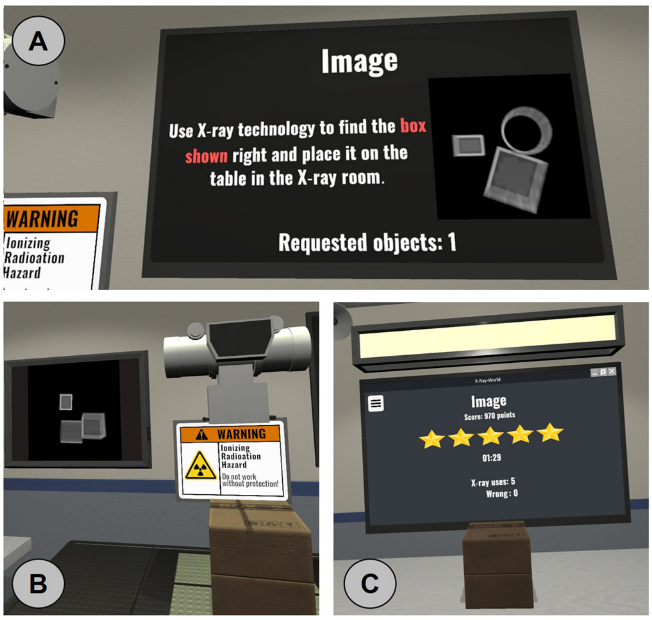


Fig. 1. Example minigame "Image" from the category *template games* (in-game screenshots) A. Instructions. B. Examination table with created X-ray image. C. Summary screen at the end of the minigame.

TABLE I: MINIGAME CATEGORIES WITH THEIR CORRESPONDING LEARNING GOALS

	Types of tasks	***Specific learning goals***
Object games	▪ Identify objects in an X-ray image. ▪ Find identical constellations of objects ▪ Count objects in an X-ray image ▪ Search for densest object	*Object recognition on X-ray image* *Different representation of density in X-ray images*
Template games	▪ Find a box based on given X-ray image. ▪ Reconstruct given X-ray images	*Improve three-dimensional thinking* *Relevance of the distance to X-ray image sensor for the representation of objects in an X-ray image*
Calculation games	▪ Evaluate values of primitive objects (e.g., balls: 5 points, cylinders: 3 points, rectangle: 1 point). ▪ Find boxes with the same overall value	*Object recognition (with additional calculation task)*
Overall learning goal ▪ Representation of a three-dimensional object in an X-ray image		

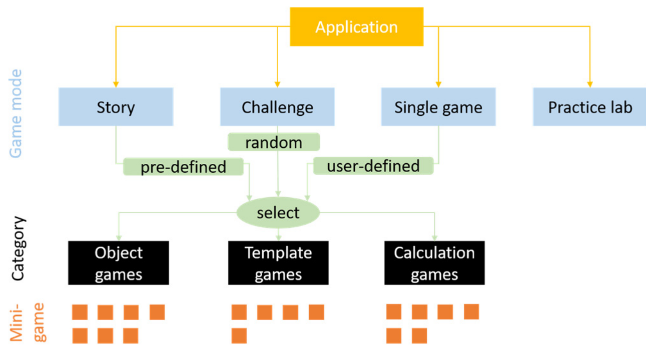


Fig. 2. Overall game structure of xRayWorld.

The player can set up a high score in every single minigame. This refers only to the minigame regardless of which game mode it was started in.

C. *Levels of difficulty*

The game modes *story*, *challenge* and *single game* can be played in five levels of difficulty ("very easy", "easy", "normal", "hard" and "expert"). The differences in difficulty arise from a variable number of boxes (three to five) as possible answers, the number of objects within such a box (one to six), as well as the representation of the objects in the virtual X-ray image, either in grayscale or in color (see Fig. 3). Grayscale X-ray images represent real X-ray images. Colored X-ray images preserve the colors of the projected objects and are supposed to be a beginner's aid, allowing players who are completely inexperienced with X-ray imaging to better distinguish different objects (see Fig. 4).

Fig. 3. Different factors for difficulty variation.

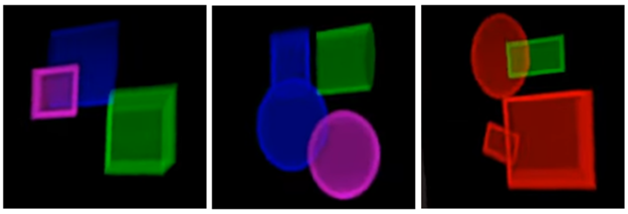


Fig. 4. Examples of colored X-ray images (from in-game screenshots).

The number of boxes grows as the difficulty increases (see Fig. 5), with the exception of two minigames from the *template games* category.

No general rule exist for the number of objects in the boxes, as this varies depending on the minigame. However, the higher the difficulty level, the more objects are usually used.

Colored X-ray images are used in most minigames for the difficulty level “very easy”. In three minigames, this feature is used for all difficulty levels. In two minigames, it is not used at all (see Fig. 6).

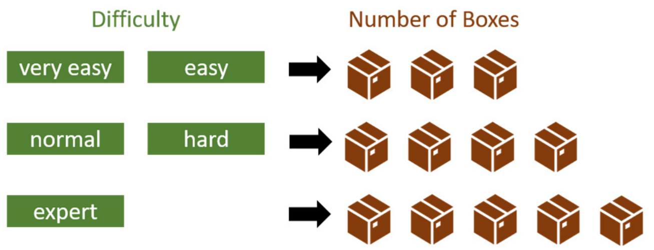


Fig. 5. Number of boxes in the different levels of difficulty (general concept).

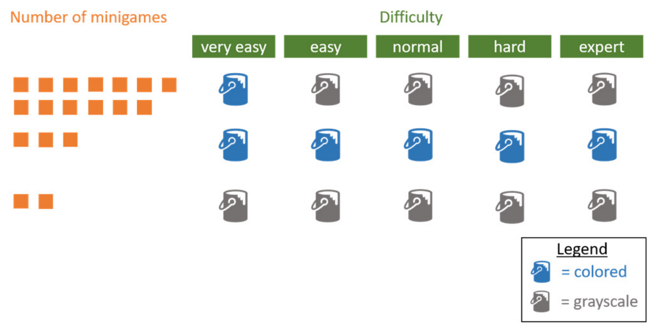


Fig. 6. Utilization of colored X-ray images in the minigames.

D. Game details

1) VR scene setup

The *challenge mode* and the *single game mode* take place in the so-called *Minigame room*. The *practice lab* takes place in a separate room, as this requires a different game setup. Each player starts in the waiting room, where game mode, level of difficulty and if applicable, a specific minigame can be chosen. Depending on these selections, one of the two doors opens, which lead to the adjacent rooms in which the following game action then takes place (see Fig. 7).

Fig. 7. Floor plan of the complete VR scene.

During all game modes, the player is supported by acoustic signals. For example, different sounds can be heard when different buttons are pressed. Furthermore, a signal sound is heard during X-ray imaging to inform the player that, in reality, dangerous radiation would be created. This is supported by warning signs (see Fig. 1, B) and the request to wear a protective suit.

2) Story mode:

In the *story mode*, the player is taught the basics of X-ray technology sequentially and with increasing difficulty. As a new employee, the player is accompanied by Professor X. Ray, who introduces him/her in a tutorial to X-ray imaging and to the game process. Subsequently, the player receives e-mails in which the background of the task is described. These are also read aloud by a background voice. After completing the *story mode*, the player is shown the total score of the game run.

3) Challenge mode:

In the *challenge mode* (see Fig. 8), a certain number of minigames has to be completed in random order in a certain amount of time to win the challenge. There are two variants: The non-infinite challenge, in which ten minigames must be solved in a maximum of ten minutes, and the infinite challenge, in which as many minigames as the player can manage can be solved in 15 minutes. In both challenge variants, an individual high score can be set up.

Fig. 8. Playing a minigame in the *challenge mode* (in-game screenshot).

4) Single game mode:

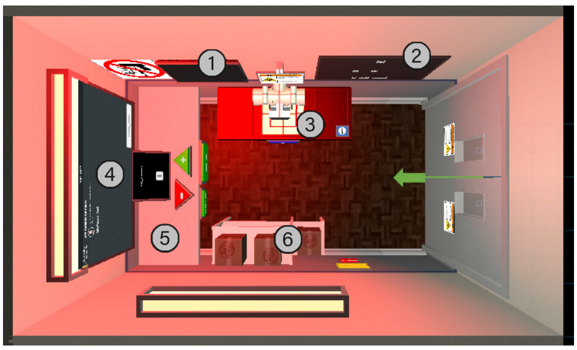
Another possibility is to start the minigames individually to specifically train certain learning aspects (see Fig. 9). Thus, the minigames can be played regardless of their chronological order in the story.

Fig. 9. Game selection menu in the waiting room (in-game screenshot).

5) *Minigame gameplay:*

Each minigame has a similar sequence (see Fig. 11). When a minigame is started, the corresponding task and the required objects/boxes are presented on the task monitor. This monitor is in the immediate vicinity of the X-ray table so that the task description can be read again during the game. The boxes that have to be examined to solve the task are placed on a shelf opposite of the X-ray table. The player can grab a box and create an X-ray image from it by touching a button on the X-ray table with the VR controller. The resulting image is displayed to the left of the X-ray table and remains there until a new image is created. An overview of the minigame room is shown in Fig. 10.

To fulfill the given task, the player has to place the required boxes on a special table (*answer table*) and touch a button labeled "Release". If the answer is incorrect, an acoustic and visual signal is emitted, and the number of wrong answers is increased by one. If the answer is correct, then the success is displayed in the form of a five-star-rating as well as an evaluation of the game on the game data monitor (see also Fig. 1, C).



① *X-ray screen* ② *Task Monitor*
③ *X-ray table incl. X-ray unit* ④ *Game data monitor*
⑤ *Answer table* ⑥ *Shelf with boxes*

Fig. 10. Bird's eye view of the *Minigame room*.

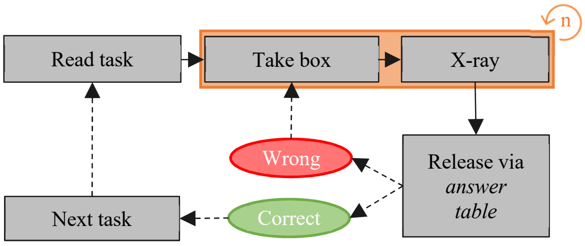


Fig. 11: Schematic flow of a typical game sequence.

6) *Practice lab:*

In the *practice lab*, players can assemble their own boxes and customize the position, size and density of the objects (see Fig. 12).

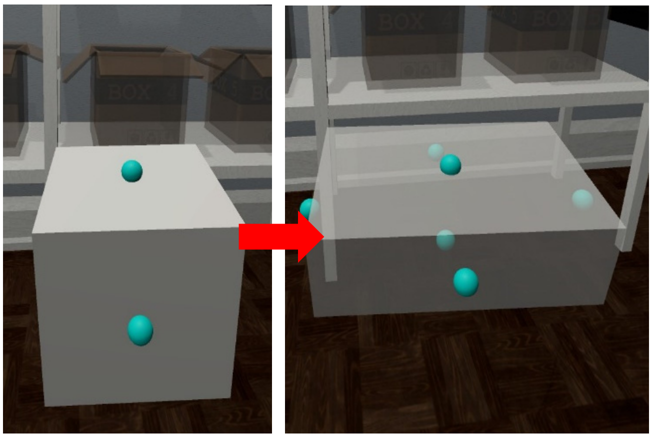


Fig. 12. Change of an object in size, shape and density (in-game screenshots).

These objects can be grouped together in boxes for subsequent X-ray imaging. These boxes can be viewed either with single X-ray images or in a fluoroscopy-like continuous X-ray mode to better recognize and understand the effect of changing position or orientation of a box or the objects therein in real-time. Fig. 13 shows in a composed image the view inside the VR environment together with an image of a player in the real world. The room interior of the *practice lab* has been adapted so that the players can directly access objects and empty boxes from their position. An overview of the *practice lab* can be seen in Fig. 14.

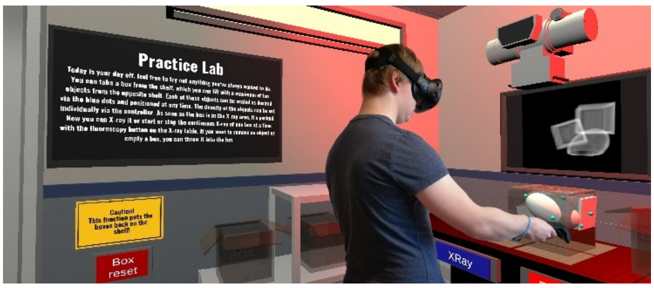


Fig. 13. Player in the *practice lab* (image composition with in-game screenshot).

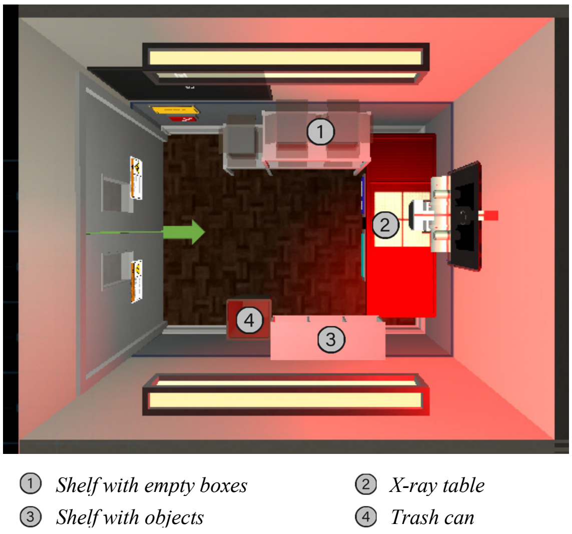


Fig. 14. Bird's eye view of the *practice lab*.

E. *Evaluation*

Twelve individuals (age 12 to 58, 6 female, 6 male) tested the developed application. Each participant was given the same tasks. First, the participants were asked to familiarize themselves with the functions of the menu. Afterwards, they were to master the *story mode* in the difficulty level "normal" to ensure they have played each minigame at least once. To evaluate the *challenge mode* as well, evaluation participants were asked to play the non-infinite challenge in the difficulty level "normal", where participants had to complete ten games in ten minutes. As the last task, participants were asked to play in the *practice lab* for at least 7:30 minutes, filling two boxes and experimenting with them.

After performing the practical tasks, participants were asked to complete an online questionnaire. The first part consisted of the User Experience Questionnaire (UEQ) as described in [10–12]. The UEQ test consists of 26 different aspects that participants are asked to rate. The second part of the questionnaire contained additional questions regarding specific aspects of the application. These were either to be answered with a scale from zero (particularly poor) to six (particularly good) or with free text. Subsequently, a semi-structured interview of about 10 to 15 minutes was conducted with each individual respondent.

III. Results

A. *UEQ*

The results of the UEQ are shown in Fig. 15. *xRayWorld* was rated particularly good regarding attractiveness and novelty. The other categories (perspicuity, efficiency, dependability, and stimulation) were rated above average as compared to other usability studies.

B. *Online questionnaire*

The results of the online survey with free text answers suggest that only half of the participants have found the high score stimulating. The button assignment of the controllers was rated as easy to use and self-explanatory, also thanks to the visual hints on the virtual controllers in the VR scene. The tasks and instructions were rated as comprehensible, with the highlighted words in the task descriptions being particularly helpful. The *practice lab* was regarded also as comprehensible, as promoting creativity and as entertaining. The game menu was rated as exceptionally clear and understandable. The results of the scale questions are shown in Fig. 16.

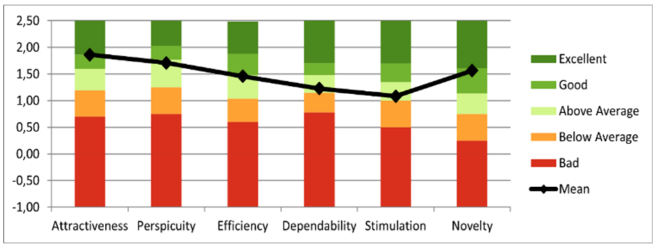


Fig. 15. Results of the UEQ for *xRayWorld* as compared to other usability studies (452 studies with of a total of 20190 participants; see [10]).

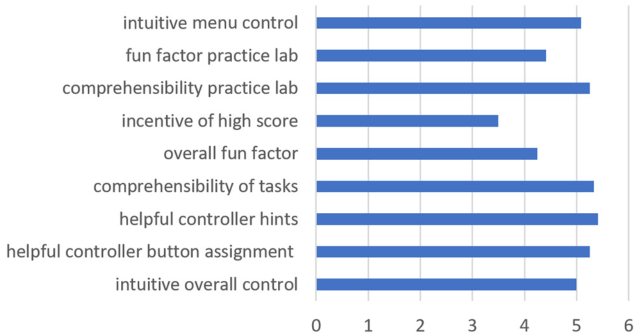


Fig. 16. Average score of application-specific scale questions (0: particularly poor score, 6: particularly good).

C. *Interviews*

During the interviews, participants were asked in more detail about their experiences with *xRayWorld*. For the first task, reading the menu functions, it was discovered that the description of the infinite *challenge mode* was not clear enough. It was confirmed that the controls were considered intuitive and simple, but that it was more difficult to grab objects in boxes in the *practice lab*. In addition, it was frequently mentioned that the density setting of the objects was not found in the *practice lab* and therefore this function was hidden from most of the participants. Also, hints in other areas of the game were frequently missed. The *story mode* was described as exciting, funny, and rich in variety. The individual minigames were also praised. Likewise, the *challenge mode* was rated as entertaining and challenging at the same time, with most of the participants managing to successfully complete this mode with the difficulty level "normal". It was also mentioned that the *challenge mode* was a new possibility to further develop what was learned in the *story mode* and to put it to the test with the aspect of time running out. The possibility of being able to arbitrary select individual minigames was found to be useful, as was the division of the minigames into categories. Participants who were inexperienced with X-ray as an imaging process learned about perspective projection as a basic principle of X-ray imaging through the *story mode* and noticed the importance of positioning objects in a three-dimensional space in a certain way to achieve a certain result in the projectional X-ray image. In the *practice lab*, the participants without any prior knowledge were able to reinforce what they had learned or to clarify previous ambiguities from the *story mode*. In general, the *practice lab* was perceived as a useful counterpart to the other minigame-based modes that provide specific tasks.

The presentation within the virtual reality environment, i.e., the rooms, the interior and the acoustic elements were generally rated positively. The decoration, such as warning signs, was described as authentic. *xRayWorld* was generally rated as valuable, with the implementation as a VR game being highlighted as positive for the gaming and learning experience. However, one participant raised the question of whether it was useful to train X-ray with color images, since these do not exist in reality.

IV. Discussion and Conclusion

The VR environment seems to have helped the users to engage with a learning application and to improve their spatial understanding. As a result, the use of VR technology as opposed to a desktop approach seems promising with regard to effective learning. However, it would be good to conduct a comparative study with a desktop-based version of *xRayWorld* to better understand the specific role of VR. A major disadvantage of using VR is the need of additional equipment to which many potential users do not have access.

The diversity of the individual minigames and the possibility of selecting different game modes enabled the users to discover aspects of the application that they particularly liked. For example, some participants preferred the *practice lab* with its opportunity to freely experiment, while others preferred the guiding aspect of the minigames, in particular within the *story mode*. Also, different users liked different minigame categories and different individual minigames.

To improve the high score principle, an online high score could be added to *xRayWorld*. This would allow a player to compete against other players, potentially increasing the motivation to continuously use the application. Also, the problem with grabbing the objects in the *practice lab* should be investigated, in particular because the general handling of the controllers was rated positively. This investigation might also reveal if this problem caused the relatively low UEQ score for "dependability" as this aspect was rated very well in the interviews with regard to all other aspects of the application. In the UEQ, stimulation was also rated relatively low, potentially because of its lack of continuity. With regard to its educational value, the feature of presenting colored X-ray images should be evaluated in more detail.

Overall, *xRayWorld* scored well with the evaluation participants, especially in terms of experienced fun and novelty. The implementation as a VR-based application gave the players the opportunity to train X-ray imaging in a realistic, but safe environment and to have fun at the same time. Although actual learning effects have not been investigated, the responses of the evaluation participants indicate that they were able to gain new knowledge from using the application.

In conclusion, *xRayWorld* can be considered an entertaining and educational VR-based game for teaching basic visuospatial aspects of medical X-ray imaging.

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