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Applying educational design research to develop a low-cost, mobile immersive virtual reality serious game teaching safety in secondary vocational education

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Abstract

Students in secondary vocational education often have to learn and practice their skills in potentially dangerous situations, operating complex machinery or working in hazardous conditions. As a consequence, they need to be trained on how to work safely, to respect safety regulations, to wear protective gear and related equipment, to consider ergonomics, and to follow emergency procedures. However, this is difficult in current teaching on hazard perception due to a lack of authentic and real-life learning conditions, and due to learning materials often not being adapted to secondary vocational students. To address these challenges, we adopted an Educational Design Approach in which we designed, developed, and tested a low-cost, mobile immersive virtual reality serious game, teaching hazard perception to secondary vocational students. We engaged 8 teachers and 50 students from 5 secondary vocational schools to co-design and test the prototype serious game. Final test results demonstrate both students and teachers valued the learning experience positively, in terms of spatial presence, involvement, design, interest/enjoyment and value/usefulness. During several iterations, we were also able to identify critical design elements, which were valued positively in terms of both enjoyment and perceived usefulness. The design elements are discussed in a detailed way to support both researchers and practitioners in their future design of immersive virtual reality learning experiences. Finally, directions for future research are presented.

Keywords Design principles · Hazard perception · Safety education · Vocational education · Serious game · Immersive virtual reality

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1 Introduction

Immersive technologies such as augmented reality (AR) and virtual reality (VR) have gained increased attention over the last years due to the improved usability and lower cost (Bower et al., 2020). Immersive virtual reality (iVR) is now being used in several domains such as entertainment, sports, medicine, architecture, healthcare, and increasingly in education too (di Natale et al., 2020; Hamilton et al., 2021).

1.1 Immersive virtual reality

Virtual reality is considered an 'immersive technology' as it immerses the user in another, virtual, reality. Following Slater and Wilbur (1997), immersion points to technological features, such as interactivity, realism, 3D-graphics, audio, and embodiment (Suh & Prophet, 2018). Embodiment is defined as "the user making choices via gesture that affect the actions on the screen" (Johnson-Glenberg et al., 2021, p. 1265). Depending on the level of immersion, users experience a feeling of presence, which can be seen as a psychological state of one feeling present in the virtual world generated by the immersive technology (Slater & Wilbur, 1997). In general, higher levels of immersion make the user feel more present in the virtual world (Buttussi & Chittaro, 2018; Makransky & Lilleholt, 2018). Presence has shown to be one of the main precursors for a satisfactory virtual reality experience (Buttussi & Chittaro, 2018; Han, 2020; Kavanagh et al., 2017).

Virtual reality reflects a long history as a desktop application, in which the virtual world was depicted on a desktop screen (Merchant et al., 2014) and the user was still surrounded by the real environment (Freina & Ott, 2015). In contrast, with a virtual reality head-mounted display (HMD), the user is fully immersed in the virtual world and becomes cut-off from the real world (Jensen & Konradsen, 2018). From then on, desktop reality was set apart from immersive virtual reality using HMDs (Suh & Prophet, 2018). The term immersive virtual reality points to the higher level of immersion a user experiences while wearing a VR headset (Buttussi & Chittaro, 2018; Makransky & Lilleholt, 2018).

1.2 Immersive virtual reality in education

Big tech companies such as Meta, HTC, and Pico have invested a lot in improving their iVR headsets, meanwhile lowering related procurement costs (Rees, 2022). This did not go unnoticed by the educational field as teachers noticed the benefits of this technology (Fransson et al., 2020; Southgate et al., 2019).

Immersive virtual reality offers opportunities for new types of learning experiences. These benefits, called affordances (Bower, 2008; Dalgarno & Lee, 2010; Shin, 2017), have been described in several review studies (di Natale et al., 2020; Jensen & Konradsen, 2018; Kavanagh et al., 2017; Maas & Hughes, 2020; Pellas et al., 2020). Some examples: students can participate in authentic and lifelike simulations which are otherwise dangerous, too expensive, or even impossible, such as going back into history or training fire safety procedures. Students can also train procedural skills without the risk of injuring others or causing damage to expensive machinery or installations. When training these skills via an iVR application, students can train at a small cost as there is no shortage of resources needed. iVR also allows for students to work from remote locations, offering opportunities for distance learning.

The effectiveness of immersive virtual reality in terms of learning gains is supported by several meta-analyses. Wu et al. (2020) found iVR to be superior to more traditional, non-immersive teaching practices and even to real-world training, although related effect sizes were small (g = 0.24). This was reinstated by the meta-analysis of Coban et al. (2022) in which iVR generated higher learning gains than other teaching methods, but again only reflecting small effect sizes (g = 0.38). Kaplan et al. (2021) found no significantly higher learning outcomes of iVR over other instructional methods, however pointed out that "[even] if the performance outcome is essentially the same, the other benefits of XR training make it a superior option." (Kaplan et al., 2021, p. 714) referring to the learning affordances discussed above. Apart from these cognitive benefits, immersive virtual reality learning experiences might also exert a positive effect on students' motivation and interest (Chavez & Bayona, 2018; di Natale et al., 2020; Kavanagh et al., 2017; Maas & Hughes, 2020; Makransky & Petersen, 2021).

Although immersive virtual reality has proven to be effective for (industry) training (e.g. Radhakrishnan et al., 2021; Renganayagalu et al., 2021) it is still unclear which design elements contribute to the effectiveness of the iVR learning experience. As stated by Jensen and Konradsen (2018; p. 1526) "the interesting question is not if HMDs should be used, but rather how and for what HMDs should be used." Similarly, Johnson-Glenberg et al. (2021) indicated that the design of an iVR learning application is more critical than the platform used, stressing the importance of embodiment. In their review study Radianti et al. (2020) listed several design elements in iVR learning experiences of which basic interactivity, realism, immediate feedback, and assembling were applied most. Still, research shows that the (design) characteristics which have been considered as effective, differ greatly depending on the level of education and the topic of the iVR learning experience (Chavez & Bayona, 2018; Radianti et al., 2020). As Wu et al., (2020, p. 2002) expressed: "more customized HMD learning applications with the sound instructional design are needed to improve its usefulness."

The current study aims to address this research gap, by identifying relevant design principles, and how they are perceived by both students and teachers in terms of interest/enjoyment and value/usefulness.

1.3 Immersive virtual reality in secondary vocational education

Although several studies have investigated how teachers and students in secondary education could benefit from iVR classes (e.g. Bodzin et al., 2021; Fransson et al., 2020; Southgate et al., 2019), Maas and Hughes (2020) and di Natale et al. (2020)

have indicated in their review studies, research involving secondary education students is still underrepresented.

When searching for relevant literature on iVR in secondary vocational education, even less studies could be found. The systematic approach of our literature search is discussed in the Appendices. Babu et al. (2018) used an iVR motorbike assembly application to investigate immediate and delayed recall results, comparing an experimental iVR group with a 2D tablet-based group. They found lower results for immediate recall in the iVR group, but significantly higher results for the experimental group one day later, suggesting iVR as “a bridge between theoretical and practical learning scenarios” (Babu et al., 2018, p. 388). Kim et al. (2020) designed and evaluated an iVR learning experience for designing gardens. Their GardenVR implemented three design elements: multiple perspectives (essential for designing tasks), a constructivist learning approach (the possibility to try, fail and try again) and going beyond physical limits (seasonal changes impact garden design). All three design elements were facilitated through the iVR technology: providing users with different viewing perspectives with a single button click, unlimited training opportunities and the ability to simply undo the unwanted changes and changing daylight at wish, are all elements which are impossible in real life. Gac et al. (2019) found that a virtual tablet to interact with the immersive virtual reality environment was considered a useful instrument to both students and teachers. However, several design issues were expressed. First, the tablet had to be held in one hand, excluding this hand to be used for other interactions, which causes problems in training when both hands are needed, for example a voltage tester. Second, when addressing this first issue, the researchers were faced with another: when fixing the tablet to the arm of the user, the size of the tablet had to be downsized, causing new issues in interaction proficiency. Further research was suggested to tackle these issues. Boel et al. (2022) concluded that iVR can be considered as a useful instrument for teaching hazard perception on a construction site.

Following the scarcity of studies on immersive virtual reality in secondary vocational education, it is of interest to investigate iVR at this educational level, especially due to its specific characteristics, such as a focus on training procedural skills (e.g. nursing skills, engine assembly training, wiring high-voltage cabins…) and educational set-ups (e.g. scheduling for the skills training, preparing for internships…). The current study is one of the few iVR studies, conducted in secondary vocational education.

1.4 Immersive virtual reality in safety education

As immersive virtual reality allows for developing skills and attitudes that otherwise are hazardous or impossible (Checa & Bustillo, 2020), it is a promising avenue for safety education. iVR has been studied in the field of hazard perception, which can be defined as a person’s ability to perceive certain situations or events as potentially dangerous, implying to alter one’s own behavior as desired or as described in protocols (Perlman et al., 2014). This has been applied in road safety (Chang et al., 2020; Lehtonen et al., 2017), laboratory safety procedures (Makransky et al., 2019a, b; Qorbani et al., 2021), training fire fighters (Rahouti et al., 2021), and to a large extent in construction site safety training (Wang et al., 2018).

Immersive virtual reality is used to train (future) construction site workers how to work and act safely in a construction site environment (Chavez & Bayona, 2018; Kanade & Duffy, 2022). The key decision to adopt iVR is the lack of access to real construction sites to train hazard perception and a lack of motivation in learners when adopting traditional tools (Wang, 2018). Nearly all studies point to higher learning outcomes in terms of hazard perception, motivation, self-efficacy, and attention (Gao et al., 2019; Guegler, 2021; Jeelani et al., 2020; Joshi et al., 2021; Yu et al., 2022). iVR outperforms non-immersive instructional methods in several studies (Buttussi & Chittaro, 2021; Nykänen et al., 2020; Rey-Becerra et al., 2021; Sacks et al., 2013) and points at long-term retention effects (Nykänen et al., 2020; Sacks et al., 2013).

However, the effects of moderating variables such as prior knowledge (Perlman, et al., 2014; Taçgın, 2020; Yu et al., 2022), prior VR experience (Gao et al., 2022), age and gender (Yu et al., 2022) are still not clear. Moreover, most studies focused mainly on evaluating the outcomes of the iVR learning experience, but did not focus on what caused the positive outcomes. Several authors (e.g. Buttussi and Chittaro, 2021; Fracaro et al., 2021; Joshi et al., 2021) pointed to the importance of engagement, however without indication of what caused this higher engagement. It has been attributed to a novelty effect (Gao et al., 2022), to its immersive nature (Li et al., 2018), to a state of flow caused by the immersion (Fracaro et al., 2021), and to the integration of gamification elements (Fracaro et al., 2021; Huang, 2022).

The current study aims to address this research gap, by investigating which individual's characteristics affect the outcome variables of presence, involvement, design, and motivation.

1.5 Serious games and gamification in education

When aiming to create a motivating and engaging learning experience, we looked at the potential of gamification. Serious games (SG) have to be distinguished from games with a purely entertaining nature, as the first are games intended to promote learning, whether it is knowledge, skills, or behavior (Mayer, 2014). A typical game consists of a three-stem structure (Bucchiarone et al., 2019): game elements (e.g. badges, leaderboard), mechanics (e.g. score update, challenge achievement) and dynamics (e.g. engagement, competition). Serious games have shown to be effective in terms of performance, motivation and self-efficacy (Girard et al., 2013; Huizenga et al., 2009; Pan et al., 2022; Platz, 2022; Zourmpakis et al., 2022), although caution is needed when generalizing its effects (Koivisto & Hamari, 2019; Pan et al., 2022; Zourmpakis et al., 2023), especially since it remains unclear which game element leads to the positive outcomes (Koivisto & Hamari, 2019). Zourmpakis et al. (2023) also pointed to the need for an adaptive gamification design, addressing the different individual player types, such as the achiever, the socializer, and the free spirit.

When applying gamification to immersive virtual reality learning experiences, similar findings are noted: most studies report a positive effect in knowledge gains, motivation and self-efficacy (Bazargani et al., 2021; Caserman et al., 2018; Capecchi et al., 2022; Checa & Bustillo, 2020; López Chávez et al., 2020), even for transfer of acquired skills (Chen & Chien, 2022; Feng et al., 2018) and when looking at long-term retention effects (Menin et al., 2018), but findings are inconsistent (Checa & Bustillo, 2020). iVR serious gaming (iVR SG) has also shown to be beneficial when training safety workers (Abed et al., 2015; Cavalcanti et al., 2021; Chen & Chien, 2022; Feng et al., 2018, 2021). However, most studies involved university students using high-end, costly iVR equipment (Checa & Bustillo, 2020). As such, results cannot simply be translated to other educational levels, such as secondary vocational education.

In addition—similar to non-iVR serious games—there is still a debate on what exactly causes the positive outcomes: whether it is the learning paradigm being used (Feng et al., 2018), a specific game element (Cavalcanti et al., 2021; Checa & Bustillo, 2020), the level of presence (Capecchi et al., 2022; López Chávez et al., 2020), ease of use (Checa et al., 2021; López Chávez et al., 2020), or prior VR experience or the video gaming experience (Feng et al., 2020). Similar to non-gamified iVR learning experiences (Wu et al., 2020), more research seems to be needed to define “the best design of VR-SGs […]” (Checa & Bustillo, 2020, p. 5516).

The current study aims to tackle this as a fourth research challenge: which gamification elements are valued positively in terms of interest/enjoyment and value/usefulness, both by students and teachers?

1.6 Problem statement and research questions

Bringing together the research opportunities and gaps as identified above, our design-based study aims to contribute to the theoretical understanding on iVR as an instructional means to teach hazard perception in vocational education.

The novelty of the paper lies in the combination of addressing four research gaps. First, it is one of the few studies on iVR in secondary vocational education; second, it adds to the identification of relevant design elements in iVR learning experiences; thirdly, it tries to present evidence of the effect of individual’s characteristics such as prior knowledge, prior gaming experience and prior iVR experience; and finally, it investigates which gamification elements are value positively in terms of interest/enjoyment and value/usefulness. Moreover, the identified design guidelines might help future researchers and practitioners in the design and evaluation of a low-cost, mobile immersive virtual reality serious game.

To address the identified gaps, two research questions are central in our study:

RQ1: To what extent can an immersive virtual reality serious game be an effective instructional strategy to teach hazard perception in secondary vocational education?

RQ2: Which design elements contribute to both teachers’ and students’ satisfaction, enjoyment, and perceived usefulness of the iVR learning experience?

2 Methodology

2.1 Context

This study is part of the InnoVET-project SAVR – safety in virtual reality. InnoVET is a funding program by the Department of Education in Flanders, Belgium and stands for Innovation in Vocational Education and Training (Onderwijs Vlaanderen, 2021). The program provides partial funding for innovative projects aiming to address challenges in secondary vocational education. InnoVET projects are typically multidisciplinary, bringing together experts from education, the industry and technology providers. Likewise, the SAVR project assembled expertise from different perspectives: teachers and students from five secondary vocational schools, a network organization aiming to bridge education and industry, a research team, a VR developer, two pedagogical advisory board members, and two members of organizations developing learning materials on safety education in Flanders. All worked together to create an iVR serious game to teach hazard perception to secondary vocational education students.

The present research, linked to the SAVR project, adopted a design-based research approach, as developed by McKenney and Reeves (2018) in their Educational Design Research framework. This methodological approach aims at the empirical assessment of specific theoretical assumptions and helps contributing to theory development as "it privileges ecologically valid studies that embrace the complexity of investigating learning in authentic (as opposed to laboratory) settings." (McKenney & Reeves, 2020, p. 82).

2.2 Participants

The SAVR SG was developed in collaboration with students and teachers, within the real context of their classrooms and focusing on the predefined set of learning goals and regulations. In total, 8 teachers and 50 students from five secondary vocational schools in Flanders were involved in the study. We used a convenience sample, as they were recruited via the SAVR project network that brought together a multidisciplinary consortium of end users: the schools, safety education experts, instructional design experts, a VR developer with expertise in XR learning experiences and finally an academic research team.

All five schools are secondary vocational schools with a focus on the engineering and construction industry, which made them appropriate to fit the goal of a construction site safety training. The schools are located in Flanders, the Dutch speaking part of Belgium. All 8 teachers were male and had a background in the construction industry before they started their teaching career. Their age ranges from 26 to 43. All students were male, too. The lack of female teachers and students is typical in vocational education (Ray and Zarestky, 2022). Students were between 14 and 18 years old and enrolled in grade 2 and grade 3. These grade levels are critical since these students are (1) engaged in internships, next to workshop-based training in school, working with potentially dangerous machinery. And (2), iVR headset manufacturers, such as Meta, Pico, HTC, and others, do not allow their devices to be used by children under the age of 13 (Meta, 2022), expressing health concerns.

Following the ethical procedures as defined in the General Ethical Protocol of the Faculty of Psychology and Educational Sciences of Ghent University, all students, their legal guardians, teachers, and principals were informed—prior to the study—about the nature and procedure of the research project. All participants gave a priori their written, active informed consent.

2.3 Educational design research

To both create a practical and useful instrument for the educational field on the one hand and to contribute to the existing literature on iVR SG for safety education on the other hand, we adopted a design-based research approach. In view of the latter, we adopted the Educational Design Research (EDR) framework of McKenney and Reeves (2018). EDR follows three phases: analysis and exploration, design and construction, and evaluation and reflection (Fig. 1).

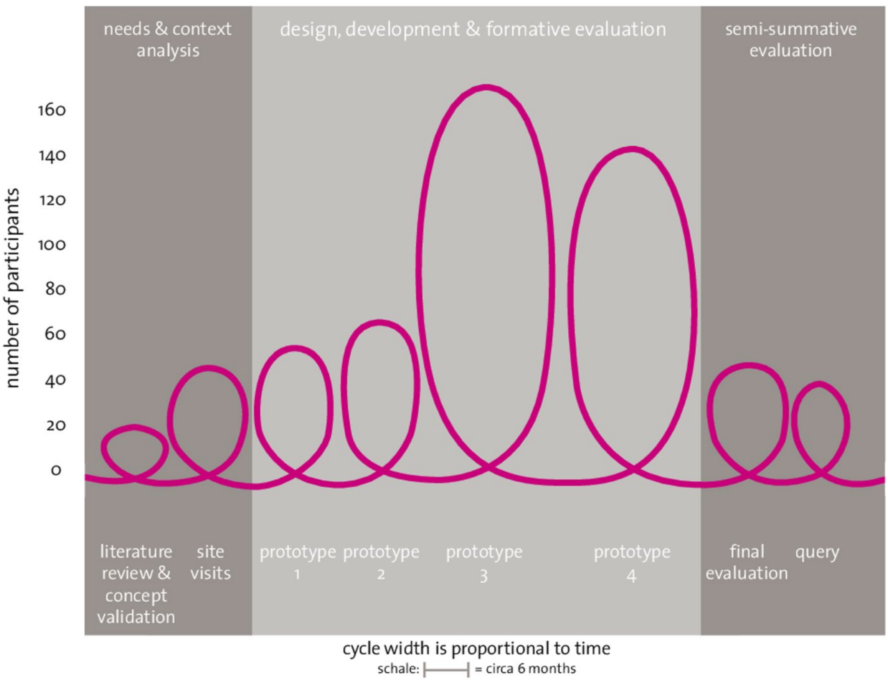

Fig. 1 Process display of a design study, adapted from McKenney, 2001

2.3.1 Analysis and exploration

The first phase focuses on analyzing the problem, exploring contextual factors, and finally delineating the needs for the design and development of the learning experience. We wanted to get a better understanding of the problem itself, but also of the context in which the safety lessons have to be taught. As such, we organized focus group sessions with one group of students in each school involved. In addition, semi-structured interviews were carried out with one or two teachers at each school, with the members of the pedagogical advisory board, and with two representatives of publishers of safety education learning materials. As expressed by McKenney and Reeves (2018) qualitative research via interviews or focus groups is the best way of getting detailed information about what teachers and students lack, in which context they operate at the start of the project and what they expect of the newly developed learning material.

In each of the five schools we interviewed the teacher or teachers involved with safety courses. All interviews focused on getting a clear overview of what learning goals students have to attain, which learning materials teachers use to teach students the course, how much time is spent on this, how students' knowledge and attitude are evaluated and so on. The second part of the interviews tried to identify the wishes for the design of the new learning materials, such as which course elements are of prior interest, what current challenges could be tackled in the iVR experience, which devices they prefer and what success factors they see for the learning solution. Apart from the schools we also interviewed the VR developer, the two members from the pedagogical advisory board, and finally the three creators of safety education learning materials, to match expectations from the schools with the regulations in the industry and with the efforts for the developer within the scope of the InnoVET program.

All interviews and focus group meetings were carried out by the research team, during online meetings using Microsoft Teams due to the Covid-19 safety restrictions at that time. All interviews and focus group meetings were recorded by the researchers, exported to MP3-files, and synthesized in a preliminary iVR development requirements document. This document was then presented to and discussed with all members of the project team. Consensus was met between needs and desires on the one hand and feasibility both technically and budget-wise. This resulted in a final list of requirements which guided the design, development, and evaluation process. The related interview questions are added in the appendices (Table 8).

Apart from the needs assessment and context analysis we also conducted a literature review as described before in the theory part of the introduction in this article. The available studies indicated immersive virtual reality was a valuable and potentially effective tool for designing an immersive virtual reality serious game to teach safety to students in secondary vocational education in Flanders. However, as expressed by Wu et al. (2020) and Checa and Bustillo (2020) it is vital to investigate which design elements contribute to the effectiveness of the iVR serious game. Therefore, we adopted this recommendation as one of our main research questions in the present study.

2.3.2 Design and construction

Findings of the needs and context analysis, together with the results from the literature review were used to create a first prototype. Typical of Educational Design Research is the iterative nature of the development phase that results in consecutive prototypes being developed and tested. Empirical feedback in relation to each version is used to improve a subsequent prototype. In this way each prototype reflects a better fit with the original user needs. This iterative approach of EDR is depicted in the middle block of Fig. 1. The design and development of the SAVR experience took 6 months and went through four stages of prototyping before the final version.

Prior to the first test session, teachers and students were familiarized with the Meta Quest 2 HMD during an introduction phase. They were taught how to operate the HMD and controllers, while playing the game *First Steps*. This game was specifically designed by Meta to familiarize users with a virtual reality environment and with interacting with virtual objects such as pushing knobs, grabbing gear, and navigating through the virtual world. Finally, the SAVR developers explained how to download, install, and update the software through their own software portal.

A first prototype was tested by all teachers and students, while being observed by the developers and the research team. Due to Covid-19 safety regulations, participants were observed remotely. This was supported by using the developers' management

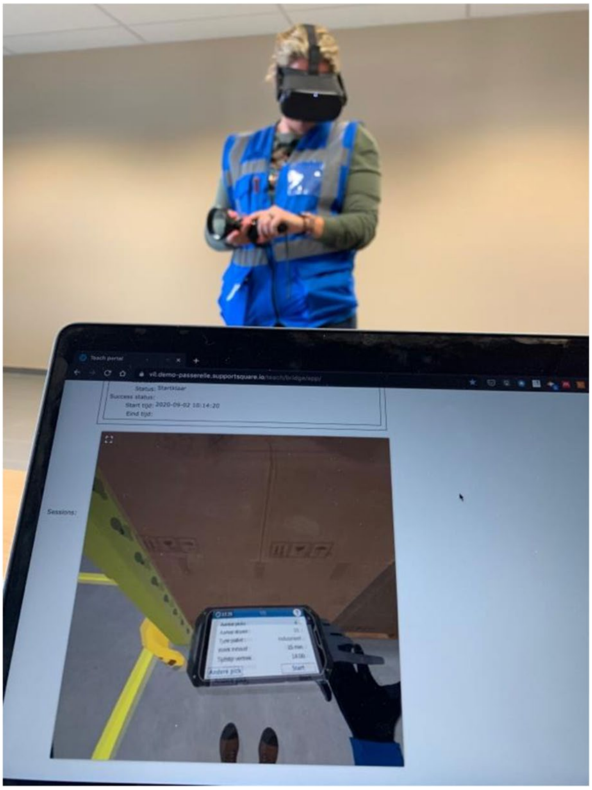

Fig. 2 Example of monitoring test session via developer's operating system

system, specifically designed for remote support, and allowing to monitor test sessions by live screen sharing: we watched and heard the livestream from inside the HMD on a desktop computer via the developer's operating system (Fig. 2). Teachers and students tested the prototypes in their own school context. The research and developers team watched participant performance during the test sessions. Besides adhering to the Covid-19 restrictions, this provided for considerably less effort for the observations as these sessions could be organized from a remote location.

After the development of each new prototype, a new test round started. The research and developers team wrote down their observations following an observation protocol. This implied the structured use of a coding system during the live monitoring of user test sessions. A set of codes was defined upfront, such as software bugs, realism, instructions, and guidance. But, when needed, new codes could be created by the observers, resulting in the development of a more meaningful picture. Afterwards, all observations and codes were discussed by the developers and the research team, resulting in a synthesis report with a list of suggestions for improvement to be implemented in the next prototype. Before starting with a new development cycle, all suggestions were presented to the students, teachers, and content experts, in order to stay in check with the needs, desires, content, and instructional approach as expressed during the first phase of analysis and exploration, but also to stay within the scope of the project.

Next, a subsequent prototype version was designed, developed, and included in a new test cycle. In total, four prototype test cycles were set up, resulting in 19 design choices. After testing the fourth prototype, a final version was presented to be included in a final evaluation study, reported in this article.

2.3.3 Evaluation and Reflection

Eight months after the start of the research and design project, a final iVR prototype was tested with 50 students and 8 teachers who played the game in their own school setting. A game session lasted approximately 23 min. Next, students were asked about their perceptions of the new instructional strategy to teach hazard perception.

Two subscales of the Intrinsic Motivation Inventory (IMI) of Deci and Ryan (Center for Self-Determination Theory, 2021) were adopted namely interest/motivation (7 items) and value/usefulness (7 items). Users' satisfaction with the iVR experience was investigated by using two subscales of the Presence Questionnaire (IPQ) by Schubert et al. (2001): 4 items about spatial presence and 4 items about involvement. Presence and involvement are generally seen as important factors affecting users' satisfaction (e.g. Makransky & Lilleholt, 2018). We also investigated student perceptions about the learning design, using the Design scale of the Web Based Learning Tools survey by Kay (2011).

Apart from some demographic elements such as age and gender, also students' and teachers' gaming experience and prior iVR experience were mapped. The two latter were measured on a 7-point Likert scale, ranging from "1 – no experience", over "4 – neutral" to "7 – extensive experience". Level 1 and 2 were subsequently categorized into the label "low", levels 3 to 5 into "medium", and level 6 and 7 into "high".

Finally, considering our investigation of effective design guidelines (RQ2), we also questioned students' and teachers' perceptions about the design choices adopted during the development of the prototype. We presented both groups with the 19 design elements that were identified as key, based on the observations during the prototyping phases. Both students and teachers were asked to rate the enjoyment and perceived usefulness of each iVR SG design choice to promote hazard perception. We used a 7-point Likert scale, ranging from "Absolutely disagree" (1), over "Neutral" (4) to "Absolutely agree" (7). The distinction between enjoyment and perceived usefulness is derived from the observation that students and teachers can dislike a particular design element, for example limited navigation, but nevertheless understand its didactic usefulness.

3 Results and discussion

During the InnoVET project SAVR – Safety in VR, we designed, developed, and tested a low-cost immersive virtual reality serious game on hazard perception for secondary vocational education. To address this challenge, we adopted the systematic approach of Educational Design Research as developed by McKenney and Reeves (2018). As a result, we could create an iVR SG experience which can readily be used by teachers and students in their actual teaching practices, but also add to the current knowledge on how to design such learning experiences. To provide the reader with a clear understanding of how SAVR was designed and of how the other results should be understood, we first present a short overview of the SAVR application.

3.1 The immersive virtual reality serious game *SAVR – safety in VR*

When the game starts, the user is situated in a dressing room inside a construction site container unit. The user is faced towards a television screen and is asked to push the start button on the screen with his hand. Then a 2D-video of one of the researchers dressed as a construction site manager pops up, explaining to the user what the goal of this game is: a Last-Minute-Risk-Analysis (LMRA). The user is told he has to check the construction site for potential hazards and unsafe working conditions. Next, the actual tutorial starts, explaining the user how to navigate in the virtual world by teleporting and taking small steps within the safety boundaries. The user is also made aware of a virtual smartphone attached to his hand, by which he can take pictures to capture the identified hazards. The virtual construction site manager explains that there is only a limited number of 15 pictures the user can take. The time is also limited to 15 min, which is typical of an LMRA (Mensura, 2021).

Next, the user enters the virtual construction site and has to look for hazardous situations. In total, 23 construction workers are depicted, carrying out several activities, such as welding, sawing wood, drilling, climbing a scaffold, and so on. Of these 23 working conditions, 10 are dangerous and have to be spotted. Each time a situation is identified the user thinks is unsafe, he takes a picture with the virtual smartphone. When it indeed was a dangerous situation, short positive feedback is given by both audio and text. The user gets a short confirmation sound and a text box in a green frame with a small picture of the construction site manager explaining in short what the desired working condition should be. The dangerous situation is also autocorrected. When there was no danger, the user gets a negative sound and is told there is no danger.

At all times the user can check the time and the number of pictures left on the virtual smartphone. When the user has spotted all 10 unsafe situations, or when 15 pictures are taken, or when the 15-min time limit has passed, the game ends with a fire alarm, fire and smoke all over the construction site and the user has to go to the assembly point which was clearly marked with several signs at the construction site; again to check whether the user has paid attention to them. The user has to reach this assembly point within one minute.

The user is then automatically transported back to the construction site container and receives a performance report about which hazards were identified and which were not. Finally, the construction site manager revisits with the user all 10 hazard items and explains what the danger was and how this should be avoided in the future by adhering to safety protocols. When the user identified the hazard item during gameplay, the feedback is provided in a green box, otherwise in a red box.

A screen recording of the video gameplay can be found at https://youtu.be/wyq-EDXR2q0.

We will now discuss the results following the three EDR phases: analysis and exploration, design and construction, and evaluation and reflection. The design elements which were identified and applied during these three phases are summarized in Table 1.

3.2 Results of phase 1—Analysis and exploration

The first phase aims to get a clear understanding of the problem faced, and in which context the new learning material should be developed. We organized focus group sessions with students and semi-structured interviews with teachers, members of the pedagogical advisory board and representatives of publishers of safety education learning materials.

During the focus groups with students, it became clear that the current teaching methods lack authenticity: students are in most cases referred to textbooks, explaining the safety regulations. In some schools, teachers spent time on teaching the several procedures, using the textbooks as a reference guide, in other schools students were asked to study this on their own. This lack of real-life learning experiences is a common need expressed in iVR safety education research (Chang et al., 2020; Gao et al., 2019; Huang, 2022; Nykänen et al., 2020; Zhang, 2020). This should be no surprise as providing for learning and training in otherwise dangerous or even impossible situations is one of the most obvious affordances of immersive virtual reality: it provides a virtual environment in which the learner can learn and practice in an unlimited way and without any risk for injuries (Chavez and Bayona, 2018; di Natale et al., 2020; Maas & Hughes, 2020; Radianti et al., 2020). Moreover, iVR has proven to be an effective tool in those cases (Guegler, 2021; Jeelani et al., 2020; Joshi et al., 2021; Yu et al., 2022).

Table 1 Challenges expressed during analysis and exploration and observed during design and implementation, and design elements addressing these challenges

#	Design elements to address the challenges	Challenges
Phase 1 – Analysis and exploration		
1	A virtual construction site with hazardous working conditions	The lack of authentic learning experiences for safety education
2	An interactive learning experience	The textual nature of the current learning materials
3	A 2D video of a pedagogical agent	The limited budget of the project
4	A narrative of a last-minute risk analysis	The limited budget of the project; the need for a general safety training focusing on hazard perception
5	A library of 29 scenarios depicting unsafe working conditions, which are randomized	The need for ample learning opportunities
6	A reduction of graphic realism to counterbalance the limited GPU-power	The need for a mobile device with limited GPU-power due to demands of mobility
Phase 2 – Design and implementation – round 1		
7	An in-game tutorial	The struggle of users with how to navigate in and interact with the virtual environment
8	A validation strategy of 3 times within 7 s	The struggle of users with how to navigate in and interact with the virtual environment
9	A reduction of interaction to one button	The struggle of users with how to navigate in and interact with the virtual environment
10	An autodirected teleportation	The struggle of users with how to navigate in and interact with the virtual environment
Phase 2 – Design and implementation – round 2		
11	A validation via a collision box close enough to the hazardous situation	The students tricking the game
12	A limited number of photos users can take	The students tricking the game
13	A sequenced addition of text to the audio instructions	The voice instructions are not audible within the noise of the workshops at the schools

Table 1 (continued)

#	Design elements to address the challenges	Challenges
Phase 2 – Design and implementation – round 3		
14	Short immediate feedback	The need to foster reflection on hazard perception
15	Visual feedback which autocorrects the hazards situation	The need to foster reflection on hazard perception
16	Blocking of user's controls during the voice instructions and feedback	The need to prevent students from clicking away the instructions and feedback without having paid attention to them
Phase 2 – Design and implementation – round 4		
17	A limited time for the users to find the hazardous situations	The need to mitigate possible sickness outcomes due to extensive duration in iVR
18	A stimulation of self-regulating skills of students by providing them with a permanent view on their progress	The need to foster reflection on hazard perception
19	A negative evaluation of student's performance	The students tricking the game

Students complained about the lack of real-life experiences, but also about the textual nature of the learning materials which are currently used to prepare them for the exam to get a certificate. This certificate is known in Flanders as VCA and stands for Safety, Health and Environment Checklist for Contractors (Constructiv, 2021) and is similar to the international Occupational Health and Safety Administration (European Agency for Safety and Health at Work, 2021). The students indicated the learning materials were, due to their textual nature, often difficult to understand. This was reaffirmed by the teachers, by the representatives of the safety learning materials publishers, and the pedagogical advisory members as well. All wished for an interactive learning experience in an authentic setting, which would give them a clear understanding of the needs and motivation for certain procedures. Again, immersive virtual reality was able to account for that, as iVR can provide for highly interactive learning applications, due to its immersive character (Makransky and Petersen, 2021; Shin, 2017).

Interactivity is also at the heart of games, creating engaging experiences (Bucchiarone et al., 2019; Checa and Bustillo, 2020; Koivisto & Hamari, 2019), opening up the opportunities for gamification, explicitly requested by the students, and which has too proven to be effective for safety education (Feng et al., 2018; Menin et al., 2018). However, due to the limited budget of the InnoVET project we had to make some concessions to the interactive nature of the learning experience. Developing a fully interactive SG in which the students could carry out the construction activities themselves, whether in a safe or unsafe condition, would imply lots of efforts on the account of the developer, which would not fit the budget.

Hence, we decided to design the game as a Last-Minute-Risk-Analysis, in which other virtual avatars would perform the construction activities, and not the students themselves. Students have to spot construction workers in unsafe conditions by means of taking a picture for their LMRA. In this way, the iVR SG would still be highly interactive, but limit the development to a large extent. By taking pictures, using a virtual smartphone, the embodiment of the user is increased, which has shown to have a significant on learning outcomes (Johnson-Glenberg et al., 2021).

Interactivity is a key element in (serious) games (Arnab et al., 2015; Gurbuz & Celik, 2022), creating engagement. Due to the limited interactivity, and possibly lower engagement, we were concerned whether this would have an effect on the learners' satisfaction. However, both students and teachers scored high on interest/enjoyment (both M = 5.75). In addition, their test results for presence (both spatial presence and involvement) were also very positive: students rated spatial presence on M = 5.78, and involvement on M = 4.53. Teachers were even more positive: M = 5.93 for spatial presence and M = 5.34 for involvement.

Research by Makransky and Lilleholt (2018) has shown presence predicts motivation and enjoyment, which is reflected in this study too, which in turn leads to higher perceived learning outcomes. In addition, flow (Csikszentmihalyi, 1988) is enhanced by the level of presence (Volante et al., 2018), again resulting in learning gains (Fracaro et al., 2021; Gao et al., 2019; Makransky & Lilleholt, 2018). So, even though the iVR SG is somewhat limited in the level of interactivity, the high scores for presence and interest/enjoyment indicate we were successful in creating a performant tool for training hazard perception. This is also reflected in both teachers' and students' positive perceptions on this design choice, both in terms of enjoyment (students: M = 6.25, teachers: M = 5.67) and perceived usefulness (students: M = 5.73, teachers: M = 6.25).

This design choice of an LMRA also fits the wish of both teachers and members of the pedagogical advisory board for a more general safety training, focusing on hazard perception, instead of a single procedural operation. Similar approaches have been applied successfully using iVR (Li et al., 2018; Nykänen et al., 2020; Yu et al., 2022). These studies however apply to higher and professional education in most cases (Checa & Bustillo, 2020), which cannot simply be expanded to secondary vocational education, which was also expressed by everyone involved in this project. The current project and present study aim to address this gap.

To frame the adapted interactivity of taking pictures of hazardous situations, we created the story of a Last-Minute-Risk-Analysis. This storytelling framing has two benefits: it provides for a narrative, and it induces the problem statement. In (serious) games, creating a story or narrative is one of the key game dynamics (Bucchiarone et al., 2019) and lack of it has shown to be correlated to no improvements in learning outcomes (Checa & Bustillo, 2020). By presenting the game as an LMRA, we also take a problem-based learning approach. Presenting the learner with a real-world problem that must be solved, promotes the learning process (Merrill, 2002). Problem-based learning has also been used successfully as a base learning theory in serious games (Gurbuz & Celik, 2022; Pan et al., 2022; Zourmpakis et al., 2023) often presented as challenges or constraints (Bucchiarone et al., 2019; Koivisto & Hamari, 2019) and in iVR learning experiences in the domain of safety education (Feng et al., 2021; Huang, 2022).

Although the SAVR game is somewhat limited in interactivity, we provide for ample learning opportunities. All stakeholders expressed the need for rehearsal: they wanted a SG which would allow the students to train several times, but each time with different hazards. To account for this, we created a library of 29 construction scenarios (Fig. 3, divided in 7 categories). Similar to Yu et al. (2022), the scenarios

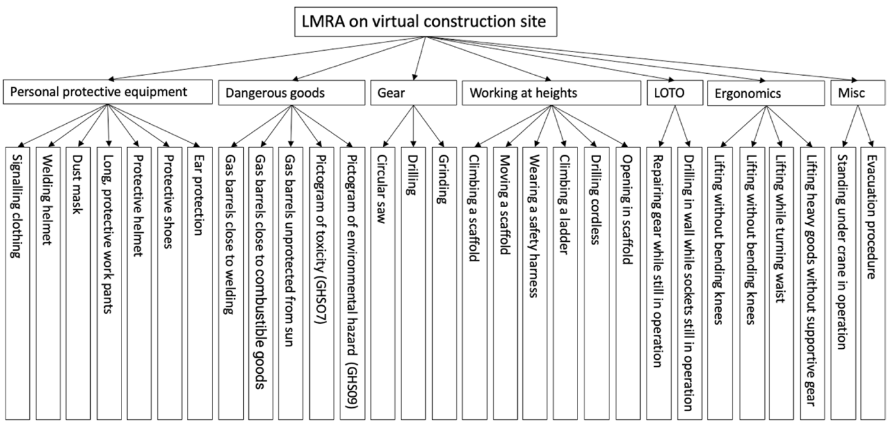

Fig. 3 Overview of 29 scenarios of construction safety hazards library in SAVR iVR SG

were based on the existing learning materials and chosen in consensus with both teachers and the safety education learning materials publishers: personal protective equipment (PPE), dangerous goods, operating electrical gear properly, working at heights, the lockout tagout procedure (LOTO), ergonomics, and a miscellaneous category. For each category two or more scenarios were defined, which were then each developed in a safe and unsafe mode. We also added the emergency procedure signaling as teachers indicated this was of utmost importance.

Each training session, the operating system randomly chooses 15 scenarios out of 29 and randomly turns 10 out of those 15 into the unsafe method. This randomization provides for a huge variability of scenarios which contributes to the effectiveness of the iVR SG (Abed et al., 2015; Caserman et al., 2018; Feng et al., 2020), making it a useful instrument for repetitive training. To motivate students to take the iVR training several times, the teachers agreed on the students' wish for gamification, but also urged not to suppress the learning content by the game elements. Although students expressed their wish for gamification elements, they did not specify which game elements they preferred.

The limited budget of the InnoVET project also faced the team with the challenge of creating the virtual assistant or pedagogical assistant. According to Makransky et al., (2019a, 2019b) the topic of pedagogical assistants has been studied widely, however without sound evidence on whether a pedagogical agent in a 3D virtual environment should be delivered as a 3D avatar too. On the contrary, Schroeder et al. (2013) indicated in their meta-analysis that there were no significant differences in learning performance, depending on how the pedagogical agent is presented. So, to save on development efforts, we decided to present the virtual teaching assistant, providing the learners with instructions and feedback, via a 2D recorded video of a real person. This person is one of the male researchers dressed as a construction site

Fig. 4 Screenshot of virtual pedagogical assistant in 2D-video

manager (Fig. 4). This design element of presenting the pedagogical agent in a 2D video, mainly induced by cost-efficiency, proved to be satisfactory as it was valued positively, both in terms of enjoyment (students: M = 5.58, teachers: M = 5.87) and perceived usefulness (students: M = 5.69, teachers: M = 5.38). Moreover, none of the participants commented on this design choice during the prototyping sessions, indicating they did not see this as a detrimental element for the design of the iVR SG.

We also chose a male person as the pedagogical agent, due to the gender matching effect, indicating learning is improved when learners are presented with a pedagogical agent of the same gender (Makransky & Lilleholt, 2018). As all students and teachers are male, this choice seemed valid.

Finally, the teachers asked for a learning solution, which is easy to use in a dynamic school setting, stressing the importance of a mobile device. Due to the demand of this mobile and affordable headset, we were somewhat restricted in the development even more. The iVR HMD preferred for this project was Meta Quest 2, which has only limited GPU-power. As a result, we had to balance the level of realism of the virtual avatars and environment. Previous research has indicated perceived realism by users has a profound impact on their sense of presence, which in its turn affects the satisfaction of the learning experience (Li et al., 2018; Suh & Prophet, 2018) and even to performance (Menin et al., 2018). However, test results for both spatial presence and involvement turned out to be good to very good, for students as well as for the teachers. Students rated spatial presence on M = 5.78 and involvement on M = 4.53. Teachers' ratings were even a bit higher: M = 5.93 for spatial presence and M = 5.34 for involvement.

The decisions described above (see Table 1, phase 1) were made upfront, before testing the prototypes.

3.3 Results of phase 2—Design and implementation

The second phase of Educational Design Research consists of several cycles of design and construction in an iterative approach in which a prototype is developed, tested, and revised into a new prototype until the third phase, the summative evaluation. While observing the four prototype test sessions and discussing their results, several other design choices were made.

During the first session, we noticed several students and teachers struggled to navigate in and interact with the virtual environment. To account for this we added a tutorial, teaching them these basic interactions. This process of familiarization has shown to be very important in terms of effectiveness (Cavalcanti et al., 2021; Taçgın, 2020), in order to avoid extraneous cognitive load during the learning process (Clark & Mayer, 2016). Instructional designers of virtual learning environments should make sure learners can fluently navigate and interact with the virtual objects without having to think about which button they should press. A tutorial, teaching the learners how to navigate and interact, was developed, as an in-game tutorial is directly related to satisfaction and performance (Checa et al., 2021).

Fig. 5 Screenshot of user taking picture of potential hazard

We decided to make the navigation and interaction as easy as possible as ease of use is also an important precursor of satisfaction and performance (Buttussi & Chittaro, 2021; Checa et al., 2021; López Chávez et al., 2020), limiting navigation to one button (trigger button) and taking pictures pressing on the picture knob of the virtual smartphone, as in real-life (Fig. 5). This too was valued consequently in a positive way, both in terms of enjoyment (students: M = 5.65, teachers: M = 5.63) and perceived usefulness (students: M = 5.56, teachers: M = 5.38).

We implemented another element to make sure learners were fully familiarized with the controls, by adding a validation: when learners are not able to perform the instructions in the tutorial within 7 s, they must start over. In this way we prevent learners from engaging with the actual learning content when still wondering about how to interact with it. This 7 s rule is in line with Feng et al. (2022) and proved to be successful during the prototyping phase, and was also positively valued by both students and teachers. Students perceived this as both enjoyable (M = 5.19) and useful (M = 5.31). Similar results were noted for the teachers: M = 4.88 on enjoyment and M = 5.25 on perceived usefulness.

To support the learner even more, we added autodirected orientation after the teleportation. We noticed during the prototyping phases that some learners were disoriented after having teleported. Although the distance of the teleport destination was already limited, the teleportation itself caused some users to be confused about what had happened. To mitigate this effect, we autodirect the learner towards the virtual television screen of the pedagogical agent. This serves then as a point of reference, helping the learners to orient themselves within the virtual environment, significantly improving the ease of use (Caserman et al., 2019). This was valued positively, both during the prototyping phase and in the evaluation (students:

enjoyment: M = 5.58, usefulness: M = 5.62; teachers: enjoyment: M = 5.13, usefulness: M = 5.38).

After the tutorial, the students enter the construction site and can wander freely in whatever direction. This freedom of player's agency, instead of a linear narrative, is seen as an important game mechanic (Arnab et al., 2015; Feng et al., 2018; Gurbuz & Celik, 2022).

During the second prototyping phase we noticed learners tried to 'trick the game', by taking as many photos as possible, and by taking wide-angle photos, both leading to successfully identifying hazardous situations, but merely by chance or by increasing their chances to success. To mitigate this, we first added a validation strategy: for a picture to be valid, we programmed a 'collision box' around each situation. A collision box is a predefined area around a virtual object, which allows for interaction with the virtual object. In this case, the student has to stand within the collision box, close enough to the situation under review. In doing so, only one situation can be photographed at the same time, excluding the factor of luck to a large extent.

Second, we added constraints both for time and for resources, in this case the number of pictures a student can take. Adding constraints for time and resources are typical gamification elements increasing engagement (Huang, 2022; Pan et al., 2022). We limited the number of pictures a student can take to 15. In this way, they really have to reflect on whether the photograph actually depicts a hazardous situation. A slightly less positive result for the implementation of the limited number of photos was noted by the students (enjoyment: M = 4.58, usefulness: M = 4.71). However, we considered this as necessary to avoid the factor of luck as much as possible. Students can always check the number of pictures left on their virtual smartphone.

As the test sessions took place in the actual classrooms and workshops of the schools involved, the future context of implementation was taken into account. This proved to be of importance as students and teachers asked to add textual instructions and feedback, next to the audio instructions and feedback which had been provided in the first prototype. Vocational students practice their construction skills in workshops, where a lot of noise is produced due to the construction activities. As a result, the instructions and feedback in the iVR SG are often not heard properly, causing dissatisfaction. Even putting on headphones proved no to be a solution. The instructions and feedback are therefore presented first in audio and immediately after in text boxes with a colored frame (green or red) accompanied by a static photo of the pedagogical agent, in line with Chittaro and Buttussi (2015) (Fig. 6).

Previous research has shown that combining both audio and text instructions is detrimental for learning, due to the redundancy principle (Clark & Mayer, 2016). Based on the dual channel assumption (Clark & Paivio, 1991), presenting instructions and feedback in audio and not in text, avoids overloading the visual channel of working memory. There are exceptions though, for example in sequencing audio and text (Clark & Mayer, 2016). Baceviciute et al. (2022) also found no evidence for the redundancy principle in a medical iVR learning experience. Building on these findings, we deliberately added text to the audio as it contains essential information (both instructions and feedback). By adding text in sequence to audio, we adhered to the redundancy principle, but also addressed this contextual need from practice. As expected, this design choice was valued positively, both by students (enjoyment:

Fig. 6 Example of feedback during post-game feedback revisit of the virtual construction site

M = 5.50, usefulness: M = 5.65) and teachers (enjoyment: M = 5.50, usefulness: M = 5.75).

During the third phase, we designed the post-game feedback. Feedback is seen as one the most impactful elements of the learning process (Hattie, 2008) and it helps the learner by providing information towards one's performance or understanding (Hattie & Timperley, 2007). Feedback can take many forms and as indicated by Wisniewski et al. (2020) differs in effectiveness, depending on the form in which it is presented. Feedback is especially effective for cognitive outcome measures and when rich in information. Therefore, we provide the learners with two types of cognitive feedback: short feedback during the game and elaborate feedback during the post-game feedback phase.

During the game the students get short, positive feedback when they have identified a hazardous situation. They are told why this was a hazardous situation, and the situation is automatically corrected in the safe mode, as a way of presenting visual feedback. This dynamic simulation is one of the six main game elements in iVR serious games in safety education (Feng et al., 2018) and taps into the affordance of iVR technology by presenting the learner with the visual consequence of one's actions (Gao et al., 2019, 2022; Huang, 2022; Li et al., 2018). During the game, we deliberately provide only short feedback, to maintain the learner's flow and sense of presence.

Research has shown that feedback can potentially have a negative effect on the motivation of the learner as it reduces the learner's sense of autonomy (Wisniewski et al., 2020). This is also in line with Fracaro et al. (2021) who indicated the importance of autonomy satisfaction via flow and gaming elements. In addition, we give a short positive sound, and a green text box. This type of positive reinforcement also has a large effect on learning outcomes, but mostly on the task level itself

(Wisniewski et al., 2020), so we considered this as an addition to the information-rich feedback itself. When students take a picture which does not hold a hazardous situation, they are given a negative buzz sound and they are told there is no danger. Although very short, this too provides feedback as it tells the students about the safe situation, and it provides them with information on their own knowledge as they have misinterpreted this situation.

Immediate feedback is also seen as an effective game element (Huang, 2022; Li et al., 2018), however Feng et al. (2021) found that post-game assessment leads to higher learning gains and higher scores for self-efficacy over prior instruction and immediate feedback. Nonetheless, they reported that the differences were not of significance, so we decided to keep the instructional mechanism of immediate feedback.

Next to this in-game, short type of feedback, we also present the students with elaborate feedback during a post-game assessment of their performance by the virtual construction site manager, indicating how well they performed. They get a score on 10 and all situations are presented. Next, we transport the students back to the virtual construction site to discuss every scenario (Fig. 6) and have them to reflect on their performance. This design choice can be considered as a kind of stimulated recall as "a subject may be enabled to relive an original situation with vividness and accuracy if he is presented with a large number of the cues of stimuli which occurred during the original situation." (Bloom, 1953, p. 161). Stimulated recall has been used to assess students' self-regulated learning and provides the learner with opportunities for reflection (Meier & Vogt, 2015). Again, the iVR technology provides for this type of reflection in a fairly easy way, as students' progress can easily be tracked, and no external video recording is needed. The students are transported back to the earlier developed virtual environment and relive the authentic situation.

During the same iteration, we realized we had to block the user's controls while the instructions were given. The player's agency is somewhat limited during the audio instructions by the pedagogical agent, as we blocked the HMD controllers. During the prototyping phase, we noticed several students simply did not listen to the instructions and started experimenting without actually having heard what to do or how to do it. In this way, they lost cognitive efforts due to the lack of instructional guidance, which has proven to be counterproductive (Durwin & Reese-Weber, 2018, p. 373; Kirschner et al., 2006). Only few games apply a pure discovery approach too (Gurbuz & Celik, 2022). Surprisingly, this design choice was positively evaluated by both students and teachers, with higher students' scores (enjoyment: $M=5.27$, usefulness: $M=5.44$) over teachers' ratings (enjoyment: $M=4.63$, usefulness: $M=4.63$). We had expected learners at least would not really enjoy this limiting their agency (Fracaro et al., 2021), but it had no effect on their enjoyment or presence as a whole either.

Similarly, students clicked away the feedback given, without actually having paid attention to it. To allow for actual reflection, the HMD controllers are blocked during the audio feedback and for at least 7 s (Feng et al., 2022), but they also have to take a picture of hazardous situations they have not yet identified. This design choice was valued somewhat moderate by teachers, especially in terms of enjoyment ($M=4.63$). Probably they experienced the earlier mentioned diminished agency as negative (Fracaro et al., 2021; Wisniewski et al., 2020).

In the fourth and final prototyping phase, we noticed some students kept playing the game until they finally spotted every hazard. This was of our concern as Kennedy et al. (2000) have shown that duration of immersive virtual reality sessions is significantly related to sickness outcomes, and although the maximum duration of an iVR session should be between 55 and 70 min (Kourtesis et al., 2019), manufacturers of iVR headsets generally propose sessions of 30 min, followed by a 10 to 15 min break before the next session (ClassVR, 2022). To prevent sickness symptoms such as dizziness and eye strain, we considered a total of 25 min as a goal. This is in line with what Abed et al. (2015) found acceptable to industrial companies for training sessions. We also presumed a time limit would add to the engagement as this is one of the most common game elements (Bucchiarone et al., 2019). As we noticed during the prototyping phase that the tutorial took 10 min, a 15-min bar was applied for the LMRA itself, which turned out to be feasible and was valued positively by both teachers and students.

To provide the students with as much info during the learning process, they can at all time see their progress, both in time left, pictures taken, and hazards found (Fig. 7). This visualization of their progress on their virtual smartphone, allows students for self-regulation during the monitoring phase of the learning process (Pintrich, 2004). Self-regulated learning has proven to be effective for academic achievement (Theobald, 2021), and has fostered deep learning in iVR safety education too (Huang, 2022).

We also presumed a time limit added to the engagement as this is one of the most common game elements (Bucchiarone et al., 2019).

Finally, students ignored the essence of the evacuation procedure and deliberately walked into the fire to see what happened. To mitigate this, students receive negative feedback when they walk into the fire and the game is automatically ended.

Fig. 7 Screenshot of indication of time and number of pictures left

3.4 Results of phase 3—Evaluation and reflection

To test whether the iVR SG was satisfactory to both students and teachers we measured their sense of presence, their involvement, and their perceptions of design, interest/enjoyment and value/usefulness. Next, we asked how they rated the design choices which were made during the iterative development process, both in terms of enjoyment and perceived usefulness.

To present the results as clear and encompassing as possible, we divided this section into two parts: first the results for the scores of satisfaction, followed by those of the design elements. Each part is subdivided in students' and teachers' results.

3.4.1 Evaluation of satisfaction

In this part we address the results of answering RQ1: *to what extent is an immersive virtual reality serious game an effective instructional instrument to teach hazard perception in secondary vocational education?*

First, we will discuss the test results for the students. Test results are presented in Table 2. We checked the unidimensionality of the measuring instruments via exploratory factor analyses using the SPSS28 package. For spatial presence item loading for two items (SP3 and SP4) were too low, so we dropped these two items for further analysis. We also dropped one item for the construct of interest due to a low factor loading (INT4). These three items were dropped for future analysis. When calculating each scale's reliability via Cronbach's alpha, results were good to very good. The high mean scores indicate the students rated the iVR SG very positively.

We were also interested in whether significant differences between groups could be found. As all students are male, the effect of gender was not further investigated. We explored differences between two age groups: students of grade two (year 3 and 4 of secondary education) and grade three (year 5 and 6). As our measures were perceptions, thus of ordinal nature, we used Mann–Whitney U tests instead of independent sample t-tests. Results of these tests are synthetized in Table 3. The tests indicated a significant difference for interest in favor for the second grade (mean rank 30.76) over the third grade (18.24) with a p-value of 0.003 and an effect size of $r = -0.426$ which can be considered as a medium to large effect. The comparison of scores for the other variables returned not be significant although significance levels for both design ($p = 0.062$) and presence ($p = 0.067$) are close to the significance level of 0.05. When investigating the effect of gaming experience and prior VR experience we had three groups: low, medium, and high experience. As we now had three groups to compare, we used Kruskall-Wallis tests (see Table 4). No significant differences were found, not for gaming experience nor for prior VR experience.

A possible explanation for the significant difference for interest between the second and third grade, could have been that older students had already had more iVR experience, and therefore had higher expectations of the iVR SG. However, no significant differences could be found for prior VR experience. This is in line with previous research (Capecchi et al., 2022; Feng et al., 2020; Gao et al., 2022). Another possible explanation could be the presumed higher prior knowledge in third

Table 2 Results of students' summative evaluation of the iVR SAVR SG ($n=50$)

Theoretical construct with respective items	Item loading	Cronbach's alpha*	Means*	SD*
Spatial Presence (IPQ)		**.602**	**5.78**	**.820**
SP1 – Somehow, I felt that the virtual world surrounded me	.670			
SP2 – I felt like I was just perceiving pictures (R)	.715			
SP3 – I did not feel present in the virtual space (R) (dropped)	.342			
SP4 – I had a sense of acting in the virtual space, rather than operating something from outside (dropped)	-.046			
SP5 – I felt present in the virtual space	.837			
Involvement (IPQ)		**.642**	**4.53**	**1.19**
INV1 – I was still aware of the real world surrounding while navigating in the virtual world (R)	.757			
INV2 – I was not aware of my real environment	.798			
INV3 – I still paid attention to the real environment (R)	.558			
INV4 – I was completely captivated by the virtual world	.650			
Design (WBLT)		**.736**	**5.99**	**.815**
D1 – The help features in the learning object were useful	.855			
D2 – The instructions in the learning object were easy to follow	.865			
D3 – The learning object was easy to use	.707			
D4 – The learning object was well organized	.645			
Interest/enjoyment (IMI)		**.906**	**5.75**	**.946**
INT1 – I enjoyed doing this activity very much	.773			
INT2 – This activity was fun to do	.857			
INT3 – I thought this was a boring activity (R)	.601			
INT4 – This activity did not hold my attention at all (R) (dropped)	.351			
INT5 – I would describe this activity as very interesting	.899			
INT6 – I thought this activity was quite enjoyable	.854			

Table 2 (continued)

Theoretical construct with respective items	Item loading	Cronbach's alpha*	Means*	SD*
INT7 – While I was doing this activity, I was thinking about how much I enjoyed it	.833			
Value/usefulness (IMI)		**.932**	**5.49**	**1.06**
VAL1 – I believe this activity could be of some value to me	.860			
VAL2 – I think that doing this activity is useful for teaching me hazard perception	.873			
VAL3 – I think this is important to do because it can teach me hazard perception	.850			
VAL4 – I would be willing to do this again because it has some value to me	.829			
VAL5 – I think doing this activity could help me to learn on hazard perception	.860			
VAL6 – I believe doing this activity could be beneficial to me	.835			
VAL7 – I think this is an important activity	.835			

* *Cronbach's alpha, means and SD were calculated after items SP3, SP4 and INT4 were dropped*

Table 3 Results of Mann–Whitney U tests for significant differences between student grades ($n=50$)

	Grade 2 ($n=29$)	Grade 3 ($n=21$)
Spatial presence	28.67	21.12
	$p=.067$	
Involvement	26.86	23.62
	$p=.436$	
Design	28.72	21.05
	$p=.062$	
Interest/enjoyment	30.76	18.24
	$p=.003$, $r=-.426$	
Value/usefulness	27.76	22.38
	$p=.197$	

Table 4 Results of Kruskall-Wallis tests for significant differences between students' groups

	Gaming experience			Prior VR experience		
	H	df	p	H	df	p
Spatial presence	.347	2	.841	.244	2	.885
Involvement	2.668	2	.263	.062	2	.970
Design	.043	2	.979	1.254	2	.534
Interest/Enjoyment	1.388	2	.500	.132	2	.936
Value/usefulness	.753	2	.686	1.184	2	.553

grade students. Research has shown the effect of prior knowledge on satisfaction and engagement (Yu et al., 2022), however contradicted by Perlman et al. (2014) and Taçgın (2020), leaving this question open to date. Future studies could investigate this further to explain the differences. We could neither find any significant differences between groups with varying gaming experience, which is in line with Morélot et al. (2021). As such, we can conclude that the iVR SAVR SG can be used effectively for all students of secondary vocational education, and especially in the second grade.

The test results for the teachers (see Table 5) indicate they were to a large extent satisfied with the final result. As we only had 8 respondents for the teachers, further between-persons analyses were redundant.

3.4.2 Evaluation of design elements

In this part we address the results of answering RQ2: *which design elements contribute to both teachers' and students' satisfaction, enjoyment, and perceived usefulness of the iVR learning experience?* As the students and teachers valued the iVR SG experience high in terms of satisfaction (see the previous section), we now focus on the enjoyment and perceived usefulness as they were evaluated separately. Students' results can be found in Table 6; the teachers' results are presented in Table 7. Two students dropped out when answering these questions, bringing a total of respondents for

Table 5 Results of teachers' summative evaluation of the iVR SAVR SG ($n = 8$)

Theoretical construct with respective items	Means	SD
Spatial Presence (IPQ)	5.93	.732
SP1 – Somehow, I felt that the virtual world surrounded me		
SP2 – I felt like I was just perceiving pictures (R)		
SP3 – I did not feel present in the virtual space (R)		
SP4 – I had a sense of acting in the virtual space, rather than operating something from outside		
SP5 – I felt present in the virtual space		
Involvement (IPQ)	**5.34**	**.906**
INV1 – I was still aware of the real world surrounding while navigating in the virtual world (R)		
INV2 – I was not aware of my real environment		
INV3 – I still paid attention to the real environment (R)		
INV4 – I was completely captivated by the virtual world		
Design (WBLT)	**6.13**	**.462**
D1 – The help features in the learning object were useful		
D2 – The instructions in the learning object were easy to follow		
D3 – The learning object was easy to use		
D4 – The learning object was well organized		
Interest/enjoyment (IMI)	**5.75**	**.454**
INT1 – I enjoyed doing this activity very much		
INT2 – This activity was fun to do		
INT3 – I thought this was a boring activity (R)		
INT4 – This activity did not hold my attention at all (R)		
INT5 – I would describe this activity as very interesting		
INT6 – I thought this activity was quite enjoyable		
INT7 – While I was doing this activity, I was thinking about how much I enjoyed it		
Value/usefulness (IMI)	**6.02**	**.538**
VAL1 – I believe this activity could be of some value to me		
VAL2 – I think that doing this activity is useful for teaching me hazard perception		
VAL3 – I think this is important to do because it can teach me hazard perception		
VAL4 – I would be willing to do this again because it has some value to me		
VAL5 – I think doing this activity could help me to learn on hazard perception		
VAL6 – I believe doing this activity could be beneficial to me		
VAL7 – I think this is an important activity		

this set of questions to 48. Results indicate the design choices which were made, are in general rated positively, both in terms of enjoyment and perceived usefulness. The students however were less positive for the limited number of photos they could take (enjoyment: M = 4.58; usefulness: M = 4.71). This reduced their chances to success, as they were forced to be parsimonious in their taking pictures. This reduced the factor of luck, which of course was our intention, but apparently led to a slightly lower satisfaction, especially in enjoyment (M = 4.58), however not to an extent of worry.

The teachers seemed to be less satisfied with four other design elements. They disliked the fact of getting feedback both on positive and negative elements (enjoyment: M = 4.63, usefulness: M = 5.00). Possibly they felt it redundant to focus on the hazards found too. However, as indicated by Feng et al. (2022) providing both positive and negative feedback results in a better understanding of the learning materials than when giving students solely negative feedback. Teachers also were less positive in their evaluation of their controls being blocked during instructions and feedback (enjoyment: M = 4.63, usefulness: M = 4.63), of them having to take a picture of the hazards not found (enjoyment: M = 4.63, usefulness: M = 5.38) and of the 7 s validation of teleportation in the tutorial (enjoyment: M = 4.88, usefulness: M = 5.25). These three elements share a rather forcing aspect of the iVR SG, limiting the player's agency. As discussed before, the player's agency is an important game mechanic (Arnab et al., 2015; Feng et al., 2018; Gurbuz & Celik, 2022) and diminishing it is being evaluated as negative (Fracaro et al., 2021; Wisniewski et al., 2020). However, reflection is an important element of learning via this iVR SG (Feng et al., 2022) and can be stimulated by these design elements.

In general, the test results for these design elements were not remarkably negative, and the positive scores for satisfaction, indicate these design elements are a valid choice, especially as they tackled some problems we noticed during the prototyping phases.

3.5 Limitations

With the SAVR project, we were successful in addressing both challenges of the applied framework of Educational Design Research: we created a practical and readily-to-use instrument to teach hazard perception to secondary vocational education students. Next, we were able to identify several design elements which can help both researchers and practitioners in the development of low-cost, mobile iVR serious games. However, our study also faces some limitations.

In this study we adopted an Educational Design Research approach, as we wanted to create both a practical instrument and identify design elements during the iteration process. As such, we mainly took a qualitative approach measuring effectiveness not in terms of learning gains, but in terms of satisfaction. Future research should investigate whether the iVR SAVR SG also leads to higher learning outcomes.

Next, results clearly indicated both students and teachers value SAVR very positively, for all measures, and nearly all design elements were valued very positively, both in terms of enjoyment and perceived usefulness. This means the iVR SG was satisfactory as a whole, but we do not yet know which design elements contributed to what extent to this satisfaction. Possibly, some elements lead to higher scores than others. Future research should test which elements contribute more to the satisfaction and to the learning outcomes of the students.

We also acknowledge the rather small convenience sample size, especially for the teachers. As we made use of a convenience sample, this may have resulted in some sampling bias, so our results should be interpreted with caution and possibly be validated in future research.

Fourth, our sample consisted of male participants only. This was not our purpose, but an exclusive or predominantly male sample is common in vocational education and training (Ray and Zarestky, 2022). The moderating role of gender in studies on iVR in education is still under debate: Makransky et al., (2019a, 2019b) have found a gender-matching effect for pedagogical agents in an iVR chemistry lab study. Southgate et al. (2019) have indicated female students are reluctant to put on an iVR headset when being watched by others. This was however not reflected in a large-scale survey study on the perceptions of secondary education students on iVR as an instructional tool (Boel et al., 2023a), neither in a parallel study with secondary education teachers (Boel et al., 2023b). Future research should investigate the role of gender on the learning outcomes, motivation, and acceptance in iVR learning experiences in greater detail.

Finally, due to the limited budget, we were not able to create a collaborative learning experience. Previous research has indicated this could be beneficial to students' learning outcomes (Caserman et al., 2018; Fracaro et al., 2021), which could be investigated further developing a collaborative SAVR experience. Similarly, we were not able to comfort for an adaptive gamification scenario, as suggested by Zourmpakis et al. (2023). Future studies on iVR serious games should integrate this design element.

4 Conclusion

Students and teachers in secondary, vocational education are faced with several challenges in their safety education courses. They lack real-life, authentic learning situations, in which they can engage actively and repeatedly, without the risk of injuries or causing damage. Current learning materials are also not adapted to their context. To address this challenge, we applied Educational Design Research to design, develop and test a low-cost, mobile immersive virtual learning experience, enhanced with gamification elements. Our results indicate both students and teachers value the iVR SAVR SG positively, which turns it into a useful instrument to teach hazard perception to secondary vocational education students. Apart from delivering an innovative and practical instructional method for safety education, we were also able to identify relevant design elements during the several design and development phases. These elements can help practitioners and other researchers in creating engaging mobile immersive virtual reality serious games within a low-budget context.

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Data availability The datasets generated during and/or analysed during the current study are available in the Open Science Framework repository: https://doi.org/10.17605/OSF.IO/3XZDB. A data management plan (DMP) had been developed to guarantee data protection.

Declarations

Ethics of approval The research was conducted according to the ethical rules presented in the General Ethical Protocol of the Faculty of Psychology and Educational Sciences of Ghent University, in accordance with the Declaration of Helsinki.

Conflict of interest There are no conflicts of interest to declare.

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