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3D Object Training Beyond the 2D Screen: Effectiveness and Experience of Virtual Reality Training for 3D CT Baggage Screening

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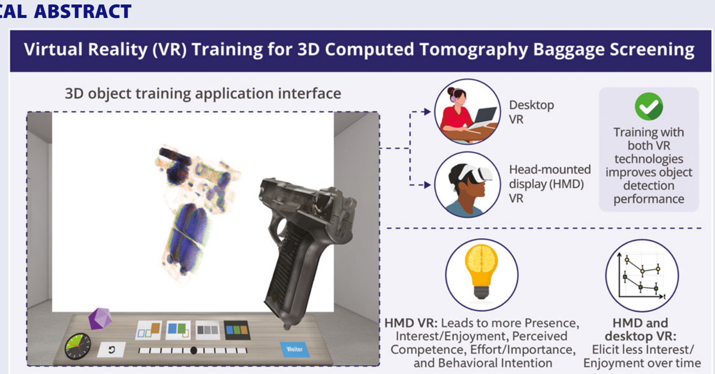
ABSTRACT

Airports are adopting 3D computed tomography (CT)-based technologies for cabin baggage screening to replace traditional 2D X-ray systems. We evaluated a novel virtual reality (VR) 3D object training application using photorealistic 3D models and 3D CT images of prohibited items. Psychology students with no 3D CT screening experience were randomly assigned to the desktop VR ($n = 16$), head-mounted display (HMD) VR ($n = 17$), or no training (control group; $n = 17$) groups. Both training groups underwent six 20-minute training sessions over two weeks. Performance was assessed pre- and post-training using X-ray image interpretation tests. Training experience ratings were collected at every other training session. Both desktop VR and HMD VR training improved performance; HMD VR training also fostered more Presence, Interest/Enjoyment, Perceived Competence, Effort/Importance, and Behavioral Intention; however, Interest/Enjoyment decreased after the initial VR training with both training media. This study demonstrates that VR-based 3D object training can significantly enhance performance and user experience, making it a promising tool for airport security screener training.

KEYWORDS

Virtual reality; desktop VR; HMD VR; airport security; computer-based training

GRAPHICAL ABSTRACT



1. Introduction

Airport security is undergoing a transformative shift from two-dimensional (2D) X-ray to advanced three-dimensional (3D) computed tomography (CT) technology for baggage screening (Cordova, 2022; Smith & Connelly, 2022). Although manufacturers of 3D CT machines aim to increase efficiency (e.g., higher baggage throughput) and add enhanced capabilities to detect prohibited items (including automatic explosives detection and prohibited item detection; Vukadinovic & Anderson, 2022), human operators remain important in baggage screening (Cordova, 2022; Hättenschwiler et al., 2019; Wetter, 2013). Several studies have demonstrated the importance of computer-based training (CBT) for achieving a good detection of

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prohibited items in 2D X-ray images (Halbherr et al., 2013; Koller et al., 2008; Madhavan & Gonzalez, 2010; McCarley et al., 2004; Schwaninger & Hofer, 2004). With 3D CT, baggage images can be rotated, which enhances the detection of prohibited items (Hättenschwiler et al., 2019; Latscha et al., 2025; Muhl-Richardson et al., 2025; Parker et al., 2022). Whereas these studies all investigated 3D CT displays on 2D screens, to our knowledge, no research has been conducted using virtual reality (VR).

We address this research gap by evaluating a novel VR 3D object training application using photorealistic 3D models and 3D CT images of prohibited items. This VR training reduces the need for costly and dangerous physical objects—and allows simultaneous views of 3D CT images, which would otherwise be impossible (cf. Bailenson & Lesher, 2024). Psychology students with no prior 3D CT screening experience were randomly assigned to one of the following training conditions: desktop VR, head-mounted display (HMD) VR, or no training. Participants in the training groups underwent six 20-minute training sessions over two weeks. Measures of performance (sensitivity in terms of d' and d_a, hit rate [HR], false alarm rate [FAR], target-present and target-absent reaction times [RTs]) were assessed pre- and post-training using a computer-based X-ray image interpretation test. Ratings of the training experience (aspects of immersion, motivation, cognitive load, and technology acceptance) were collected every other training session. In the remaining introduction, we discuss the relevant literature and the hypotheses.

1.1. Training media (desktop VR vs. HMD VR)

Many publications define VR as a computer-generated and interactive 3D environment that simulates real-world experiences for users (e.g., Bowman & McMahan, 2007; Jerald, 2016; Wohlgenannt et al., 2020). Virtual reality can be accessed through different systems, with two primary media types used in practice: desktop VR and HMD VR. These two types and a control group form our first independent variable: training media. Desktop VR (also called low-immersive VR; e.g., Checa & Bustillo, 2020; Parong & Mayer, 2018) typically involves a computer monitor to display the virtual environment, and users can interact with the virtual experience using, for example, a computer mouse (cf. Lee & Wong, 2014; Makransky & Petersen, 2019). In contrast, current HMD VR (also called immersive VR; for systematic reviews, see, e.g., serious games [Checa & Bustillo, 2020]; K12 to higher education [Di Natale et al., 2020]; procedural training [Jongbloed et al., 2024]; safety training [Lampropoulos et al., 2024; Stefan et al., 2023; Sudiarno et al., 2024]; training in general [Strojny & Dużmańska-Misiarczyk, 2023; Won et al., 2023; Wu et al., 2020]) delivers a more immersive experience by presenting the virtual world stereoscopically through an HMD, which results in higher display fidelity (Ragan et al., 2015), blocks visual distractions from the real world, and enables users to rotate and move their heads in any direction to look around, allowing them to visually explore their virtual environment in six degrees of freedom (6DOF; resulting in a higher interaction fidelity [Ragan et al., 2015]). Tracked hand-held VR controllers are commonly used to interact with HMD VR systems, enabling natural gestures and controlling virtual objects in 6DOF.

In their systematic review, Abich et al. (2021) identified that VR training particularly enhances psychomotor performance, knowledge acquisition, and spatial ability. Coban et al.'s (2022) meta-analysis, comparing VR to computer-based learning environments, revealed that learning with VR is beneficial, yielding a small effect size. Similarly, the recent analysis of Conrad et al. (2024) identified an overall advantage of VR compared to other media types. Considering applications in aviation, Buttussi and Chittaro (2018) observed comparable knowledge retention in airplane evacuation training, regardless of whether it was delivered via desktop VR or HMD VR. For broader overviews of VR application opportunities in aviation, see Marron et al. (2024) and Torrence and Dressel (2022); for security-related applications, refer to de Armas et al. (2020) and Steven et al. (2023).

1.2. Time (pre- vs. post-training; after 2nd, 4th, 6th training)

The present study includes time as the second independent variable, considering its dual influence anticipated on the outcomes studied. First, repeated exposure to the assessment test could induce a learning effect (even without 3D object training, as first-time users become more familiar with the system and task), thereby influencing detection performance (Section 1.3). Thus, we focused on the potential differences in learning regarding the training media (interaction effect). Second, initial exposure to novel technology can elicit a novelty effect (e.g., Chen et al., 2016; Huang et al., 2021; Moos & Marroquin, 2010), influencing cognitive processing, risk-reward evaluations (Wells et al., 2010), and user satisfaction (Talukdar & Yu, 2024). A longitudinal perspective on how ratings of the training experience (Sections 1.4–1.7) change over time offers valuable insights beyond single-session comparisons.

1.3. Detection performance

Previous studies have demonstrated the benefits of 3D CT imaging over 2D X-ray imaging for object recognition (Hättenschwiler et al., 2019; Latscha et al., 2025; Muhl-Richardson et al., 2025; Parker et al., 2022). These findings align with those of object-recognition research (Tarr & Vuong, 2002; Vuong & Tarr, 2004), suggesting that exposure to 3D imagery, along with its enhanced visual information, results in richer visual representations (Hättenschwiler et al., 2019). Integrating photorealistic 3D models of prohibited items with their 3D CT images into 3D object training can further enhance recognition performance by enabling active exploration (Harman et al., 1999; James et al., 2001; Lee & Wallraven, 2013; Won et al., 2023) from multiple perspectives (Bingham & Lind, 2008; Lind et al., 2014) and fostering deeper mental representations (Palmiero et al., 2019) to leverage the current technology to provide true-to-scale photorealistic 3D objects enriched with motor (Jang et al., 2017; Koßmann et al., 2023) and sensory modalities (Ernst & Bülthoff, 2004; Mathias & von Kriegstein, 2023).

This multisensory approach allows for the mapping of motor interactions with visual perception, potentially improving object perception (Korisky & Mudrik, 2021) and attention (Gomez et al., 2018; Palmiero et al., 2019). Therefore, we propose the following hypotheses:

Hypothesis 1a. Desktop VR training leads to greater improvements in detection performance compared to no training.

Hypothesis 1b. HMD VR training leads to greater improvements in detection performance compared to no training.

Compared to desktop VR, HMD VR offers features that can enhance complex visual-spatial perception. First, HMD VR provides stereoscopic depth cues through binocular disparity (Scarfe & Glennerster, 2019). This affords users richer information regarding 3D object structure and spatial relationships (Cristino et al., 2015; Lee & Saunders, 2011; Oliver et al., 2018) compared to desktop VR. Desktop VR, in contrast, typically relies on monocular depth cues such as shading, texture (cf. Arguin et al., 2019), and motion parallax (Rogers & Graham, 1979). McIntire et al. (2014) analyzed 160 publications and found that 60% of the experiments reported an improvement with stereoscopic displays over traditional 2D displays. Stereoscopic displays' advantage was particularly found "for tasks involving the manipulation of objects and for finding/identifying/classifying objects" (p. 18). Second, the immersive quality of HMD VR, combined with natural 6DOF controller interaction (Rettinger & Rigoll, 2023), allows for grasping and object manipulation, facilitating intuitive exploration and embodied learning (Johnson-Glenberg, 2018). The integration of congruent sensory signals (i.e., visuomotor proprioceptive integration) is posited to foster a deeper comprehension of object properties (Ernst & Bülthoff, 2004; Mathias & von Kriegstein, 2023). To our knowledge, no prior studies have evaluated the advantages of HMD VR in the context of 3D object learning for 3D CT image interpretation. Given that HMD VR's superior depth cues are critical for visual-spatial interpretation and its support for natural, embodied object exploration, thereby fostering the creation of enriched mental models, we hypothesize that HMD VR training will yield greater improvements in detection performance than desktop VR training.

Hypothesis 1c. HMD VR training leads to greater improvements in detection performance compared to desktop VR training.

1.4. Immersion (Presence and Flow)

Immersion is a concept with multifaceted definitions (e.g., Chen et al., 2024) that refers to the degree to which a media environment engages a user's senses and cognition. Through a technical lens, immersion is understood as the objective level of a display's ability to deliver an "inclusive, extensive, surrounding and vivid illusion of reality to the senses of a human" (Slater & Wilbur, 1997, pp. 604–605). Aligned with Game Immersion Theory (Brown & Cairns, 2004), VR experiences can foster Presence (conceived as a feeling of "being there": e.g., Lee, 2004; Sanchez-Vives & Slater, 2005; Slater, 2003; see also Suzuki et al., 2023) and Flow (characterized by complete absorption in an activity, resulting in a loss of self-consciousness and distorted sense of time: Csikszentmihalyi, 1990; Nakamura & Csikszentmihalyi, 2014) which are key factors in creating engaging and impactful VR training applications (e.g., Shin, 2018; Wan & Chiu, 2023; Xu et al., 2024). Cummings and Bailenson's (2016) meta-analysis suggested a significant medium effect size of the immersion level (e.g., low-immersive vs. immersive VR) on presence. Other studies have found that HMD VR significantly enhances spatial presence compared to desktop VR (Klingenberg et al., 2020, after experiencing both media types; Shu et al., 2019) or 2D screens (De Witte et al., 2024; Makransky et al., 2019). These findings led us to propose the following hypothesis:

Hypothesis 2. Participants in the HMD VR group rate Presence significantly higher than participants in the desktop VR group.

However, the literature on flow in the context of VR media remains limited. For example, Kim and Ko (2019) found that HMD VR enhanced the flow experience of sports media consumers with HMD VR compared with 2D screens because of its greater vividness and interactivity. Although this finding suggests the benefits of HMD VR in sports media, it remains uncertain whether it can be generalized to the context of 3D object training. Similarly, literature on the time factor remains unclear. For instance, Huang et al. (2021) reported that presence did not decrease significantly over time, contrary to the expected novelty effect. Therefore, we explored the effects of time on presence and flow without proposing hypotheses.

1.5. Aspects of motivation

Intrinsic motivation is a key driver of learning and behavior, fostering engagement and curiosity (e.g., Di Domenico & Ryan, 2017; Froiland & Worrell, 2016; Ryan & Deci, 2017). The use of HMD VR has been shown to promote intrinsic motivation compared with less immersive methods (De Witte et al., 2024; Makransky et al., 2019; Makransky & Klingenberg, 2022; Zhao et al., 2020). Although research on medical VR applications has explored intrinsic motivation; e.g., Parkinson's disease (over 10 training sessions: Cikajlo & Peterlin Potisk, 2019), stroke rehabilitation (Höhler et al., 2023), and brain injury (Wenk et al., 2023); few studies have examined the underlying constructs of intrinsic motivation (see, Intrinsic Motivation Inventory [IMI]: Self-Determination Theory, 2024) with VR media in other domains, such as for serious games (de Vries et al., 2018) and language learning (Lin & Wang, 2021). This study focused on four constructs of the IMI.

First, interest and enjoyment (cf. Ainley & Hidi, 2014) are considered essential to a person's motivation to engage in a task and comprehend learning material. Several studies have found that experiencing learning content in VR HMDs is significantly more enjoyable than on 2D displays (Klingenberg et al., 2020, after experiencing both media types; Makransky et al., 2021; Meyer et al., 2019). Based on these findings, we propose the following hypothesis:

Hypothesis 3. Participants in the HMD VR group rate Interest/Enjoyment significantly higher than participants in the desktop VR group.

Second, perceived competence (feeling able and effective when performing a task: Peters et al., 2018; Ryan & Deci, 2017) is linked to the motivation to achieve mastery and overcome challenges. Although research on perceived competence with VR applications is limited (e.g., Arayaphan et al., 2022), three studies have indicated that training with VR HMD significantly enhances perceived competence compared to 2D presentations (Cikajlo & Peterlin Potisk, 2019; Sattar et al., 2020; Wenk et al., 2023). Based on these findings, we propose the following hypothesis:

Hypothesis 4. Participants in the HMD VR group rate Perceived Competence significantly higher than participants in the desktop VR group.

Third, we examine the perceived effort and importance invested in VR training. The Effort/Importance construct is integral to intrinsic motivation (Ryan & Deci, 2017), as it reflects investment of energy and the perceived value of a task. Although the literature reviewed did not provide definite evidence, two studies showed a trend toward higher ratings with HMD VR than with 2D displays (Cikajlo & Peterlin Potisk, 2019; Wenk et al., 2023). To investigate this further, we formulate the following hypothesis:

Hypothesis 5. Participants in the HMD VR group rate Effort/Importance significantly higher than participants in the desktop VR group.

Fourth, we explore perceived pressure and tension, which negatively impact intrinsic motivation (Kácovský et al., 2023; Ryan & Deci, 2017). Although HMD VR can experimentally induce stress (e.g., Hanshans et al., 2024), to our knowledge, its impact on perceived performance pressure compared to desktop VR is largely unexplored (other than Cikajlo & Peterlin Potisk, 2019 and Wenk et al., 2023, both of which produced no significant findings). Given the potential negative consequences of technology-induced stress, we conducted an exploratory analysis of the Pressure/Tension factor.

Although few studies evaluating time-related effects on intrinsic motivation, interest, or enjoyment with VR media did not provide significant evidence (Cikajlo & Peterlin Potisk, 2019; Huang et al., 2021), there is a recognized pattern where the novelty of a technology can initially increase feelings of interest and enjoyment (Ainley & Hidi, 2014, for a neuroscientific discussion). Such a novelty effect (Moos & Marroquin, 2010; see also Talukdar & Yu, 2024, for perceived novelty with VR) may diminish over time, a phenomenon supported by the concept of affective habituation (Leventhal et al., 2007) and the four-phase model of interest development (Renninger & Hidi, 2015). For example, Chen et al. (2016) evaluated a multi-user desktop VR learning application with middle school students over 10 days: they found an overall decline in students' Interest/Enjoyment, measured across three waves, indicating a novelty effect. Based on this, we propose the following hypothesis:

Hypothesis 6. Interest/Enjoyment in VR training significantly decreases over the course of six training sessions.

However, given the sparse literature on the novelty effect (apart from a novelty effect in relation to familiarization with VR's usability, e.g., Miguel-Alonso et al., 2023, 2024), the specific training session at which Interest/Enjoyment ratings decline remains uncertain. Concerning other motivational aspects, due to the lack of conclusive findings on the dependence of temporal effects, we conducted an exploratory analysis to understand their progression across multiple training sessions.

1.6. Cognitive Load

The Cognitive Load Theory (Sweller et al., 2011) posits that human cognitive processing is constrained by limited working memory. Excessive task demand induces cognitive overload, which hinders information processing and knowledge acquisition (cf. Chen et al., 2021). Dan and Reiner (2017, 2018) showed that learning to fold origami with stereoscopic 3D displays resulted in a lower cognitive load than learning with 2D displays (see also Sagehorn et al., 2024). Other studies found no significant difference in cognitive load between HMD VR and 2D screen media (De Witte et al., 2024, by learning factual knowledge; Parong & Mayer, 2021b, in a history lesson; Ristor et al., 2023, for fire safety training), or even reported higher cognitive load in HMD VR experiencing a 360° video (Breves & Stein, 2023), in a surgical simulation (Frederiksen et al., 2020), in a science lab simulation (Makransky et al., 2019), or in a classroom compared to a slideshow (Parong & Mayer, 2021a), due to its claimed sensory richness and interactivity (see also Han et al., 2021).

Regarding the effect of multiple training sessions, the literature on the influence of practice (cf. Smith & Scarf, 2018) and the positive effect of prior knowledge on learning in VR (e.g., Delgado & Mayer, 2025; Meyer et al., 2019; Petersen et al., 2020) could lead to the assumption that the cognitive load of repeated VR training decreases over time (see also Andersen et al., 2016). Relativizing these lines of research, Howard and Lee (2020) found no significant effects of habituation on the learning outcomes of VR. Given these inconsistent findings on the potential effects of training media and time, we did not propose hypotheses on cognitive load. However, because it is important to consider cognitive load when designing technology-assisted training (cf. Sweller, 2020) and to promote a better understanding in the context of VR, we analyzed this dependent variable exploratively.

1.7. Technology acceptance

The core constructs of the Technology Acceptance Model (TAM3; Venkatesh & Bala, 2008; see also Davis, 1989), namely Perceived Usefulness (PU; the degree to which a person believes a system enhances their performance), Perceived Ease of Use (PEOU; the degree to which a person believes a system is free from effort), and Behavioral Intention (BI; a predictor of technology usage), allow a structured evaluation of user acceptance and adoption of this novel application. The first two (PU and PEOU) relate to the functions and features of the application, whereas the third (BI) refers to its effects on the user. Research on VR has shown that PEOU influences PU, and both influence BI (e.g., Fussell & Truong, 2022; Thohir et al., 2023; Villena-Taranilla et al., 2023; see also Wang et al., 2024). To the best of our knowledge, no previous studies have compared PU and PEOU with different VR media, or the temporal evolution of PU and PEOU over multiple training sessions. Therefore, we investigated the effects of training media and time on PU and PEOU. However, recent research has emphasized the strong link between hedonic perceptions (e.g., enjoyment) and the intention to use (Fussell & Truong, 2022; Lee et al., 2019; Manis & Choi, 2019; Oyman et al., 2022; Shamy & Hassanein, 2017; Syed-Abdul et al., 2019; Xu et al., 2023).

Based on these indications and our assumption in Hypothesis 3, which posits that HMD VR will result in higher Interest/Enjoyment ratings than desktop VR, we suggest the following hypothesis:

Hypothesis 7. Participants in the HMD VR group rate BI significantly higher than participants in the desktop VR group.

Building on the established strong link between motivational factors and their positive influence on BI, as well as Hypothesis 6, which suggests that Interest/Enjoyment decreases over the six training sessions, we conclude the following hypothesis:

Hypothesis 8. In VR training, BI significantly decreases over the course of six training sessions.

2. Methods

2.1. Participants

We determined the number of participants in the two experimental groups based on an a priori power analysis (Faul et al., 2007; medium effect size, with two groups, three measurements, an alpha error of .05, and power of .85). The participants were psychology students ($n = 50$; age: $M = 26.76$ years, $SD = 4.99$, range = 22–43 years; gender: 68% female, 32% male [0% identified as "other"]). They enrolled voluntarily in the study (informed of the airport security context and evaluating VR as a training medium). This study complied with the American Psychological Association Code of Ethics and was approved by the Institutional Review Board of the FHNW School of Applied Psychology, University of Applied Sciences and Arts Northwestern Switzerland (reference number: EAaFE2019007). None of the participants had professional experience with 3D CT technology for airport security, while two-thirds had previous experience with VR (mobile VR only, $n = 6$; HMD VR only, $n = 13$; both types, $n = 14$). All participants who started the study also completed it, and each received equal monetary compensation for their 7.5 hours of participation at the end of the study.

2.2. Design

This study used two research designs. First, we evaluated the performance using a 2 (training media as between-subjects factor: desktop VR, HMD VR, control group not undergoing training; pairwise comparisons) × 2 (time as within-subjects factor: pre-training, post-training) mixed design. Second, we evaluated the ratings of the training experience using a 2 (training media as a between-subjects factor:

desktop VR, HMD VR) × 3 (time as a within-subjects factor: after the 2nd, 4th, 6th training) mixed design.

2.3. 3D object training and apparatus

The training stimuli consisted of 40 items that were prohibited in cabin baggage and were divided into four categories with ten objects each: guns, gun parts, knives, and others (Figure 1). In cooperation with customs and police authorities and the Center for Adaptive Security Research and Applications (CASRA, 2024), each physical object was digitized using high-resolution techniques (Figure 2) to create photorealistic 3D models using Space Spider and Eva scanners (Artec, 2024) and 3D CT recordings using a HI-SCAN 6040 CTiX (Smith Detection, 2024), which were then virtually aligned. The 3D CT images of the prohibited items were merged into 3D CT recordings of real cabin baggage trays using a realistic algorithm by CASRA, resulting in 40 3D CT images of bags containing a prohibited item

Figure 1. Examples of training stimuli (prohibited items) used in the study.
Note: Guns: pistol and revolver. Gun parts: magazine and revolver drum. Knives: knife in the sheath and folding knife. Other: brass knuckles and pepper spray.

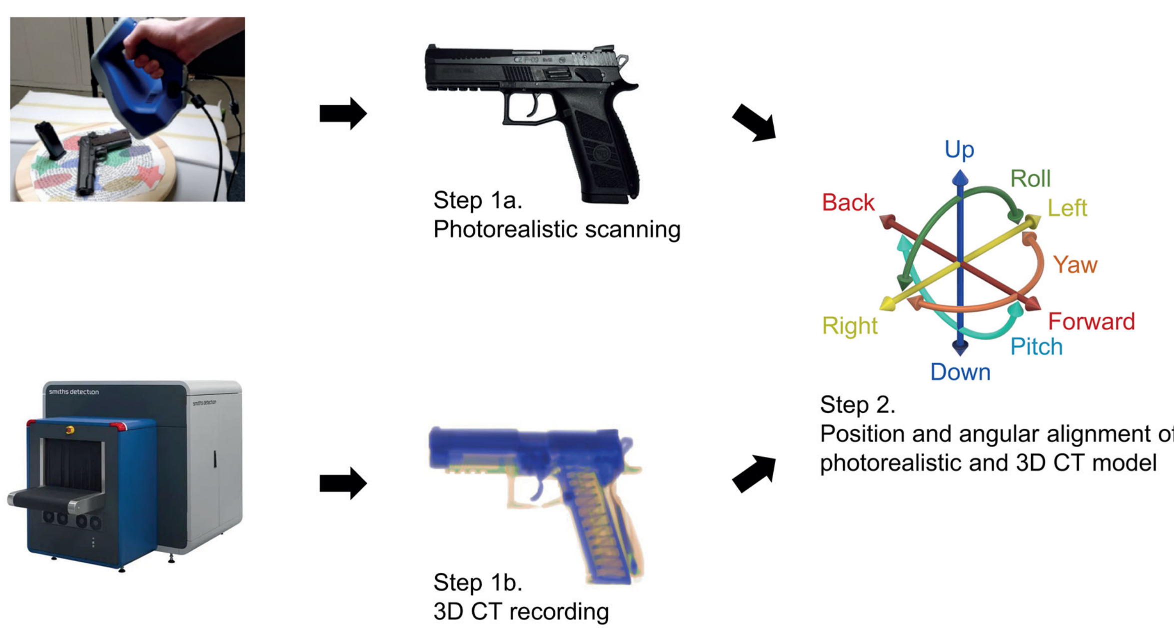

Figure 2. Digitalization process for photorealistic scans and 3D CT recordings.
Note: The physical objects were digitized using 3D scanners (Step 1a: scanning, merging of point clouds, editing [e.g., removing identification numbers on objects], and converting to a 3D model) and 3D CT technology (Step 1b: recording, editing, and removing artifacts, color mapping, and file conversion). Both digital models were then aligned in six degrees of freedom (6DOF), and a rotation point was set in the 3D CT image using software developed specifically for this purpose (Step 2).

(target-present images). Furthermore, 40 3D CT recordings of trays without prohibited items were included in the training (target-absent images).

We developed a single-player 3D object training application designed for seated use, utilizing Unity, 2021.1.0f1 (Unity, 2021). The application was compiled into two versions (desktop VR and HMD VR) both of which presented the same virtual environment and interaction features without auditory elements (Figure 3).

The 3D object training stimuli were organized into ten blocks, each including four prohibited items (one from each category) to learn, followed by a decision task involving eight 3D CT baggage images. To learn about the visual features of the prohibited items, participants could rotate, move, and zoom in on the photorealistic object (ensuring continuous perspective change, e.g., Bingham & Lind, 2008). The virtual screen in the background displays the perspective (rotation, zoom) of the 3D CT image synchronized with the current view of the photorealistic object in the foreground (Figure 3).

The participants were instructed to memorize the visual features of the training object for subsequent recognition in the 3D CT baggage images. Participants could proceed to the next object after exploring each object for at least 15 s (but not more than 90 s; self-paced and system-controlled). Following this, eight 3D CT baggage images were displayed in sequence: four of these images contained a prohibited object learned in the present block, and four baggage images did not contain a prohibited item. Adapted from the interaction concept with prohibited items, participants could interact with a colored cube (instead of a photorealistic object; Figure 4(a)) to rotate, zoom, and inspect the 3D CT baggage image before deciding whether the bag contained a prohibited item (e.g., by clicking on the OK button).

In addition to searching for prohibited items, the participants were instructed to try to identify the bag's regular content (also called everyday objects; cf. Sterchi et al., 2017). The same minimum and maximum decision times (15 s and 90 s, respectively; self-paced and system-controlled) were applied to

Figure 3. Interface of the 3D object training application (presenting a gun as prohibited item).
Note: Users interacted with the photorealistic 3D object (by rotating, moving, and zooming), and the 3D CT image on the screen moved accordingly (rotation, movement, and zoom). The user interface on the virtual table provides the following functions (from left to right): a clock showing the current time (the green segment visualizes the 20-minute period of the training session); a 20-sided cube with a colored indication of the object orientation already viewed (the cube rotated according to the current object orientation while its sides changed color depending on the time spent on the corresponding orientation, analogous to a 3D heatmap); a button to reset the 3D CT image enhancement functions: opacity slider (bottom), organic material enhancement, organic material stripping, black and white view, and negative colors; on the right side, context-sensitive buttons (e.g., to continue).

this task. Figure 4(b) shows an example of the feedback on the decision provided after each image, considering aspects of gamified learning (cf. Landers, 2014; Sailer & Homner, 2020), self-assessment (cf. Fiorella & Mayer, 2016; Yan et al., 2023), and building self-efficacy (cf. Kovari & Katona, 2023). The related data were not used for further analyses. Each training session lasted approximately 20 min and ended with a completed block (system-controlled). The composition of each block was randomized (random sampling without replacement: items per block, order of items, and baggage). The block sequence was restarted once all ten blocks were completed within the six training sessions.

The desktop VR application ran on laptops equipped with an Intel i7-7700HQ processor, NVIDIA Quadro P4000 graphics processing unit, 16-gigabyte random access memory, and 64-bit (Windows 10). The display was a 24-inch LCD monitor (1920 × 1200 pixel resolution) placed on a desk and partially enclosed with pinboards to minimize visual distraction (Figure 5(a)). Participants interacted with the training application using a standard computer mouse to interact with the photorealistic object (left mouse button: drag to rotate; right mouse button: drag to move; mouse wheel: change in distance to the viewer) and activate buttons on the virtual table.

In the HMD VR training condition (Figure 5(b)), the participants experienced the training application on a Meta Quest 2 (1832 × 1920 pixels per eye) tethered to a VR-ready laptop (equipped with an Intel i7-9850H processor, NVIDIA Quadro RTX 5000 graphics processing unit, 32 gigabytes of random access memory, and 64-bit Windows 10 in Meta Link mode) running the HMD VR version of the training application. Compared to the desktop VR condition, the HMD VR headset allowed for

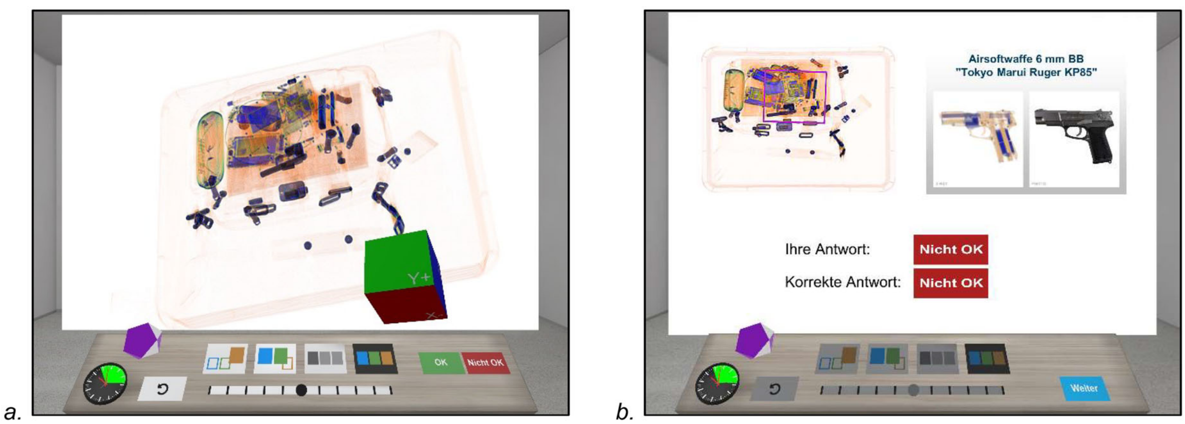

Figure 4. Visual inspection task in the 3D object training (desktop VR version; airsoft gun).
Note: (a) Users interacted with the colored cube (by rotating, moving, and zooming) while the 3D CT image followed the cube orientation (rotation of view and size). (b) Feedback to users after a correct decision ("your answer: not OK; correct answer: not OK").

Figure 5. Training settings with the 3D object training during the experiment.
Note: (a) Participants were trained with desktop VR using a computer mouse for interaction. (b) Participants training with HMD VR used tracked handheld VR controllers for interactions.

stereoscopic perception of the classroom-like environment and the photorealistic 3D object, enabling participants to explore the virtual world in 6DOF freely. To interact with the training application, users in the HMD VR condition can grab the photorealistic object to move it to any desired viewing orientation and position in 6DOF (the virtual controller was hidden while holding an object) and touch the buttons on the virtual table with Meta Quest 2 Touch controllers. To accommodate handedness and mitigate hand rotation constraints (cf. Sasaoka et al., 2019), users can interact with an object using both hands similarly and temporarily place objects on the virtual table for retrieval. The functions of both VR controllers were identical.

2.4. X-ray image interpretation test and apparatus

We used an X-ray image interpretation test to assess participants' detection performance. The test stimuli were created using the same process as we used to create the training stimuli, but without photorealistic objects. The test consisted of 200 trials with 40 target-present images (bags with one prohibited item) and 160 target-absent images (bags without prohibited items), resulting in a target prevalence rate of 20%. Prohibited items used in the training were not included in the test. However, with a focus on learning transfer (cf. Lintern et al., 2025), each test stimulus resembled a prohibited item used in training regarding the object type, size, and material composition (cf. Yang & Zelinsky, 2009). The X-ray image interpretation test was conducted using the test functionality of X-ray Tutor version 4 (XRT4; CASRA, 2024). Testing was conducted on the same type of laptops as those used in the training and with 24-inch LCD monitors (with a resolution of 1920 × 1200 pixels).

2.5. Procedure

Figure 6 illustrates the different phases of this study. At the beginning of the pre-training phase, all participants were briefed on the study's procedures, objectives, and right to discontinue the study at any time without negative consequences. The 50 participants were then randomly assigned to one of the three groups (desktop VR, HMD VR, or control group) by drawing a user pin from a pool containing an equal number of pins for each group (up to eight participants attended an assessment session simultaneously). Hence, the group sizes were as follows: *desktop VR*, $n = 16$; *HMD VR*, $n = 17$; and *control group*, $n = 17$.

The participants then completed a survey that included questions on demographics, lecture courses attended before testing, and their experiences with 3D CT and VR as control variables (see Section 3.2). The X-ray image interpretation test started with an e-learning explanation of the task (identifying 3D CT images of cabin baggage that contained a prohibited item of one of the four categories), target-present prevalence, and the relevant functions of the application.

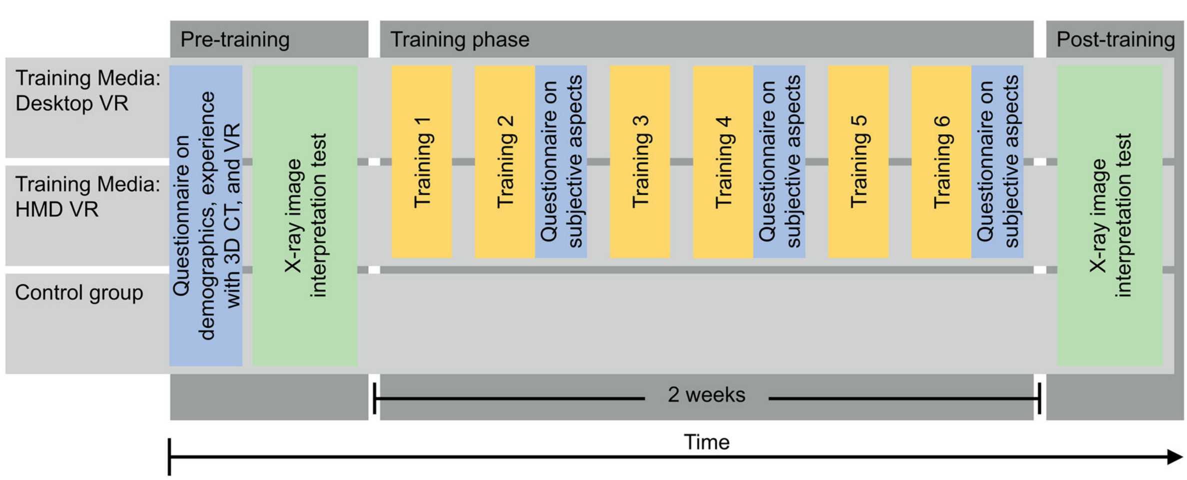

Figure 6. Illustration of the different phases of the study.

To familiarize the participants with the knobology (cf. Biggs et al., 2018; Kramer et al., 2019) and task, they conducted 16 trials with 3D CT images (eight targets present and eight targets absent) and direct feedback on their responses. The X-ray image interpretation test was then administered (200 trials with 3D CT images, as explained above, with no feedback and a maximum decision time of 30 s per image). To avoid effects of fatigue during the X-ray image interpretation test, the test was divided into two blocks of 100 trials. The block order was randomized across participants. Each block took about 35 min, and the participants took a 10-minute break between the two blocks. Taking into account the results of Buser et al. (2020, 2023) and Latscha et al. (2024), this approach should be sufficient to avoid fatigue effects. At this point, the pre-training phase was complete (Figure 6).

At the beginning of the training phase (Figure 6), we announced the individual group allocation defined by the user pin drawn in the pre-training phase (as explained above). While the control group participants were dismissed, the participants of the two training groups were guided to their separate training rooms after a 10-minute break, where they received a briefing on the 3D object training application, including how to use their training media and how to clean the equipment after use. With access to their media-specific training room (for desktop VR and HMD VR training, each equipped with six training stations), participants trained independently for the subsequent two weeks (six training sessions, with a system-controlled maximum of two training sessions per day and a break of at least 30 min between sessions).

The 3D object training application automatically administered surveys to rate the training experience (immersion, motivation, cognitive load, technology acceptance, and simulator sickness) after the 2nd, 4th, and 6th training session. After two weeks, all participants were assessed again using the X-ray image interpretation test. For the following two weeks, both training groups could try out the other media. Participants in the control group participated in subsequent 3D object training experiences and interviews that were not part of the present study (we evaluated additional gamification and auditive features of the HMD VR application that were not reported in this publication).

2.6. Measures

We used the X-ray image interpretation test described above before and after 3D object training to assess training effectiveness using sensitivity in terms of d' and d_a with a slope parameter of 0.5, HR, and FAR (Hautus et al., 2021).

$$HR = \frac{Hits}{Hits + Misses}$$

$$FAR = \frac{False\ alarms}{False\ alarms + Correct\ rejections}$$

$$d' = z(HR) - z(FAR)$$

$$d_a = \left(\frac{2}{1+s^2}\right)^{\frac{1}{2}} \times \left[z(HR) - sz(FAR)\right]$$

Several studies have found that d_a with a slope parameter of 0.5–0.6 is more valid than d' for X-ray image inspection (Godwin et al., 2010; Sterchi et al., 2019; Van Wert et al., 2009; Wolfe et al., 2007; Wolfe & Van Wert, 2010). Therefore, we followed the recommendation of Sterchi et al. (2019) to calculate d_a with a slope parameter of 0.5 in addition to d'. The response tendency (criterion) was not analyzed because of the unclear interpretation of this measure across varying sensitivity levels (Hautus et al., 2021). The RTs were measured as the time from image onset to the decision of participants using the means of the target-present RT and target-absent RT trials.

Table 1 lists the scales used to assess the ratings of training experience over the course of the six training sessions. Immersion (Presence, Flow) was assessed using the Total Immersion Subscale of the Augmented Reality Immersion (ARI; Georgiou & Kyza, 2017) questionnaire. The ARI roots in Game Immersion Theory (Brown & Cairns, 2004) and has been adapted to serious educational games (Cheng et al., 2015). Participants' motivation was assessed using the IMI subscales, which have their roots in Self-Determination Theory (Ryan & Deci, 2017). The IMI scales have been repeatedly validated (e.g.,

Table 1. Measures of ratings of the training experience used in the current study.

Source	Scales and subscales	Items
Georgiou and Kyza (2017)	Augmented Reality Immersion – Total Immersion	
	• Presence: feeling of being there	4
	• Flow: feeling that the activity is all that matters	3
Ryan (1982), Ryan et al. (1983)	Intrinsic Motivation Inventory	
	• Interest/Enjoyment: How much participants inherently enjoy and find pleasure in an activity itself	7
	• Perceived Competence: How effective individuals feel when they are performing a task	6
	• Effort/Importance: The dedication and energy a person puts into an activity as they consider it valuable and worthwhile	5
	• Pressure/Tension: The degree of anxiety or stress that a person experiences due to feeling pressured to perform well in an activity	5
Paas (1992)	• Cognitive Load: Overall mental effort invested in the task. "My invested mental effort was … "	1
Venkatesh and Bala (2008)	Technology Acceptance Model	
	• Perceived Usefulness: Belief of a system enhancing performance	4
	• Perceived Ease of Use: Believe a system is free from effort	4
	• Behavioral Intention: Predictor of technology usage	3

Deci et al., 1994; McAuley et al., 1989; Monteiro et al., 2015) and applied in VR-related studies (e.g., Cikajlo & Peterlin Potisk, 2019; de Vries et al., 2018; Lin & Wang, 2021; Wenk et al., 2023). Cognitive Load was assessed using a single-item subjective rating scale (Paas, 1992), which is one of the most used subjective measures of cognitive load (Korbach et al., 2017; Mutlu-Bayraktar et al., 2019). It has been demonstrated to be a reliable and valid measure of overall cognitive load (e.g., Szulewski et al., 2017) and has been widely applied (e.g., Skulmowski, 2022; Sweller et al., 2019). To assess the participants' technology acceptance, we used the three core scales of the well-established TAM3 (Venkatesh & Bala, 2008).

To control for the negative effects of visually induced simulator sickness, we used a single item from the Fast Motion Sickness Scale (Keshavarz & Hecht, 2011), allowing an efficient measurement of simulator sickness and capturing changes over time (Somrak et al., 2021). The participants rated their feelings of discomfort during the 3D object training that they had completed. They were instructed to focus on nausea, general discomfort, and stomach problems and to ignore any other possible distorting effects, such as nervousness, boredom, or fatigue. We added an open-ended question asking those who felt discomfort to describe it. All scales were rated on a seven-point Likert scale ranging from (1) *strongly disagree* (Cognitive Load: *very low*; Simulator Sickness: *no discomfort*) to (7) *strongly agree* (Cognitive Load: *very high*; Simulator Sickness: *frank discomfort*).

All survey items were administered in German (see Appendix A for the disclosed items). For the scales used to assess immersion, cognitive load, technology acceptance, and simulator sickness, we followed the translation procedures suggested by Beaton et al. (2000). The items used to measure motivation were taken from Self-Determination Theory (2024), although some items were slightly reworded (e.g., "this task" was changed to "this training" and altered to past tense).

2.7. Data analyses

We aggregated the data from the application's log files using Python and R; next, we analyzed them with the statistical software JAMOVI (Jamovi, 2023, v. 2.3.28) with the alpha set to .05. Descriptive plots were generated using the ggplot package (Wickham, 2016) in R, with error bars representing the standard error (*SE*) for each condition. We adjusted for multiple *t*-tests in *post hoc* analyses using the Bonferroni-Holm correction (Holm, 1979). In case Mauchly's sphericity test was significant, we applied Greenhouse-Geisser correction for $\varepsilon < .75$ and Huynh-Feldt correction for $\varepsilon \geq .75$ (Girden, 1992, p. 49). The effect sizes of all analyses of variance (ANOVAs) are reported using partial eta-squared (η_p^2) and interpreted for between-subjects effects with .01, .06, and .14 as small, medium, and large effects, respectively (Cohen, 1988).

To compare desktop VR with the control group, HMD VR with the control group, and desktop VR with HMD VR in terms of detection performance, we conducted 2 (training media) × 2 (time: pre-and post-training) mixed ANOVA, with training media as a between-subjects factor and time as a within-subjects factor. Significant interactions indicate a disproportional improvement of one of the analyzed groups. As an additional indicator of practical relevance, we report the groups' means and standard deviations of the improvement (calculated as post-training score - pre-training score; reported as M_{diff}, SD_{diff}) and between-subjects Cohen's d. Cohen's d is interpreted as small ($d = 0.20$), medium ($d = 0.50$), and large ($d = 0.80$) based on Cohen (1988).

For the ratings of the training experience, we used 2 (training media: desktop VR, HMD VR) × 3 (time: after the 2nd, 4th, 6th training) mixed ANOVAs with training media as between-subjects and time as within-subjects factors. If there were statistically significant effects of the training media on the questionnaire data, the mean and standard deviation of the ratings aggregated over the three measurement times were reported. The significant main effects of time were followed up by within-group simple effects analyses (t-tests). If we only detected an interaction effect, we followed up with one-way repeated-measures ANOVAs for both training media; if significant, we further conducted t-tests within the training media. As an indicator of practical relevance, we also report between-subjects Cohen's d for significant effects.

3. Results

We analyzed the data from all participants ($n = 50$), and no data were excluded.

3.1. Psychometrics

The reliability of the multi-item ratings of training experience is presented in Table 2 (according to DeVellis & Thorpe, 2022, p. 130: between .70 and .80 = respectable; between .80 and .90 = very good). Although the Perceived Competence and PEOU scales initially exhibited lower reliability, they improved over time and reached very good levels by the third measurement (Cronbach's α = .81 for both). This pattern of reliability improvement was observed for most scales, indicating that participants' familiarity with the training procedure and items reduced measurement error, contributing to improvements in internal consistency after the 6th training (Cronbach's α ranging from .72 to .94). The BI scale showed very high internal consistencies (Cronbach's $\alpha \geq .94$ across all three measurements), which may indicate item redundancy (DeVellis & Thorpe, 2022, p. 130). Given the evolution of ratings over time and the scales' widespread use in their original form, no changes were made to the original constructs and items.

3.2. Control variables

To rule out accidental sample differences, we assessed whether three randomly created participant groups differed significantly in terms of demographics or training time. A one-way between-subject

Table 2. Psychometric properties of the scales and subscales.

	Time: after											
	2nd Training				4th Training				6th Training			
Scales	*M*	*SD*	Range	α	*M*	*SD*	Range	α	*M*	*SD*	Range	α
Augmented Reality Immersion (Georgiou & Kyza, 2017)												
Presence	3.36	1.48	10.25–60.50	.82	3.05	1.46	10.00–60.75	.86	2.99	1.57	10.00–60.00	.87
Flow	4.42	1.69	10.33–70.00	.84	3.75	1.62	10.00–70.00	.86	3.94	1.57	10.00–70.00	.90
Intrinsic Motivation Inventory (Self-Determination Theory, 2024)												
Interest/Enjoyment	5.34	1.01	2.86–7.00	.87	4.83	1.11	2.57–6.57	.92	4.85	1.10	1.86–6.86	.89
Perceived Competence	4.89	0.60	3.83–6.50	.54	4.83	0.80	3.33–6.67	.85	5.16	0.69	3.83–7.00	.81
Effort/Importance	5.12	1.03	2.80–7.00	.78	4.84	1.10	2.40–7.00	.81	5.02	1.20	2.20–7.00	.86
Pressure/Tension	2.45	1.23	1.00–5.80	.85	2.44	1.21	1.00–6.00	.86	2.23	1.01	1.00–5.20	.76
Cognitive Load (Paas, 1992)	4.36	1.14	2.00–6.00	–	4.12	1.36	2.00–7.00	–	3.91	1.38	1.00–7.00	–
Technology Acceptance Model (Venkatesh & Bala, 2008)												
Perceived Usefulness	5.48	1.16	2.25–7.00	.85	5.82	0.79	4.00–7.00	.71	5.83	0.93	3.50–7.00	.72
Perceived Ease of Use	5.70	0.91	3.50–7.00	.69	5.86	0.83	4.25–7.00	.61	5.97	0.91	3.00–7.00	.81
Behavioral Intention	4.37	1.92	1.00–7.00	.94	4.64	1.99	1.00–7.00	.95	4.84	2.02	1.00–7.00	.94

Note: $n = 33$. α: Cronbach's α; no Cronbach's α was computed for Cognitive Load, as it contains only one item.

ANOVA yielded no significant difference in age between the conditions, $F(2, 47) = 0.42$, $p = .660$, $\eta_p^2 = 0.02$. Furthermore, χ^2 tests showed no significant differences regarding the proportion of women and men, χ^2 (2, $n = 50$) = .33, $p = .849$, their current education level, χ^2 (2, $n = 50$) = .52, $p = .772$, and experience with VR (mobile VR or with HMD), χ^2 (2, $n = 50$) = 4.54, $p = .104$. As data collection for detection performance took place on regular class schedule, we compared the groups attending lessons on the same day before conducting the X-ray image interpretation tests to control for the effects of possible fatigue and attention differences. One-way ANOVAs revealed no significant difference in preceding lessons between the three groups (desktop VR, HMD VR, and control group) in both the pre- and post-training tests, $F(2, 47) = 0.90$, $p = .414$ and $F(2, 47) = 0.34$, $p = .716$, respectively.

Because we expected a learning effect when conducting the X-ray image interpretation test with novices twice, we aimed to keep the two-week interval (overall $M = 14.10$ days, $SD = 0.77$) consistent between the two assessments, taking into account participants' availability. One-way ANOVA did not reveal a significant difference in the interval between the pre- and post-training X-ray image interpretation tests between the three groups, $F(2, 47) = 0.19$, $p = .831$. Because the duration of each training session varied slightly owing to the system-controlled completion of a block at the end of the training sessions, we evaluated the total training time for both training groups. A t-test revealed no significant difference between the two training media in total training time (desktop VR: $M = 118.95$ min, $SD = 6.41$; HMD VR: $M = 116.66$ min, $SD = 4.18$), $t(25.55) = 1.21$, $p = .239$, with all participants completing six training sessions. The self-paced viewing duration of each item or baggage (four prohibited items and eight baggage items, each between 15 s and 90 s) led to varying block durations. The t-test showed no significant difference between the groups in the total number of blocks trained over all six training sessions (desktop VR: $M = 24.81$ blocks, $SD = 5.10$; HMD VR: $M = 25.59$ blocks, $SD = 3.57$), $t(26.70) = -0.50$, $p = .619$. Finally, we examined whether the training media or time affected Simulator Sickness. A mixed ANOVA (Table 3) of the overall low ratings revealed no significant main effects of training media ($p = .294$), time ($p = .154$), or an interaction effect ($p = .178$).

The open response revealed that one participant in the HMD VR group reported multiple symptoms of simulator sickness at all three trainings surveyed, which were consistent with the quantitative ratings after the 2nd training (6/7), 4th training (5/7), and 6th training (5/7). Because the participant completed the study (including all six training sessions) without expressing a desire to discontinue or contact the experimenters, we included this person's data for analysis.

3.3. Effects of training media on detection performance

We used two-way ANOVAs to evaluate the training media (permutated for the three pairings; Table 4) on the effectiveness of object training in terms of sensitivity d' (Figure 7), d_a (Figure 8), HR (Figure 9), FAR (Figure 10), target-present RT (Figure 11), and target-absent RT (Figure 12).

First, we explored the differences in detection performance between the desktop VR and control group and identified the interaction effects of training media and time on d' and d_a. The ANOVAs yielded a significant interaction effect for d_a ($p = .017$), indicating a significantly greater improvement with desktop VR compared to not receiving training, but not for d' ($p = .191$). The improvement on d_a was larger for the desktop VR ($M_{diff} = 0.48$, $SD_{diff} = 0.29$) than for the control group ($M_{diff} = 0.24$, $SD_{diff} = 0.26$, Cohen's $d = 0.88$). The effect size, Cohen's d, indicates that the mean performance of the desktop VR group surpassed that of the control group by 0.88 standard deviations – signifying a

Table 3. Means, standard deviations, and two-way ANOVA statistics for Simulator Sickness.

	TM:							
	Desktop VR		HMD VR		ANOVA			
Variable	M	SD	M	SD	Effect	F ratio	df	η_p^2
Simulator Sickness								
Time: after 2nd training	1.19	0.40	1.82	1.38	TM	1.14	1, 31	.04
Time: after 4th training	1.44	1.09	1.53	1.18	Time	1.98	1.68, 62	.06
Time: after 6th training	1.13	0.34	1.35	1.00	TM × Time	1.82	1.68, 62	.06

Note: $n = 33$; violation of the sphericity assumption ($\varepsilon = 0.75$), Huynh-Feldt correction applied.
ANOVA: analysis of variance; TM: training media; VR: virtual reality; HMD: head-mounted display.

Table 4. Means, standard deviations, and two-way ANOVA statistics for detection performance.

	TM:							ANOVAs					
	Desktop VR		HMD VR		Control group			Desktop VR vs. control group		HMD VR vs. control group		Desktop VR vs. HMD VR	
Variable	*M*	*SD*	*M*	*SD*	*M*	*SD*	Effect	F (1, 31)	η_p^2	F (1, 32)	η_p^2	F (1, 31)	η_p^2
Sensitivity *d′*							TM	**5.64***	**.15**	**4.38***	**.12**	0.11	.00
Time: pre-training	1.55	0.41	1.37	0.34	1.34	0.30	Time	**55.42*****	**.64**	**87.52*****	**.73**	**91.78*****	**.75**
Time: post-training	2.06	0.35	2.16	0.43	1.70	0.46	TM × Time	1.79	.05	**12.64****	**.28**	**4.25***	**.12**
Sensitivity d_a							TM	**9.30****	**.23**	**4.30***	**.12**	0.75	.02
Time: pre-training	1.29	0.30	1.12	0.34	1.10	0.33	Time	**58.09*****	**.65**	**80.90*****	**.72**	**114.31*****	**.79**
Time: post-training	1.78	0.26	1.79	0.36	1.34	0.41	TM × Time	**6.36***	**.17**	**17.50*****	**.35**	2.85	.08
Hit rate							TM	**7.13***	**.19**	1.68	.05	2.08	.06
Time: pre-training	.69	.07	.65	.11	.65	0.11	Time	**13.40*****	**.30**	**15.62*****	**.33**	**49.57*****	**.62**
Time: post-training	.78	.07	.75	.07	.66	0.10	TM × Time	**7.64****	**.20**	**9.59****	**.23**	0.24	.01
False alarm rate							TM	0.24	.01	0.80	.02	0.12	.00
Time: pre-training	.16	.10	.18	.11	.18	0.09	Time	**18.74*****	**.38**	**34.44*****	**.52**	**22.60*****	**.42**
Time: post-training	.11	.08	.08	.04	.12	0.08	TM × Time	0.17	.01	1.79	.05	2.26	.07
Target-present RT [s]							TM	0.05	.00	0.03	.00	0.00	.00
Time: pre-training	15.54	2.89	16.10	4.21	15.61	2.08	Time	**115.77*****	**.79**	**165.41*****	**.84**	**99.92*****	**.76**
Time: post-training	10.87	2.09	10.28	2.20	10.49	2.17	TM × Time	0.25	.01	0.67	.02	1.20	.04
Target-absent RT [s]							TM	1.99	.06	0.27	.01	0.47	.01
Time: pre-training	19.56	3.47	19.68	5.16	19.89	3.20	Time	**60.52*****	**.66**	**94.59*****	**.75**	**29.91*****	**.49**
Time: post-training	16.64	3.85	14.85	3.36	13.46	2.99	TM × Time	**8.54****	**.22**	1.91	.06	1.82	.06

Note: $n = 33$. ANOVA: analysis of variance; TM: training media; VR: virtual reality; HMD: head-mounted display; RT: reaction time.
Bolded values indicate statistical significance ($^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$).

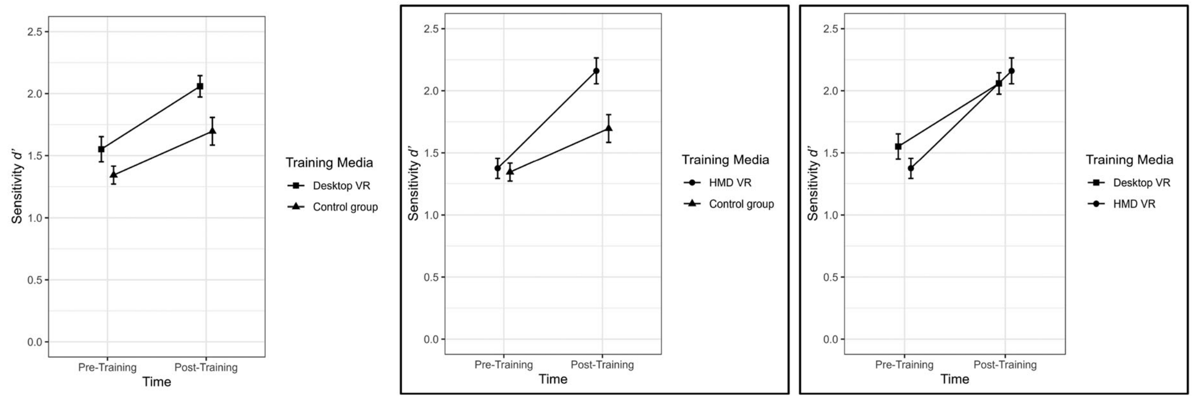

Figure 7. Interaction plots for sensitivity d'.

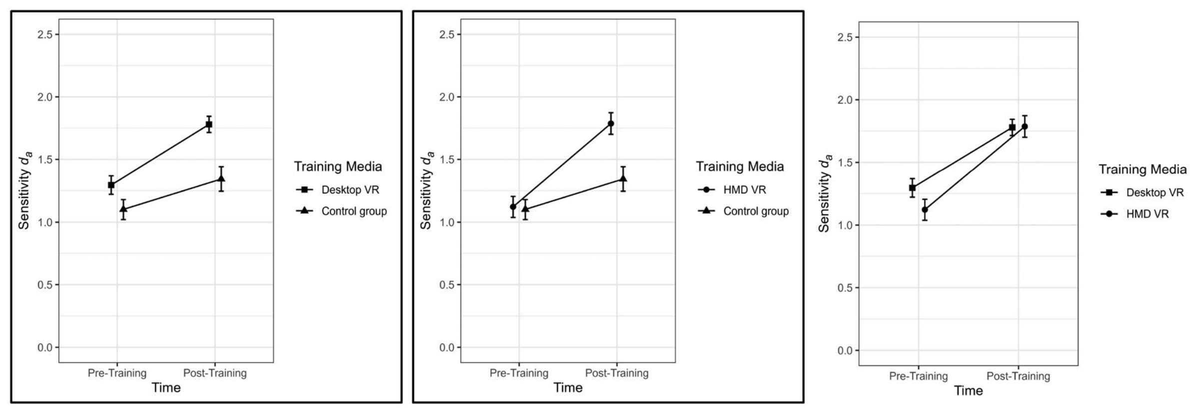

Figure 8. Interaction plots for sensitivity d_a.

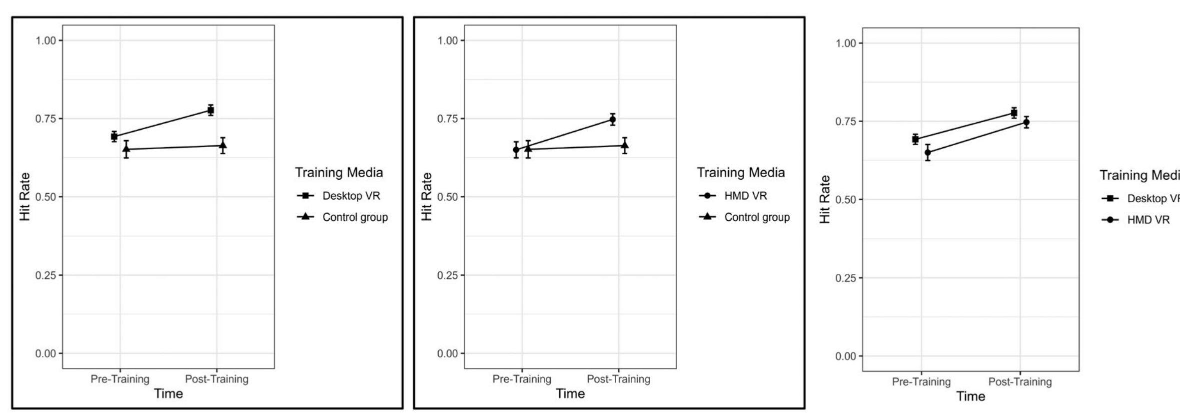

Figure 9. Interaction plots for hit rate.

substantial practical difference between the groups. The ANOVA on HR yielded a significant interaction, pointing to a disproportionate improvement in the desktop VR condition compared to the control group ($p = .010$): The desktop VR group increased the HR ($M_{diff} = 0.08$, $SD_{diff} = 0.07$) more than for the control group ($M_{diff} = 0.01$, $SD_{diff} = 0.08$, Cohen's $d = 0.96$). No significant interaction effect was found for FAR ($p = .630$). Although we found no significant interaction for target-present RT ($p = .622$), the ANOVA revealed a significant interaction for target-absent RT ($p = .006$): The control group reduced the target-absent RT ($M_{diff} = -6.43$ s, $SD_{diff} = 2.63$) more than the desktop VR group ($M_{diff} = -2.92$ s, $SD_{diff} = 4.15$, Cohen's $d = 1.02$).

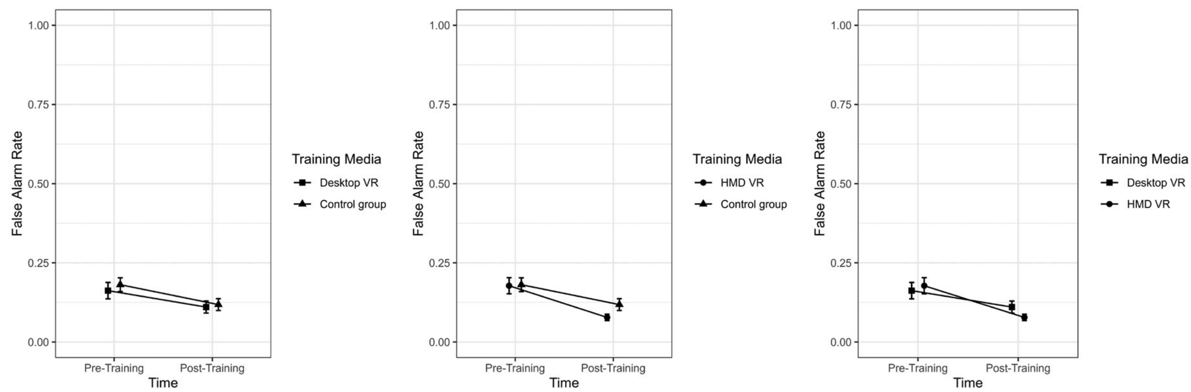

Figure 10. Interaction plots for false alarm rate.

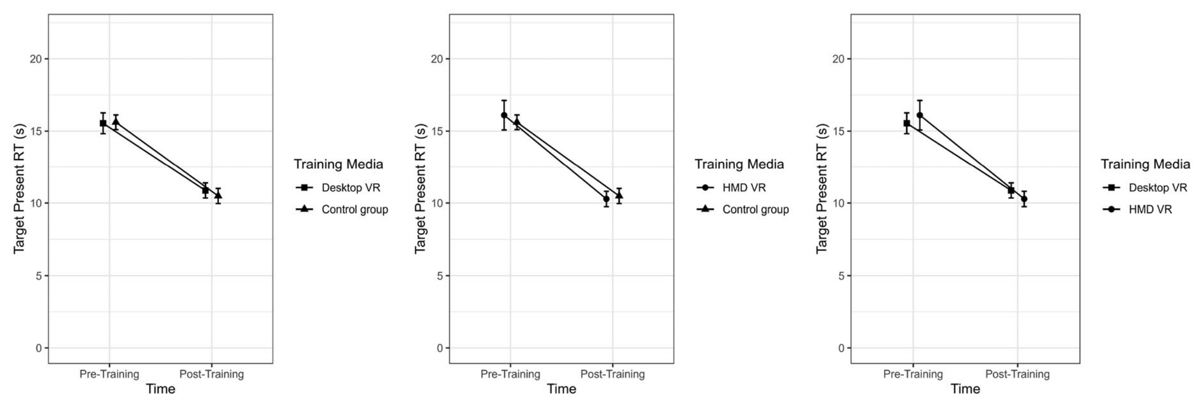

Figure 11. Interaction plots for target present RT.

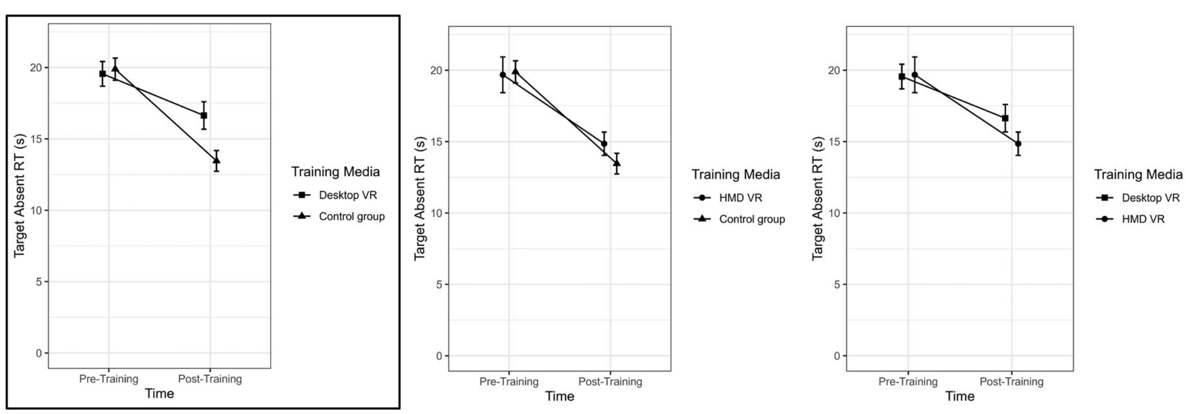

Figure 12. Interaction plots for target absent RT.

Second, we compared the VR HMD group with the control group. The ANOVAs revealed significant interaction effects for d' ($p = .001$) and d_a ($p < .001$), suggesting a significantly greater improvement with HMD VR than without training: The sensitivity d' improved with HMD VR ($M_{diff} = 0.79$, $SD_{diff} = 0.41$) more than in the control group ($M_{diff} = 0.35$, $SD_{diff} = 0.30$, Cohen's $d = 1.22$); also d_a increased with HMD VR ($M_{diff} = 0.67$, $SD_{diff} = 0.33$) more than in the control group (see above for M_{diff} and SD_{diff}, Cohen's $d = 1.43$). The ANOVA found a significant interaction on HR, indicating a disproportional improvement in the HMD VR group than the control group ($p = .004$): Training with HMD VR increased HR ($M_{diff} = 0.10$, $SD_{diff} = 0.08$) more than not training (see above for M_{diff} and SD_{diff}, Cohen's $d = 1.06$). No significant interaction effect was found for FAR ($p = .190$) or on RTs (target-present RT: $p = .420$; target-absent RT: $p = .176$).

Third, we analyzed the differences between the participants trained with desktop VR and those trained with HMD VR. The ANOVAs yielded a significant interaction effect for d' ($p = .048$) but not for d_a ($p = .101$). The sensitivity d' improved with HMD VR (see above for M_{diff} and SD_{diff}) more than with desktop VR (see above for M_{diff} and SD_{diff}, Cohen's $d = 0.72$). No significant interaction effects between training media and time were observed for HT ($p = .626$), FAR ($p = .143$), and either RTs (target-present RT: $p = .282$; target-absent RT: $p = .187$).

3.4. Effects of training media and time on immersion (Presence and Flow)

We then explored the effects of the two independent variables (training media: desktop VR, HMD VR; time: after the 2nd, 4th, 6th training) on Presence and Flow by conducting two-way ANOVAs (Table 5; Figures 13 and 14).

The ANOVA yielded a significant main effect of the training media on Presence. The HMD VR condition led to a higher Presence than the desktop VR condition ($p = .038$, Cohen's $d = 0.76$; desktop VR: $M = 2.62$, $SD = 1.12$; HMD VR: $M = 3.62$, $SD = 1.49$). We found no significant main effect of time ($p = .072$) or interaction effect ($p = .510$) on Presence. For Flow, no main effect of training media was found ($p = .230$), but ANOVA yielded a main effect of time ($p = .031$; see Table 2 for *M*s and *SD*s).

Table 5. Means, standard deviations, and two-way ANOVA statistics for immersion.

	TM:							
	Desktop VR		HMD VR		ANOVA			
Variable	*M*	*SD*	*M*	*SD*	Effect	*F* ratio	*df*	η_p^2
Presence								
Time: after 2nd training	2.95	1.25	3.74	1.61	TM	**4.70***	**1, 31**	**.13**
Time: after 4th training	2.52	1.16	3.56	1.56	Time	2.74	2, 62	.08
Time: after 6th training	2.39	1.23	3.56	1.67	TM × Time	0.68	2, 62	.02
Flow								
Time: after 2nd training	4.27	1.70	4.57	1.71	TM	1.50	1, 31	.05
Time: after 4th training	3.54	1.40	3.94	1.83	Time	**3.67***	**2, 62**	**.11**
Time: after 6th training	3.40	1.46	4.45	1.54	TM × Time	1.26	2, 62	.04

Note: $n = 33$. ANOVA: analysis of variance; TM: training media; VR: virtual reality; HMD: head-mounted display. Bolded values indicate statistical significance (*$p < .05$).

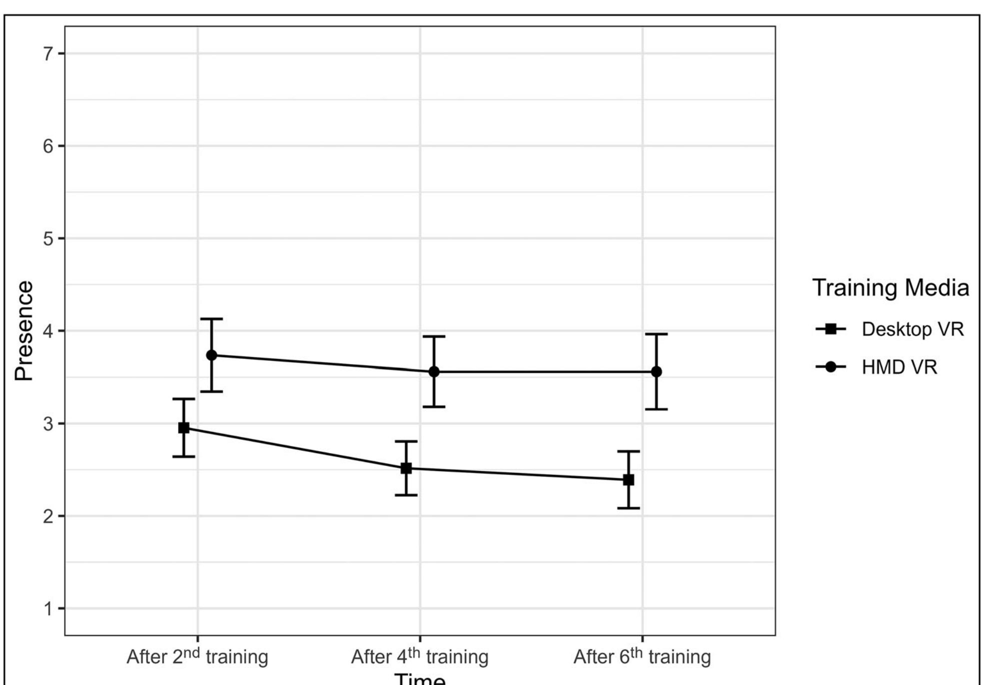

Figure 13. Interaction plot for Presence.

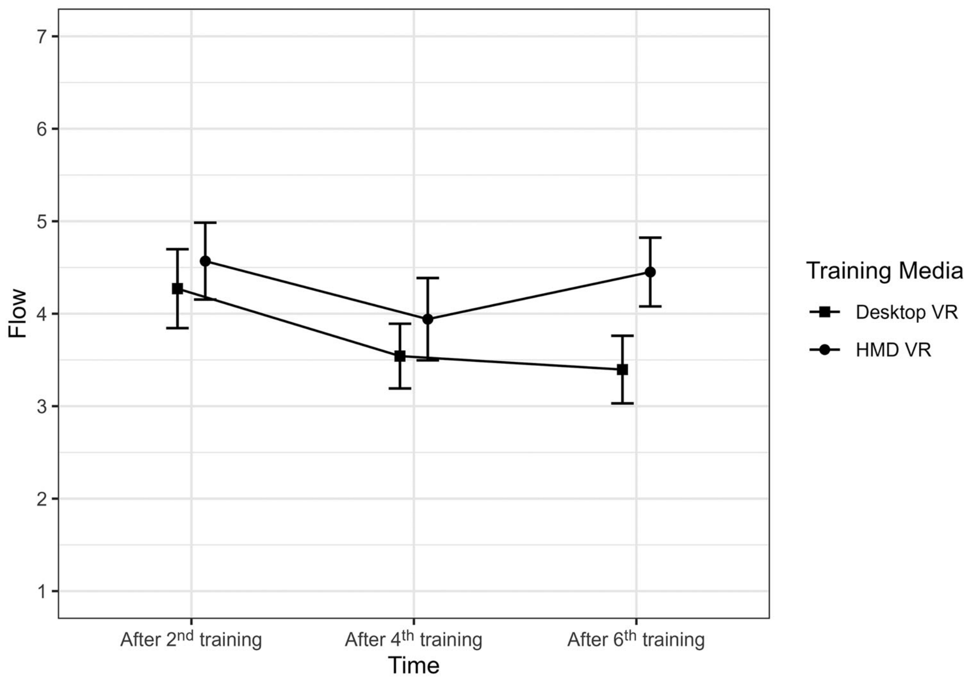

Figure 14. Interaction plot for Flow.

Table 6. Means, standard deviations, and two-way ANOVA statistics for intrinsic motivation.

	TM:							
	Desktop VR		HMD VR		ANOVA			
Variable	*M*	*SD*	*M*	*SD*	Effect	*F* ratio	*df*	η_p^2
Interest/Enjoyment								
Time: after 2nd training	4.93	1.07	5.73	0.80	TM	**7.54****	**1, 31**	**.20**
Time: after 4th training	4.44	0.99	5.19	1.11	Time	**7.16****	**2, 62**	**.19**
Time: after 6th training	4.38	1.08	5.30	0.94	TM x Time	0.17	2, 62	.01
Perceived Competence								
Time: after 2nd training	4.69	0.60	5.08	0.56	TM	**5.13***	**1, 31**	**.14**
Time: after 4th training	4.53	0.70	5.11	0.80	Time	**3.26***	**2, 62**	**.10**
Time: after 6th training	5.06	0.56	5.25	0.80	TM × Time	0.93	2, 62	.03
Effort/Importance								
Time: after 2nd training	4.74	1.08	5.47	0.87	TM	**4.98***	**1, 31**	**.14**
Time: after 4th training	4.53	1.02	5.14	1.11	Time	2.38	2, 62	.07
Time: after 6th training	4.55	1.20	5.47	1.05	TM × Time	0.74	2, 62	.02
Pressure/Tension								
Time: after 2nd training	2.38	1.23	2.53	1.27	TM	0.15	1, 31	.00
Time: after 4th training	2.70	1.03	2.19	1.35	Time	0.89	2, 62	.03
Time: after 6th training	2.25	0.98	2.21	1.06	TM × Time	1.66	2, 62	.05

Note: $n = 33$. ANOVA: analysis of variance; TM: training media; VR: virtual reality; HMD: head-mounted display. Bolded values indicate statistical significance (*$p < .05$; **$p < .01$).

However, follow-up with *post hoc t*-tests did not reveal significant differences between the three measurements: between 2nd and 4th training, $t(31) = 2.53$, $p = .050$; between 2nd and 6th training, $t(31) = 1.95$, $p = .121$; between 4th and 6th training, $t(31) = -0.72$, $p = .459$. No significant interaction effect was found for Flow ($p = .291$).

3.5. Effects of training media and time on intrinsic motivation

We then explored the effects of training media and time on Interest/Enjoyment, Perceived Competence, Effort/Importance, and the negatively connotated Pressure/Tension scale using two-way ANOVAs (see Table 6; Figures 15, 16, 17, and 18).

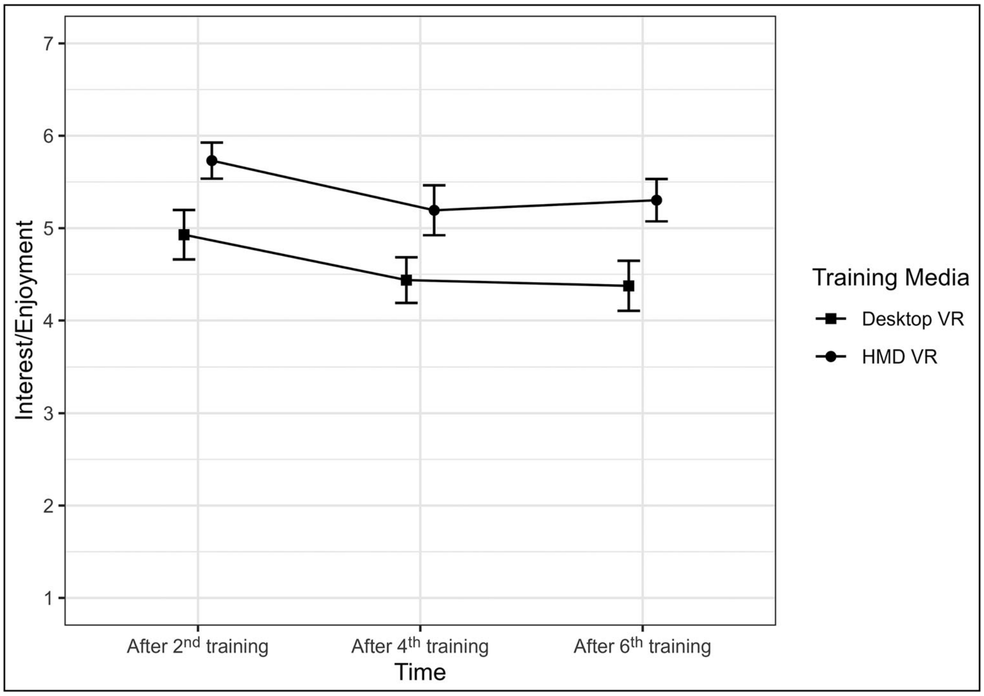

Figure 15. Interaction plot for Interest/Enjoyment.

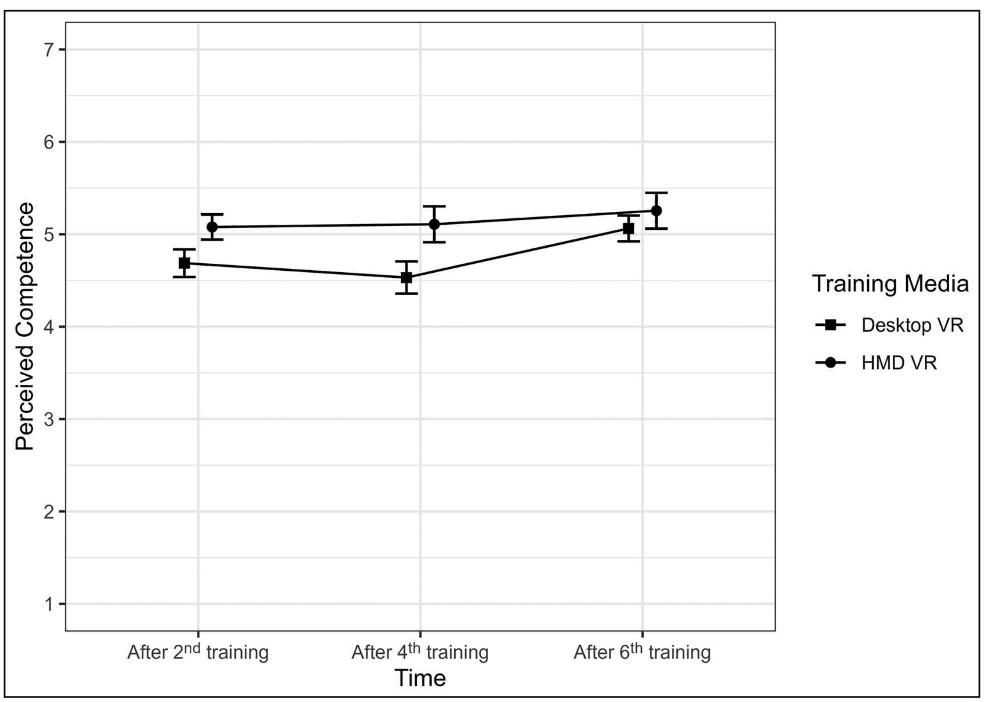

Figure 16. Interaction plot for Perceived Competence.

For Interest/Enjoyment, ANOVA showed significant main effects of both training media ($p = .010$, Cohen's $d = 0.96$) and time ($p = .002$). Participants using HMD VR ($M = 5.41$, $SD = 0.80$) rated Interest/Enjoyment higher than those in the desktop VR group ($M = 4.58$, $SD = 0.93$). *Post hoc t*-tests (see Table 2 for *M*s and *SD*s) of the factor time showed a significant decrease in Interest/Enjoyment between the 2nd and 4th training, $t(31) = 3.25$, $p = .008$, Cohen's $d = 0.49$, as well as between the 2nd and 6th training, $t(31) = 3.18$, $p = .010$, Cohen's $d = 0.46$; however, no statistical difference was found

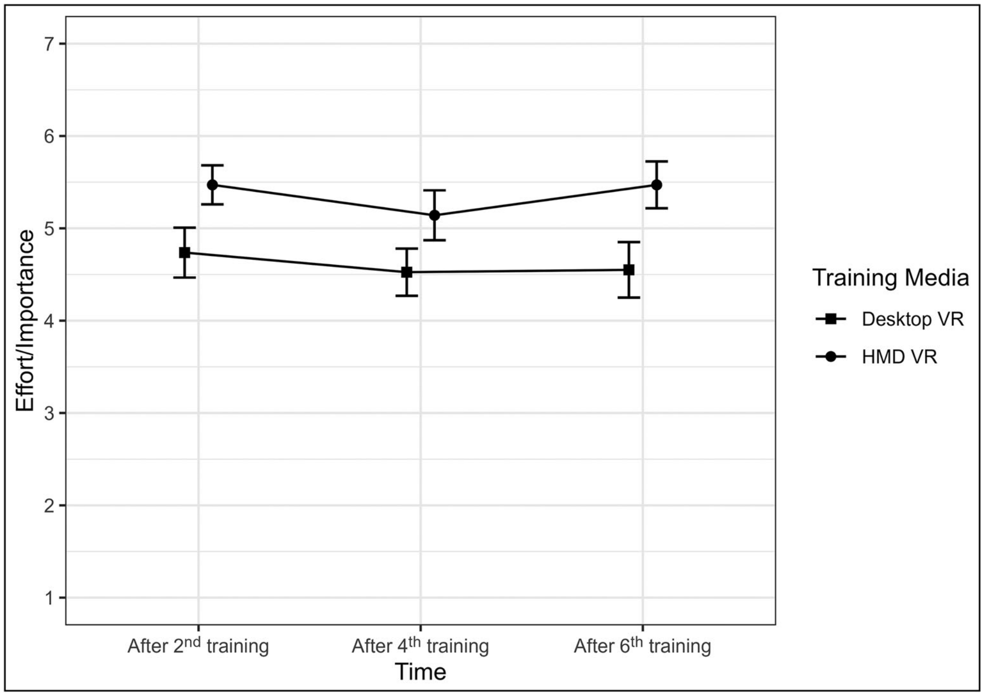

Figure 17. Interaction plot for Effort/Importance.

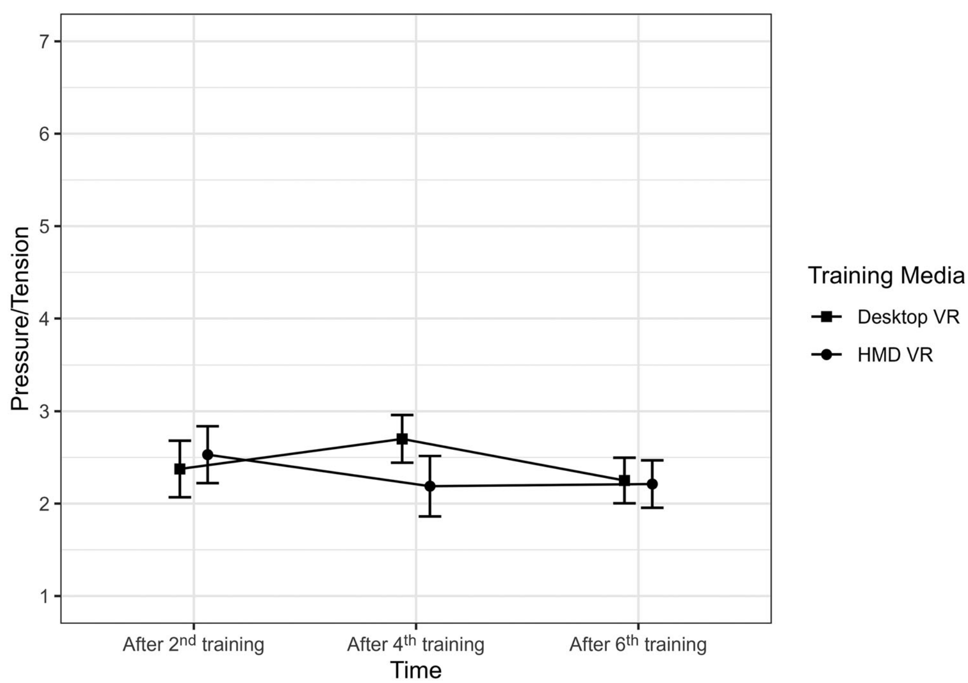

Figure 18. Interaction plot for Pressure/Tension.

between the 4th and 6th training, $t(31) = -0.16$, $p = 1.000$. No significant interaction effect was found for Interest/Enjoyment ($p = .846$).

The ANOVA revealed significant main effects on Perceived Competence for both training media ($p = .031$, Cohen's $d = 0.79$) and time ($p = .045$). Participants trained with HMD VR reported significantly higher Perceived Competence ($M = 5.15$, $SD = 0.59$) than those in the desktop VR group ($M = 4.76$, $SD = 0.35$). However, considering the factor time, *post hoc* analysis did not confirm the effect, as it revealed no significant differences between the three measurements (see Table 2 for *M*s and *SD*s): neither between the 2nd training and both the 4th training, $t(31) = 0.43$, $p = .673$ and 6th

Table 7. Means, standard deviations, and two-way ANOVA statistics for Cognitive Load.

	TM: Desktop VR		TM: HMD VR		ANOVA			
Variable	*M*	*SD*	*M*	*SD*	Effect	*F* ratio	*df*	η_p^2
Cognitive Load								
Time: after 2nd training	4.06	1.18	4.65	1.06	TM	1.67	1, 31	.05
Time: after 4th training	4.06	1.39	4.18	1.38	Time	1.80	2, 62	.05
Time: after 6th training	3.56	0.89	4.24	1.68	TM × Time	0.78	2, 62	.02

Note: $n = 33$. ANOVA: analysis of variance; TM: training media; VR: virtual reality; HMD: head-mounted display.

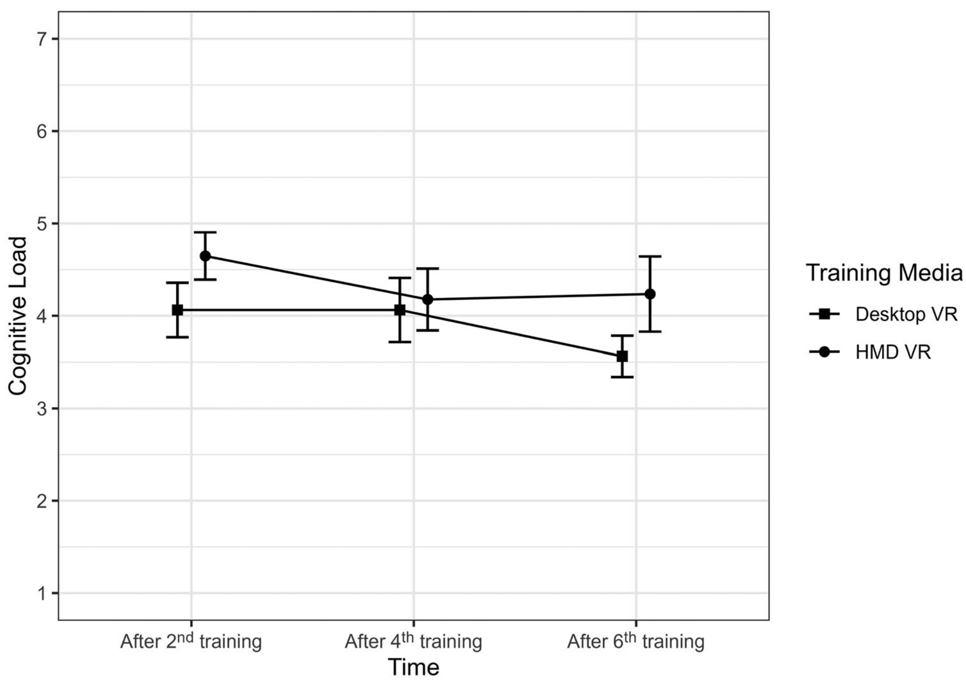

Figure 19. Interaction plot for Cognitive Load.

training, $t(31) = -2.02$, $p = .105$, nor between the 4th and 6th training, $t(31) = -2.46$, $p = .059$. Additionally, no significant interaction effect was found for Perceived Competence ($p = .402$).

The ANOVA on Effort/Importance computed a main effect for the training media ($p = .033$, Cohen's $d = 0.78$), revealing that participants using HMD VR rated it significantly higher ($M = 5.36$, $SD = 0.93$) than participants in the desktop VR group ($M = 4.60$, $SD = 1.02$). No significant main effect of time ($p = .101$) or interaction of training media and time ($p = .480$) was found for Effort/ Importance. ANOVA revealed no main effects (training media: $p = 0.703$; time: $p = .416$) or interaction effects ($p = .198$) for Pressure/Tension.

3.6. Effects of training media and time on Cognitive Load

We then analyzed the effects of training media and time on Cognitive Load using a two-way ANOVA (Table 7, Figure 19); however, no significant main effects (training media: $p = .206$; time: $p = .174$) or interaction effect ($p = .463$) were found for Cognitive Load.

3.7. Effects of training media and time on technology acceptance

We examined the effects of training media and time on PU, PEOU, and BI using two-way ANOVAs (Table 8, Figures 20, 21, and 22).

Based on ANOVA for PU, no significant main effects (training media: $p = .154$; time: $p = .164$) or interaction effects ($p = .947$) were found. Although the ANOVA for PEOU yielded no significant main

Table 8. Means, standard deviations, and two-way ANOVA statistics for technology acceptance.

	TM:				ANOVA			
	Desktop VR		HMD VR					
Variable	*M*	*SD*	*M*	*SD*	Effect	*F* ratio	*df*	η_p^2
Perceived Usefulness								
Time: after 2nd training	5.30	1.27	5.66	1.05	TM	2.13	1, 31	.06
Time: after 4th training	5.61	0.57	6.01	0.93	Time	1.79	1.39, 43.19	.06
Time: after 6th training	5.66	1.04	5.99	0.82	TM × Time	0.02	1.39, 43.19	.00
Perceived Ease of Use								
Time: after 2nd training	5.84	0.79	5.57	1.02	TM	1.19	1, 31	.04
Time: after 4th training	5.86	0.87	5.87	0.82	Time	2.79	2, 62	.08
Time: after 6th training	6.30	0.61	5.66	1.04	TM × Time	**3.93***	**2, 62**	**.11**
Behavioral Intention								
Time: after 2nd training	3.63	1.99	5.08	1.61	TM	**5.94***	**1, 31**	**.16**
Time: after 4th training	3.81	2.27	5.41	1.32	Time	1.80	1.65, 51.04	.05
Time: after 6th training	4.21	2.34	5.43	1.51	TM × Time	0.29	1.65, 51.04	.01

Note: $n = 33$. Violation of the sphericity assumption regarding Perceived Usefulness ($\varepsilon = 0.70$; Greenhouse-Geisser correction applied) and Behavioral Intention ($\varepsilon = 0.79$; Huynh-Feldt correction applied). ANOVA: analysis of variance; TM: training media; HMD: head-mounted display; VR: virtual reality. Bolded values indicate statistical significance (*$p < .05$).

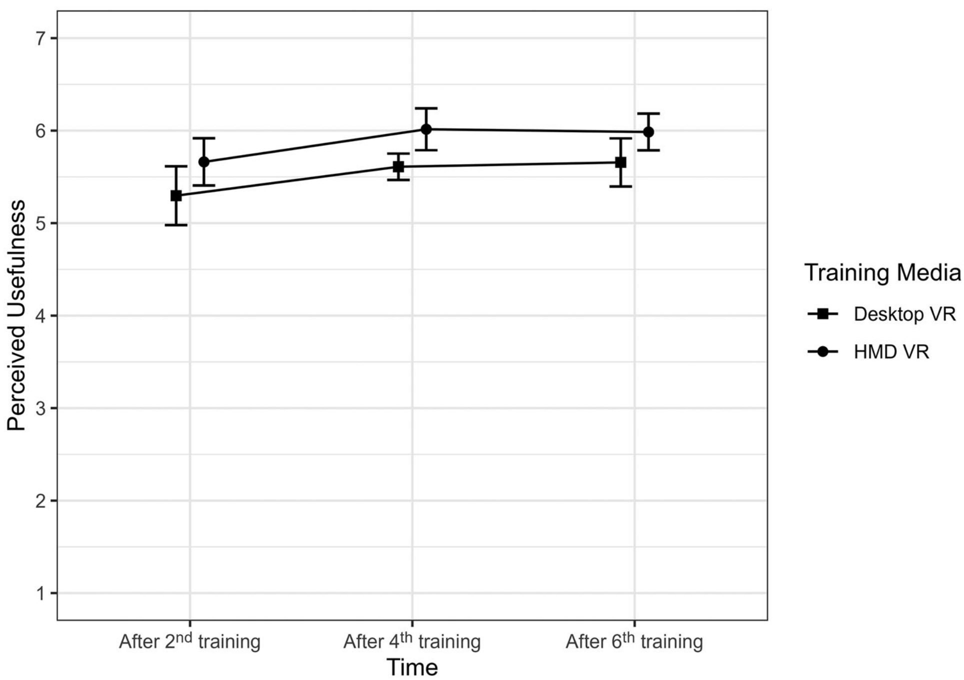

Figure 20. Interaction plot for Perceived Usefulness.

effects (training media: $p = .283$; time: $p = .069$), there was a significant interaction effect ($p = .025$), indicating that the two training media groups responded differently to changes over the three measurements. The follow-up one-way ANOVAs showed that no significant differences were found for the HMD VR group, $F(2, 32) = 1.80$, $p = .182$, $\eta_p^2 = .10$, but the desktop VR group yielded significant differences in the factor time, $F(2, 30) = 4.79$, $p = .016$, $\eta_p^2 = .24$. *Post hoc* comparisons for the desktop VR showed no significant difference between the 2nd and 4th training, $t(15) = -.09$, $p = .930$. However, *t*-tests computed a significant increase between the 2nd and 6th training, $t(15) = -2.67$, $p = .037$, Cohen's $d = 0.29$, as well as between the 4th and 6th training, $t(15) = -2.84$, $p = .037$, Cohen's $d = 0.29$. The ANOVA on BI yielded a main effect of training media ($p = .021$), indicating that the HMD VR participants rated it significantly higher ($M = 5.31$, $SD = 1.33$, Cohen's $d = 0.85$) than the desktop VR group ($M = 3.88$, $SD = 1.98$). There was no significant main effect of time ($p = .181$) or interaction effect ($p = .703$) of training media and time on BI.

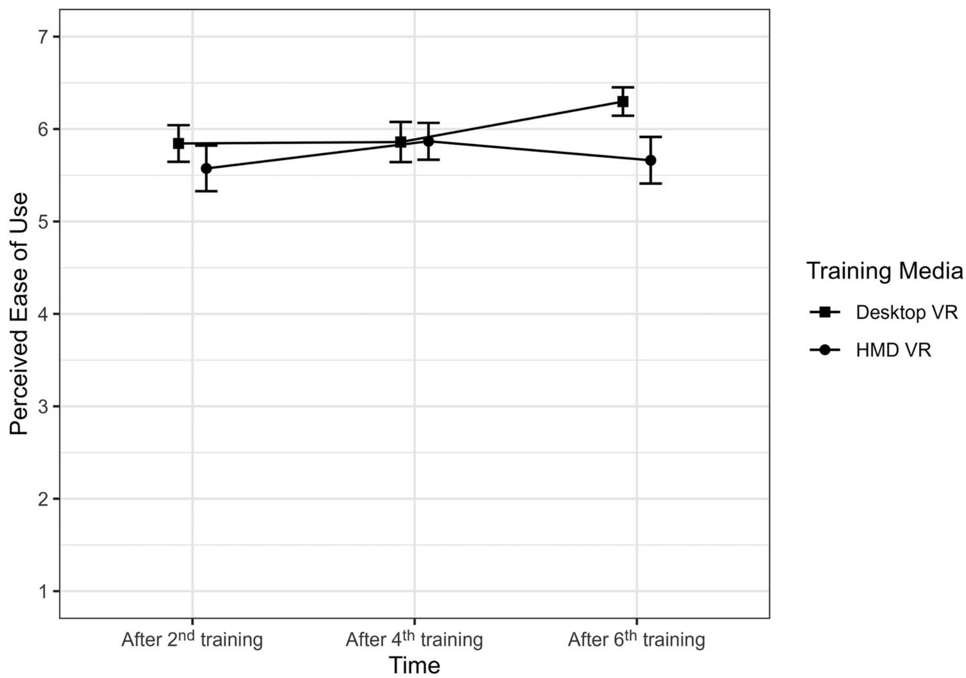

Figure 21. Interaction plot for Perceived Ease of Use.

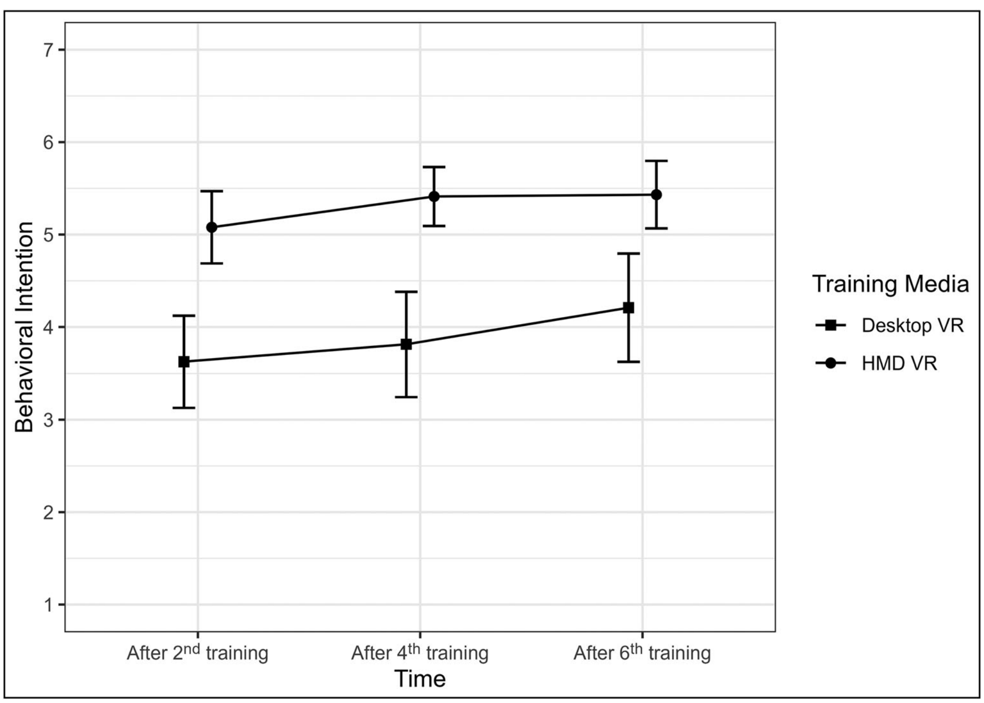

Figure 22. Interaction plot for Behavioral Intention.

4. Discussion

This study investigated the effectiveness of virtual reality (VR)-based three-dimensional (3D) object training, designed to complement existing computer-based training (CBT) for cabin baggage screening (CBS). Compared to traditional training methods, our novel approach allows trainees to interact with photorealistic 3D models and simultaneously view rotating 3D computed tomography (CT) images of prohibited items. We analyzed the impact of training media (desktop VR vs. head-mounted display [HMD] VR) and time (pre-training vs. post-training) on performance (sensitivity d', sensitivity d_a, hit

Table 9. Hypotheses and results.

No.	Hypothesis	Main result
1a	Detection performance: desktop VR > control group	Confirmed
1b	Detection performance: HMD VR > control group	Confirmed
1c	Detection performance: HMD VR > desktop VR	Rejected (not significant)
2	Presence: HMD VR > desktop VR	Confirmed
3	Interest/Enjoyment: HMD VR > desktop VR	Confirmed
4	Perceived Competence: HMD VR > desktop VR	Confirmed
5	Effort/Importance: HMD VR > desktop VR	Confirmed
6	Interest/Enjoyment: decreases over time	Confirmed (significant decrease between 2nd and 4th as well as 2nd and 6th training)
7	Behavioral Intention: HMD VR > desktop VR	Confirmed
8	Behavioral Intention: decreases over time	Rejected (not significant)

Note: VR: virtual reality; HMD: head-mounted display.

rate (HR), false alarm rate (FAR), target-present reaction time (RT), target-absent RT; compared to a control group without conducting training) and ratings of the training experience (aspects of immersion, intrinsic motivation, cognitive load, and technology acceptance; over a six-fold training sequence) with psychology students without prior experience with 3D CT security screening. The hypotheses and main results are presented in Table 9. Two of the three hypotheses regarding performance were confirmed. Our study also confirmed the hypotheses that VR HMD leads to significantly higher Presence, Interest/Enjoyment, Perceived Competence, and Effort/Importance. Furthermore, our hypothesis that Interest/Enjoyment decreases after an initial VR experience was confirmed.

Regarding technology acceptance, HMD VR resulted in a significantly higher Behavioral Intention (BI) than desktop VR, confirming our hypothesis, although the expected decrease over time could not be confirmed. Our exploratory analysis revealed no significant effects on Flow, Pressure/Tension, Cognitive Load, or Perceived Usefulness (PU). We discuss our findings in the following sections.

4.1. 3D object learning with desktop VR and HMD VR improves detection performance

Compared to the control group, 3D object training with HMD VR resulted in better performance, evidenced by the ANOVAs' significant interaction effects. Specifically, we observed large effect sizes for d', d_a, and HR, confirming Hypothesis 1b. Similar results were also found for desktop VR, but only for d_a (large effect size) and HR (small effect size), not for d'. Previous research showed that d_a with a slope parameter of 0.5–0.6 is more valid than d' (Godwin et al., 2010; Sterchi et al., 2019; Van Wert et al., 2009; Wolfe et al., 2007; Wolfe & Van Wert, 2010). Our study shows that it is important to calculate d_a in addition to d' to avoid incorrect conclusions, and if there are discrepancies, d_a should be preferred (Sterchi et al., 2019). Based on the results of d_a and HR, Hypothesis 1a was confirmed. Different results for d' and d_a were found regarding the training effectiveness of HMD VR compared with desktop VR, which showed no significant difference for d_a and HR, whereas the interaction between training media and time (pre- vs. post-training) was significant for d' (medium effect size). Therefore, based on the suggestions of Sterchi et al. (2019), Hypothesis 1c is rejected. We found a small decrease in the FAR from the first (pre-training) to the second measurement (post-training) for all three groups (desktop VR, HMD VR, and control group; Table 4). A low FAR simplifies alarm resolution at airport security checkpoints and lessens the demand for extra resources dedicated to manual searches (e.g., Sterchi & Schwaninger, 2015). However, in the current study, the ANOVAs did not yield significant interaction effects when comparing the pairings of the three groups, which would have indicated a benefit of a particular training method.

Similarly, target-present and target-absent RTs were shorter in all three groups post-training (Table 4). The only interaction between training media and time was found when comparing the desktop VR and control group for target-absent RT; the control group reacted disproportionately faster post-training (large effect size). Overall, the FAR and RTs results (Table 4) suggest a general learning and stimulus repetition effect, which might be due to learning how to use system functions (knobology; Kramer et al., 2019).

4.2. Effects on immersion (Presence and Flow)

Effects on immersion were investigated using ratings of Presence and Flow. The training media influenced Presence (medium effect size), supporting Hypothesis 2: Participants training with HMD VR rated their sense of being there higher than those using desktop VR at all three measurements (after the 2nd, 4th, and 6th training). This finding aligns with the results reported in a meta-analysis by Cummings and Bailenson (2016) and corroborates more recent research (De Witte et al., 2024; Klingenberg et al., 2020; Makransky et al., 2019; Shu et al., 2019). The practical implications of this finding are substantial. HMD VR's ability to foster presence while absorbing visual distractions and allowing spatial independence offers unique advantages for training applications.

Regarding the second aspect of immersion, Flow, our data did not reveal a significant main effect of media type, although the data suggests that both HMD VR and desktop VR can induce a flow state (considering the respectable initial ratings on the seven-point Likert scale, $M \geq 4.27$). ANOVA revealed a significant main effect of time, which could not be confirmed with Bonferroni-Holm-corrected *post hoc* tests comparing the three measurements.

4.3. Training media and time influence Interest/Enjoyment

As Hypothesis 3 suggested, the training media significantly influenced Interest/Enjoyment. Participants training with HMD VR consistently rated the experience more positively than those training with desktop VR (large effect size), confirming previous findings (De Witte et al., 2024; Klingenberg et al., 2020; Makransky et al., 2021; Meyer et al., 2019). This suggests that the immersive qualities of VR HMDs can enhance the overall training experience by catalyzing intrinsic motivation, which is a key factor in learning and performance (Deci & Ryan, 2008; Di Domenico & Ryan, 2017; Froiland & Worrell, 2016). Interestingly, the Interest/Enjoyment ratings for both training media decreased over time (confirming Hypothesis 6), suggesting a decrease that may be due to the initial novelty effect fading over time (Chen et al., 2016). More specifically, we found a significant decrease after the second training session (compared with the 4th and 6th training; both comparisons with medium effect sizes). The observed novelty effect may also be attributed to factors other than the training media alone, as the 3D technology of the visualizations used in 3D object training was identical and novel for users of both media types. Thus, the decline in initially high motivation ratings can also be explained by the fading novelty of the 3D imaging technology used in the training application (cf. Rodrigues et al., 2022). Overall, our findings not only support the use of HMD VR for this applied training case but also underscore the importance of evaluating motivational factors with novel technology in more than one initial experience.

4.4. Training media influences Perceived Competence and Effort/Importance

Hypothesis 4 suggested that using HMD VR would lead to significantly higher Perceived Competence ratings than desktop VR. Our data confirm this hypothesis (medium effect size) and reinforce indications in the literature (Cikajlo & Peterlin Potisk, 2019; Sattar et al., 2020; Wenk et al., 2023). Similarly, Hypothesis 5 suggested that HMD VR leads to significantly higher Effort/Importance than desktop VR. This hypothesis was confirmed by our data (medium effect size), which supports conclusions drawn from the literature (Cikajlo & Peterlin Potisk, 2019; Wenk et al., 2023). Overall, individuals' perception that using HMD VR for 3D object training makes them more able and effective increases the expectation that they will perform better in task training, potentially leading to greater engagement and commitment. Although the ANOVA suggested a main effect of time for Perceived Competence, *post hoc* tests did not confirm a significant difference between the three measurements. No significant effects were observed for Pressure/Tension for training media and time. The low Pressure/Tension scores ($M \leq 2.70$) suggest that VR technology induced only low levels of anxiety, if at all, in our sample. However, the individual differences in responses (resulting in larger variances) emphasized the importance of a well-designed introduction of the technology and VR experiences tailored to the specific needs of users.

4.5. No significant effects found on Cognitive Load

We explored the effects of training media and time on Cognitive Load. No significant main or interaction effects were found using the single-item subjective rating scale developed by Paas (1992). Although this result is consistent with the analyses of some studies (e.g., De Witte et al., 2024; Parong & Mayer, 2021b; Ristor et al., 2023), other studies that have found significant effects with 3D visualizations resulted in lower (Dan & Reiner, 2017, 2018; Sagehorn et al., 2024) or higher (e.g., Breves & Stein, 2023; Frederiksen et al., 2020; Makransky et al., 2019; Parong & Mayer, 2021a) cognitive loads than 2D displays. These inconclusive findings suggest that when comparing media types, the effects on Cognitive Load may be related to other factors, such as varying task designs (cf. Han et al., 2021; Sagehorn et al., 2024).

4.6. Training media influences Behavioral Intention

Our data support Hypothesis 7—suggesting that BI is rated higher with HMD VR than with desktop VR (large effect size)—and highlights another benefit of HMD VR as a medium for 3D object training. Given the paucity of literature evaluating different VR training media regarding technology acceptance, we based our hypothesis on the apparent strong relationship between Interest/Enjoyment and BI (e.g., Fussell & Truong, 2022; Manis & Choi, 2019; Oyman et al., 2022) and assumed that immersion increases motivation (Hypothesis 3; Interest/Enjoyment: HMD VR > desktop VR). Based on this line of argument and combined with Hypothesis 6 (Interest/Enjoyment decreases over time), we suggest that BI decreases over time (Hypothesis 8). However, our analysis did not find a significant effect of time on BI. This finding is particularly interesting because it indicates the existence of one or more factors that compensate for the expected influence of the novelty effect. Therefore, the time factor should be considered when applying and developing acceptance models for immersive technologies. With reference to the applied Technology Acceptance Model 3 (TAM3; Venkatesh & Bala, 2008), we explored the effects on PU and Perceived Ease of Use (PEOU) without stating the hypotheses. Our analyses yielded neither main effects of training media or time nor any interaction thereof on PU. For PEOU, the ANOVA found no main effects of training media or time; however, a significant interaction was indicated between the two independent variables. *Post hoc* analyses revealed a significant increase in the ratings after the 4th training on PEOU for desktop VR (comparisons between 2nd and 6th as well as 4th and 6th training yielded small effect sizes), possibly indicating a learning effect on abstract interaction with 3D objects on a 2D computer screen using a computer mouse.

4.7. Limitations and future research

First, our participants (university students) participated in six 20-minute training sessions over two weeks. Airport security screeners undergo regulated selection and assessment procedures and receive more extensive training (Halbherr et al., 2013; Koller et al., 2008; Swann et al., 2020; Sudiarno et al., 2024). Thus, conducting a study with airport security screeners would be interesting to investigate whether our findings apply to airport security screeners with 3D CT experience (Hättenschwiler et al., 2019; Latscha et al., 2025) and how this affects their self-efficacy (cf. Kovari & Katona, 2023). Second, the relatively short training duration (six 20-minute sessions over two weeks) presents a limitation. Although this design enabled controlled comparisons, it is unclear whether the observed VR training effects persist over longer periods. Therefore, follow-up studies could investigate long-term retention rates and determine if booster sessions, administered in predefined time intervals, are necessary to maintain performance gains. Third, 3D object training should be adaptive to be more effective (cf. Halbherr et al., 2013; Schwaninger, 2006; Schwaninger et al., 2007) by considering an individual's detection performance over time for different prohibited items. Furthermore, to address the potential for declining engagement over extended training (as implied by decreasing motivation over time), future implementations could integrate strategies such as adaptive difficulty levels or gamification elements (Landers, 2014; Sailer & Homner, 2020; in the context of VR, see also Lampropoulos & Kinshuk, 2024; Ulmer et al., 2022) to sustain user interest and promote long-term adoption. Fourth, our study focused on learning the 3D objects of prohibited items. The inclusion of everyday objects (e.g., electronic devices; cf. Sterchi et al., 2017) and additional contextual information (e.g., about specific visual distinguishing features and material variants; cf. Fuhrman et al., 2021; Lauer et al., 2021) can further increase the training effectiveness. Fifth, the current study compared desktop VR and HMD VR against no training. On the one hand, this study design did not allow isolating the effects of specific VR features (e.g., stereoscopic depth, interaction fidelity, model realism). On the other hand, we did not compare the VR interventions against established training benchmarks (e.g., traditional CBT, experience with real-world screening), limiting conclusions about relative effectiveness. Future research could employ ablation designs to determine the contribution of specific VR features, and separate comparative studies are needed to evaluate VR training against benchmarks of existing training methods. Sixth, our data did not yield a significant effect on Cognitive Load. More advanced measures for cognitive load (e.g., for subjective scales: Ouwehand et al., 2021; for eye-tracking approaches: Katona, 2023; Kácovský et al., 2023) and fatigue (cf. Souchet et al., 2022) could allow further insights into their potential relations to training performance.

4.8. Practical implications

With the increasing adoption of 3D CT technology for CBS, novel 3D object training with VR can complement traditional CBT for inexperienced airport security screeners. By allowing users to learn the visual features of prohibited items from all perspectives, complemented by motor and sensory modalities, 3D object training can create enriched mental representations that facilitate efficient and effective learning. Training with HMD VR outperformed desktop VR in terms of training experience ratings (aspects of immersion, motivation, and technology acceptance). Although initial costs are associated with implementing VR-based training programs (such as hardware procurement, software and content development), the potential benefits in terms of reducing the need for expensive real-world prohibited items, immersion (location independence), motivation (more satisfying training), and technology acceptance (self-driven use) may outweigh these expenses. This study demonstrated that VR technologies allow the creation of new training methods that are feasible for practical use. Furthermore, 3D object training using VR technology has the potential to benefit other fields that require visual object recognition, such as healthcare (cf. Javan et al., 2020).

4.9. Conclusion

As the transition from traditional 2D X-ray to 3D CT technology for cabin baggage screening continues, existing training concepts have remained largely unchanged. Given the rapid developments in 3D graphics and VR, with their increasing feasibility for practical application, this study evaluated a novel 3D object training method for airport security. Our results demonstrate the effectiveness of VR-based 3D object training for improving detection performance while evaluating both training media (desktop VR and HMD VR). HMD VR offers significant advantages over desktop VR in terms of immersion, motivation, and technology acceptance. These findings suggest that 3D object training with VR can be a valuable complement to traditional CBT for screeners and contribute to the few previous studies on training for 3D CT in airport security. Our study also shows that evaluating motivational factors with a novel technology should consider more than one initial experience, as the novelty effect decreases over time.

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Ethical approval

Before data collection was initiated, the project and study were reviewed and approved by the Research Ethics Review Board of the School of Applied Psychology, University of Applied Sciences and Arts Northwestern Switzerland (reference number: EAaFE2019007).

Author contributions

CRediT: **Thomas Wyssenbach**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Visualization, Writing – original draft, Writing – review & editing; **Kaspar Kaufmann**: Conceptualization, Investigation, Methodology, Validation, Writing – review & editing; **Adrian Schwaninger**: Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

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No potential conflict of interest was reported by the author(s).

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Data availability statement

The data analyzed in the current study are available from the corresponding author upon reasonable request.

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Appendix A

Table A1. Questionnaires and items used in the current study.

Questionnaire, construct	English	German translation (used in the current study)
Augmented reality immersion (Georgiou & Kyza, 2017, p. 33; adapted for VR)		
Total Immersion: Presence	The activity felt so authentic that it made me think that the virtual characters/objects existed for real.	Ich fühlte mich, als wäre ich in einer sehr realistischen Aktivität, bei der ich kaum unterscheiden konnte, was virtuell oder real war.
Total Immersion: Presence	I felt that what I was experiencing was something real, instead of a fictional activity.	Ich hatte das Gefühl, dass das, was ich erlebte, etwas Reales und nicht eine fiktive Aktivität war.
Total Immersion: Presence	I was so involved in the activity, that in some cases I wanted to interact with the virtual characters/objects directly.	Ich war so in die Aktivität vertieft, dass ich in einigen Fällen direkt mit den virtuellen Figuren/ Objekten interagieren wollte.
Total Immersion: Presence	I so was involved, that I felt that my actions could affect the activity.	Ich war so vertieft, dass ich das Gefühl hatte, meine Handlungen können die Aktivität beeinflussen.
Total Immersion: Flow	I didn't have any irrelevant thoughts or external distractions during the activity.	Ich hatte keine irrelevanten Gedanken oder äussere Ablenkungen während der Aktivität.
Total Immersion: Flow	The activity became the unique and only thought occupying my mind.	Die Aktivität wurde zum einzigen und alleinigen Gedanken, der mich beschäftigte.
Total Immersion: Flow	I lost track of time, as if everything just stopped, and the only thing that I could think about was the activity.	Ich verlor das Zeitgefühl, als wäre alles stehen geblieben und das Einzige, woran ich denken konnte, war die Aktivität.
Intrinsic Motivation Inventory (based on the 45-item version of the questionnaire available from Self-Determination Theory, 2024; items cannot be disclosed due to copyright restrictions; the English version of the items can be found in Wenk et al., 2023)		
Cognitive load (Paas, 1992)		
Mental effort	My invested mental effort was …	Meine mentale Anstrengung während dieser Aktivität war …
Technology acceptance model (Venkatesh & Bala, 2008, pp. 313–314)		
Perceived Usefulness	Using the system improves my performance in my job.	Die Nutzung des Trainingssystems würde meine Leistung bei meiner Arbeit verbessern.
Perceived Usefulness	Using the system in my job increases my productivity.	Die Nutzung des Trainingssystems würde meine Produktivität bei meiner Arbeit erhöhen.
Perceived Usefulness	Using the system enhances my effectiveness in my job.	Die Nutzung des Trainingssystems würde meine Effektivität bei meiner Arbeit erhöhen.
Perceived Usefulness	I find the system to be useful in my job.	Ich finde, das Trainingssystem wäre nützlich bei meiner Arbeit.
Perceived Ease of Use	My interaction with the system is clear and understandable.	Der Umgang mit dem Trainingssystem ist für mich klar und verständlich.
Perceived Ease of Use	Interacting with the system does not require a lot of my mental effort.	Die Nutzung des Trainingssystems erfordert von mir keine grosse mentale Anstrengung.
Perceived Ease of Use	I find the system to be easy to use.	Ich finde, das Trainingssystem ist einfach zu benutzen.
Perceived Ease of Use	I find it easy to get the system to do what I want it to do.	Ich finde, das Trainingssystem macht ohne Probleme das, was ich möchte.
Behavioral Intention	Assuming I had access to the system, I intend to use it.	Angenommen, ich hätte nach dieser Studie Zugang zum Trainingssystem, dann würde ich beabsichtigen, es zu nutzen.
Behavioral Intention	Given that I had access to the system, I predict that I would use it.	Wenn ich nach dieser Studie Zugang zum Trainingssystem hätte, sage ich voraus, dass ich es nutzen würde.
Behavioral Intention	I plan to use the system in the [next months].	Ich plane, das Trainingssystem in den [kommenden Monaten] wieder zu nutzen.

Note: Reverse-coded items are marked with an asterisk and formulations deviating from the original questionnaires mentioned by the authors are marked with square brackets.