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Virtual reality for older people: effectiveness of a training program for accident prevention

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Background: As people age, physical and cognitive limitations increasingly affect the daily mobility of older adults. Virtual reality (VR) applications offer novel opportunities for senior citizens to enhance their functional abilities. Routine activities, like crossing a street, can be simulated and practiced within a virtual environment.

Objective: This intervention study investigated the impact of a VR training application ('Wegfest') on physical function, fall-related confidence, and cognitive status in senior citizens. It was hypothesized that participation in the VR-based training program would lead to improvements in functional mobility, fall-related self-confidence, and cognitive performance.

Method: For this study, the VR application 'Wegfest' was developed to simulate various road scenarios. Over a 4-week training period, senior citizens practiced navigating diverse road-crossing situations. The effectiveness of the application was evaluated through measures of physical and cognitive performance, including the Timed Up and Go (TUG) Test, the Falls Efficacy Scale-International (FES-I), and the Montreal Cognitive Assessment (MoCA). In total, 29 senior citizens (M = 74.95 years) were recruited, with 20 participants included in the final analysis. Data collection and statistical analyses were performed using a database specifically created for Wegfest.

Results: The VR application "Wegfest" received positive feedback from participants. Significant improvements were found between pre- and post-intervention measurements for TUG, t (19) = 3.50, p = 0.002, and for FES-I, z = −2.82, p = 0.005. No significant differences were observed in MoCA scores, z = 0.58, p = 0.564.

Conclusion: Virtual reality (VR) shows promise as an effective tool for supporting older adults in their daily activities. As a pilot (exploratory) study with a small sample size and a relatively high dropout rate, the results should be interpreted as preliminary and indicative rather than conclusive. The lack of behavioral outcome measures further underscores the exploratory nature of this investigation. Further research with larger samples and more comprehensive outcome measures is needed to evaluate the effectiveness and generalizability of 'Wegfest' and similar VR applications for enhancing everyday mobility.

KEYWORDS

virtual reality, senior citizen, training application, crossing the road, healthy ageing

Introduction

In recent years, the variety of multimedia and interactive applications has steadily expanded. These applications are now widely used across different age groups and social backgrounds, becoming increasingly common in diverse communities (Nguyen et al., 2017). Examples include strategy and simulation games, brain-training programs, and entertainment applications. Known as serious games, these computer-based tools are designed to convey knowledge and skills in an engaging way (Nguyen et al., 2017). Through gamification—the incorporation of playful elements—serious topics are often presented in an appealing manner (Deterding et al., 2011). Serious games are seen as an innovative, target group-specific trend with promising future potential (Damaševičius et al., 2023). In the field of virtual reality (VR), serious games deliver content in an immersive and educational format.

Virtual reality (VR) refers to the computer-generated simulation and perception of environments that overlay or replace the real world (Caponnetto et al., 2021). VR is widely regarded as a safe and standardized research method with minimal adverse effects; however, ethical concerns about potential long-term risks require further investigation. VR facilitates ecologically valid studies, enables the accurate simulation of basic social interactions—even in non-photorealistic environments—and introduces new possibilities through virtual embodiment techniques (Kruk, Mętel and Cechnicki, 2019). By creating fully immersive, computer-generated environments, VR blurs the boundaries between physical reality and the digital world, offering users interactive experiences in real time. Immersion refers to the sensory experience of feeling present within a VR environment, achieved by replacing real-world stimuli with virtual ones. The level of immersion depends on hardware quality factors such as image resolution, refresh rate, and surround sound; greater fidelity enhances the sense of realism. In an ideal scenario, users would perceive no distinction between the virtual and physical worlds (Kruk, Mętel and Cechnicki, 2019). However, VR usage can induce motion sickness or cybersickness due to sensory conflicts between visual inputs and the vestibular system, leading to symptoms such as nausea, dizziness, headaches, eye strain, and disorientation (Buele et al., 2023).

In education, VR enables learners to explore otherwise inaccessible scenarios—such as historical events, remote locations, or complex scientific concepts—thereby fostering engagement and motivation through experiential learning. Several theoretical frameworks have been developed to understand immersive learning processes in VR. The Cognitive Affective Model of Immersive Learning (CAMIL) highlights presence and agency as key psychological factors enhanced by immersion and realism while linking cognitive and affective elements such as interest, motivation, and self-regulation to knowledge acquisition (Makransky and Petersen, 2021). The Educational Framework for Immersive Learning (EFiL) integrates immersive learning into Helmke's pedagogical model and emphasizes presence as a central factor influencing learning outcomes; these outcomes are shaped by both technological immersion and learner-specific factors (Dengel and Mägdefrau, 2018). The Meaningful-Immersive Virtual Reality-Learning Framework (M-iVR-L) focuses on designing VR-based instruction for elementary school students by involving educators in creating student-centered learning opportunities (Bakenhus et al., 2022).

The transformative potential of VR in education lies in its ability to make learning interactive and inclusive while accommodating diverse learning styles and overcoming physical limitations. Studies have demonstrated that VR contributes to improved comprehension of educational content (Elendu et al., 2024; Huai et al., 2024). Furthermore, research indicates that VR enhances the clarity with which content is conveyed through virtual experiences (Lin et al., 2024; Duarte et al., 2020). Beyond education, VR has also been applied in therapeutic settings—for example, in prevention and rehabilitation programs targeting various groups.

VR is increasingly applied in gerontology to support senior citizens in various domains. Virtual applications are used, for example, in memory training, movement and pain therapy, as well as for relaxation (Napetschnig et al., 2023). Additionally, they can be used to promote activities of daily living (ADLs) (Napetschnig et al., 2023). Participating in virtual training environments offers seniors the opportunity to preserve or improve their skills.

Zitti et al. (2025) investigated the applicability and effectiveness of an immersive VR intervention for addressing pain, depression, and quality of life in older adults. Their findings indicate that a 6-week immersive VR intervention can reduce pain intensity and thereby improve the physical wellbeing of seniors. Similarly, Hajder et al. (2025) propose that VR-based cognitive training could help seniors with mild cognitive impairment or Alzheimer's disease improve their ability to perform activities of daily living (ADLs). Donath et al. (2016) examined the impact of VR-based balance training on functional mobility in older adults and concluded that balance performance improved as a result of VR training, making it an appealing option for this demographic. Chan et al. (2021) demonstrated that VR applications featuring natural environments effectively reduce stress levels in seniors. These findings emphasize that VR not only positively impacts physiological factors but also promotes psychological wellbeing by enhancing seniors' overall quality of life.

VR has also shown promising results in addressing mental health disorders (Kruk et al., 2023). For instance, Kruk et al. (2023) examined the effects of 360-degree videos on eliciting social paranoia in individuals susceptible to such experiences, including patients with schizophrenia. In their study, schizophrenia patients and healthy controls watched 360-degree videos while their heart rate and anxiety levels were recorded. Patients with schizophrenia reported higher momentary anxiety levels, and a significant correlation emerged between daily paranoid ideation and VR-induced paranoia. These findings indicate that 360-degree videos are effective in triggering paranoid responses and offer a cost-effective, ecologically valid tool for research and potentially treating paranoia.

The studies mentioned above highlight the relevance of VR in various areas of daily life and its potential for training essential activities. The present study investigates the impact of VR on road-crossing behavior in senior citizens—a critical issue in light of the rising number of road traffic accidents involving older adults in Germany (Federal Statistical Office - Destatis, 2020). According to statistics, 12% of those injured and 29% of those killed in traffic accidents belong to the age group of 65 years and older. The consequences of road traffic accidents are often more severe for older adults due to their diminished physical resilience (Lukas, 2018). The risk increases substantially from the age of 75, with incorrect behavior frequently identified as a leading cause (Federal

Statistical Office - Destatis, 2023). Age-related declines in motor skills, cognitive functions, and visual acuity make it especially difficult for seniors to cross roads safely, particularly when vehicles are moving at high speeds (Mukli et al., 2022; Sukpramote and Senavongse, 2024).

This study aimed to assess the effects of the VR training application 'Wegfest' on physical function, fall-related confidence, and cognitive status in senior citizens. Specifically, the study seeks to answer the research question:

What effects does the VR intervention "Wegfest" have on physical function (as measured by the Timed Up and Go Test), fall-related confidence (as measured by the Falls Efficacy Scale-International), and cognitive status (as measured by the Montreal Cognitive Assessment) in senior citizens?

By focusing on road-crossing scenarios, this study addresses a critical aspect of mobility that combines cognitive, physical, and behavioral demands. The primary aim was to investigate the effectiveness of a VR-based training program in promoting safer traffic behavior among older adults. However, the evaluation mainly concentrated on general physical and cognitive functions, without systematically collecting or analyzing specific behavioral data from the VR sessions. Additionally, the study seeks to provide insights into how VR interventions can be effectively applied to enhance safety and independence in the daily lives of older adults.

Methods

VR application wegfest

The VR application used in this intervention study, titled "Wegfest," is designed to train senior citizens in road-crossing scenarios within a virtual environment. "Wegfest" offers diverse street scenarios to simulate different conditions for crossing roads safely. The application was developed using the Unity Engine development environment, with programming carried out in C# by the development team at vobe GbR. The modeling process involved designing individual scenes that incorporate various environmental backgrounds and objects.

For this project, the Meta Quest two head-mounted display (HMD) was utilized. Interactions within the VR environment are facilitated through physical walking and hand gestures enabled by hand-tracking technology. Continuous pre-tests conducted by programmers and senior staff allowed iterative adjustments to be made during the development of the application.

Before beginning the training sessions, participants complete an integrated tutorial within "Wegfest." The tutorial introduces users to interaction patterns and helps them navigate the virtual world. It allows participants to individually practice various movement sequences, serving both as onboarding for senior citizens—most of whom are unfamiliar with VR—and as a test of its usability. The tutorial explains and tests functionalities, interaction processes, and overall applicability. It also assesses the combination of wearing the VR headset while physically walking.

Upon successful completion of the tutorial, participants proceed to the first scene, which loads a predefined iteration. An iteration consists of several consecutive road-crossing scenarios configured via a web application. These scenarios feature various vehicle models, including motorized and non-motorized types. A white circle on the opposite side of the curb serves as a target marker (see Figure 1).

The scene configuration parameters in the VR application "Wegfest" are designed to replicate real-world road-crossing conditions, incorporating both acoustic and visual stimuli. Acoustic inputs include vehicle mobility sounds (e.g., electric or motorized vehicles) and ambient noises such as voices or music. Visual inputs encompass various crossing distances (e.g., lane width), crossing aids (e.g., traffic lights, crosswalks, traffic islands), and different daytime conditions (e.g., day, twilight, night). Figure 2 illustrates a nighttime scenario in "Wegfest," featuring an e-scooter or bicycle.

Scenes can be generated in "Wegfest" that contain the following configuration parameters:

- Lane type: single lane, dual lane, with cycle path (if cyclists intend to ride)
- Crossing aids: Traffic light, crosswalk, traffic island, no crossing aid
- Traffic volume: low, medium, high
- Speed zones: 30 km/h zone, 50 km/h zone, 70 km/h zone
- Time of day: Day, twilight, night
- Electromobility: low, medium, high
- Cyclists: present (yes) or not present (no)

The selection of scenes for each iteration in the VR application "Wegfest" is based on predefined parameters that reflect real-world road-crossing conditions. These parameters include acoustic and visual stimuli relevant to the crossing environment. To ensure adaptive progression in training, the difficulty level of individual training units is continuously increased across iterations. This is achieved by configuring the scenes based on weighted parameters derived from research assessing their relevance as influencing factors in road-crossing scenarios. These weighted parameters form the basis for training variability.

The training design utilizes a value-based system, where scenes are configured by selecting parameters with corresponding difficulty gradations (e.g., 1 = easy; 3 or 4 = difficult). By summing the numerical values assigned to each parameter, a total score is calculated that represents the difficulty level of a given scene. Table 1 provides an example of a training unit consisting of seven distinct scenes with varying difficulty levels, resulting in a total parameter sum of 48.

This adaptive approach ensures that the training sessions are tailored to progressively challenge participants while maintaining engagement. By systematically increasing the complexity of road-crossing scenarios, "Wegfest" aims to enhance cognitive, physical, and behavioral skills critical for safe road-crossing among senior citizens.

Intervention study

Research design and test subjects

As part of the intervention study, the effects of VR training with "Wegfest" were investigated by simulating various road-crossing

FIGURE 1
Intervention setup showing a participant using the Wegfest VR application (left) and a screenshot of the virtual environment (right). The scene demonstrates the use of hand-tracking and physical walking for interaction, as well as the visual layout of a typical road-crossing scenario in "Wegfest".

FIGURE 2
Screenshot of a nighttime road-crossing scenario in "Wegfest" featuring non-motorized vehicles (e.g., e-scooter or bicycle). The figure illustrates the range of configurable scene parameters, including time of day, vehicle types, and crossing aids, used to simulate real-world conditions and progressively increase training difficulty.

scenarios. The sample size was determined using a G*Power analysis. Given that this was an experimental study aimed at collecting initial data, a large effect size ($dz = 0.8$) was deemed sufficient. The research question was undirected, with a significance level of $\alpha = 0.05$ and a β-*error* not exceeding 0.05, resulting in a test power of $1-\beta = 0.95$.

This high statistical power was chosen to minimize the likelihood of Type II errors and to ensure that even moderate to large effects could be reliably detected, which is particularly important in exploratory studies with novel interventions. Additionally, the sample size calculation accounted for potential dropouts and non-compliance, which are common in studies involving older adults and technology-based interventions. By adopting these parameters, the study aimed to balance feasibility and statistical rigor, thereby providing a robust foundation for future, larger-scale investigations.

A total of $n = 29$ participants were recruited for the study, of which $n = 20$ met the inclusion criteria and were included in the final analysis. Table 2 outlines the inclusion and exclusion criteria defined for participation in the intervention with the VR application. Particular care was taken to ensure that participants were in good health to minimize potential risks associated with VR usage.

Senior citizens aged 75 and older are disproportionately affected by traffic accidents, often due to incorrect road-crossing behaviors (Federal Statistical Office - Destatis, 2021). To address this issue preventively, the intervention study recruited participants aged 70 years and older. The age of the participants ranged from 71 to 81 years ($M = 74.95$, $SD = 3.17$). Of the total sample ($N = 20$), 60% were male ($n = 12$) and 40% were female ($n = 8$). Additional participant characteristics are presented in Table 3.

Additional exclusion criteria, not listed in Table 2, were applied during the screening process. These criteria included failure to meet specific cut-off values in pre-intervention assessments and an individual evaluation by the study management based on anamnestic abnormalities. To ensure participant safety, only individuals in good health were selected for the study.

TABLE 1 Configuration of a scene in "Wegfest".

Scene	Lane width	Speed zones	Crossing aids	Time of day	Traffic volume	Electromobility	*Score*
1	1	1	1	1	1	1	*6*
2	1	1	1	1	1	2	*7*
3	1	1	1	1	2	1	*7*
4	1	1	1	2	1	1	*7*
5	1	1	2	1	1	1	*7*
6	1	2	1	1	1	1	*7*
7	2	1	1	1	1	1	*7*
							48

TABLE 2 Inclusion and exclusion criteria of the test subjects.

Inclusion criteria	Exclusion criteria
Age>70 years	Contraindications for VR, e.g., epilepsy, dizziness
No risk of falling	Severely restricted walking ability
Independent living	Severe balance problems
Physically fit	Cognitive limitations
	Bedriddenness
	Severe cardiovascular diseases
	Use of aids (rollator, walking stick, etc.)
	Severely impaired vision
	Disease of the eyes with severe visual impairment
	Severely impaired hearing

TABLE 3 Sample characteristics and health conditions.

Characteristic	Value (n = 20)
Age, mean (SD), years	74.95 (3.17)
Age range, years	71–81
Health conditions, n (%)	
Diabetes mellitus	4 (20)
Rheumatic disease	2 (10)
Hypertension	3 (15)
Osteoarthritis	11 (55)
Hypothyroidism	1 (5)
Initial sample size	29
Excluded due to low attendance (<75%)	6
Final sample size	20

Participants received detailed information about the study's procedures, duration, and objectives during a personal interview and through written documentation. Informed consent was obtained in writing before participation, ensuring compliance with data protection regulations.

Assessments

Before conducting the VR intervention, various questionnaires and assessments are utilized to evaluate the physical and psychological suitability of the test subjects. To ensure a high level of reliability, all screening procedures are conducted by the study management. Each procedure is carried out individually with the test subjects, allowing any questions or concerns to be addressed directly.

A specialized questionnaire is employed to assess susceptibility to cybersickness or motion sickness. The questionnaire combines elements from the Cybersickness Susceptibility Questionnaire (CSSQ) (Freiwald et al., 2020) and the Simulator Sickness Questionnaire (SSQ) (Bimberg et al., 2020). These tools provide a comprehensive evaluation of potential adverse effects related to VR usage.

To assess health status and physical performance, several evaluations are performed both at the beginning of the intervention (pre) and after the final training session (post). One key assessment is:

1. Timed Up and Go (TUG) test: This test evaluates functional performance in terms of mobility, agility, and balance (Podsiadlo and Richardson, 1991). It also provides insights into fall risk among senior citizens. The test involves measuring the time taken for a participant to rise from a chair, walk 3 m, turn around, return to the chair, and sit down. A cut-off value of less than 20 s indicates unrestricted everyday mobility, while higher times may suggest increased fall risk or mobility impairments.
2. Falls Efficacy Scale-International (FES-I): The German version of the Falls Efficacy Scale-International (FES-I) was employed to assess fall-associated self-efficacy among participants. The scale consists of 16 items addressing complex functional activities and social aspects of self-efficacy (Dias et al., 2006). The FES-I demonstrates high internal consistency (*Cronbach's* $\alpha = 0.96$), excellent test–retest reliability ($r = 0.96$), and an average inter-item correlation of $r = 0.55$ (range = 0.29–0.79).

3. Montreal Cognitive Assessment (MoCA): To evaluate cognitive deficits, the Montreal Cognitive Assessment (MoCA) was administered at both measurement points (pre and post-intervention). The MoCA assesses various cognitive domains, including memory, abstraction, executive functions, attention, and visuospatial abilities. This screening tool is particularly relevant for the VR application "Wegfest," as executive functions and attention are critical for road-crossing scenarios (Nicholls et al., 2022). A cut-off score above 26 points indicates normal cognitive function

The inclusion of cut-off values aims to ensure that only the healthiest participants are recruited for the VR intervention study. Additional individual factors were recorded and evaluated through a medical history procedure conducted by the study management. To complement these assessments, participants' subjective perceptions of self-confidence during road crossings were recorded after each VR scene. Using integrated selection buttons in VR, participants answered the question: "How safe did you feel during this road crossing?" with response options ranging from (1) very unsafe to (4) very safe.

Ethics approval for the study was granted by the German Sport University Cologne under reference number 095/2022.

Data analysis was performed using IBM SPSS Statistics 22© for Windows and Microsoft Excel 2010©. The Shapiro–Wilk test was used to assess the normality of the data, which is appropriate for sample sizes of $n < 50$. If the p value exceeded 0.05, the null hypothesis of normality was not rejected.

Intervention study procedure

A spacious training room is essential for conducting the intervention study, which led to the consideration of several suitable venues. These included a training room at a physiotherapy practice in Cologne, a large meeting room at a medical facility in Düsseldorf, and the parish hall of the Protestant church in Düsseldorf.

The training design of 'Wegfest' is based on the recommendations of the American College of Sports Medicine (ACSM, 2006), which advocate a maximum of 8–10 exercises per session. Due to the innovative VR-based training approach employed in this study, the number of scenarios per session was limited to seven, with each scenario considered an individual 'exercise.' A buffer was also incorporated into the program to allow for repetitions, enabling participants to safely experience potentially hazardous situations or accidents. Each training session lasted between 20 and 30 min.

The ACSM guidelines also recommend conducting training sessions twice per week, with a rest day in between. This protocol serves as the basis for the study's 4-week training program, comprising eight sessions carried out over a 3-month intervention period. Schönhuth and Jerrentrup (2019) highlight that seniors require repeated exposure to new technologies to become familiar with them and use them effectively. Therefore, participants receive individualized support during each session to address questions and provide assistance as needed.

As the training progresses, the difficulty level is gradually increased by presenting different scenarios adjusted through specific parameter settings. To ensure consistency, the training plan remains identical for all participants. VR content is mirrored onto a tablet, allowing external observers to monitor participants' actions within the virtual environment. For safety, participants are closely supervised by the study director, who remains present to respond promptly to unexpected reactions such as stumbling, falling, or nausea.

Results

The drop-out rate for the study was 31.03%. Reasons for exclusion included the following: one participant exceeded the TUG cut-off value with a time of 23 s; two participants discontinued training due to symptoms of motion sickness during the second or third session; and six participants were excluded due to irregular training attendance (i.e., less than 75%, or fewer than six out of eight sessions), which was necessary to ensure data reliability and validity (Schmucker et al., 2016).

The results demonstrated a normal distribution for the Timed Up and Go (TUG) test at both measurement points. A paired-samples t-test was conducted to compare pre- and post-intervention measurements. There was a statistically significant difference between pre-intervention and post-intervention scores; $t\ (19) = 3.50$, $p = 0.002$. The mean difference was 0.46 ($SD = 0.59$), 95% *CI* [0.19, 0.73]. *Cohen's d* was 0.78, indicating a large effect size, with a 95% confidence interval [0.27, 1.28].

For the Montreal Cognitive Assessment (MoCA) and the Falls Efficacy Scale-International (FES-I), normality was not observed; therefore, the Wilcoxon signed-rank test was used for analysis. The significance level was set at $\alpha = 0.05$. For the MoCA, there was no significant difference between pre- and post-intervention measurements, $z = 0.58$, $p = 0.564$, $SE = 7.79$. Thus, the null hypothesis could not be rejected, indicating no significant change in cognitive performance.

In contrast, analysis of the FES-I revealed a significant difference between measurement times, $z = -2.82$, $p = 0.005$, $SE = 12.42$. These findings suggest that the VR intervention led to improvements in fall-related self-efficacy and potentially mobility among older adults.

Subjective assessments were also analyzed alongside objective measures at both time points. Participants rated their perceived safety during virtual road crossings on an ordinal scale from 1 (very unsafe) to 4 (very safe). Statistical analysis using the Wilcoxon signed-rank test, based on 140 paired ratings from 20 participants, showed a significant change in subjective perception, $z = 7.16$, $p < 0.001$, $SE = 313.67$, $\alpha = 0.05$. The high z-value results from the large number of paired observations included in the analysis, as calculated by SPSS. These results indicate that participants reported a significant improvement in their perceived safety following the VR intervention, suggesting that VR training not only enhances objective performance but also positively influences self-perception among older adults.

Discussion

Key findings

The VR training application 'Wegfest' offers a promising approach to promoting healthy aging by providing older adults with a safe and realistic environment to practice street crossing. In addition to physical training, the application aims to enhance self-efficacy in navigating real-world traffic situations. The study results indicate that training with 'Wegfest' can lead to positive outcomes, as reflected in significant improvements across various assessments. Notably, participants demonstrated marked improvements in their TUG scores, suggesting enhanced mobility and agility, as well as in their FES-I scores, indicating a reduced fear of falling. These improvements, observed between pre- and post-intervention measurements, suggest that the VR training program effectively supports both physical competence and psychological well-being—two critical factors for maintaining independence and quality of life in older age.

The findings are in line with previous research on the use of VR-based training to enhance mobility and prevent falls among older adults. Studies by Corregidor-Sánchez et al. (2021) and Zahedian-Nasab et al. (2021), for example, show that VR-supported interventions can achieve effects on functional mobility parameters, such as the TUG, that are comparable to or even surpass those of traditional training methods. Similarly, other studies (e.g., Donath et al., 2016; Zitti et al. (2025)) report significant reductions in fear of falling (FES-I) following VR interventions, reflecting increased self-efficacy and a greater sense of safety in daily life. The observed improvements in TUG and FES-I scores are consistent with international findings that recognize VR as an effective tool for promoting mobility and preventing falls in older adults. At the same time, the results underscore the importance of adapting VR training programs to the specific needs and abilities of the target group to ensure lasting effects beyond the training context.

The integration of simultaneous visual and auditory cues—such as conversations in a café, music, and traffic sounds—significantly enhanced the sense of realism and presence within the VR environment. This heightened presence, as supported by the findings of Cowan and Ketron (2019), improves the learning experience by making the training more engaging, memorable, and ultimately more effective in fostering positive behavioral changes. The study demonstrates that VR interventions aimed at enhancing mobility can be developed on a scientifically sound basis. It also underscores the potential of innovative technologies like 'Wegfest' to improve the mobility of older adults, contributing to the growing body of evidence supporting the feasibility and effectiveness of immersive learning. The careful selection of participants and the development of specific assessments for VR suitability also speak to the practicality and potential impact of the application.

In summary, the results of the 'Wegfest' study suggest a trend toward improved mobility and enhanced self-efficacy among older adults participating in VR-based interventions. These improvements support healthy aging, independence, and overall wellbeing in later life. By offering a safe, engaging, and effective way to practice street-crossing skills, 'Wegfest' helps older adults maintain their autonomy and participate more actively in their communities. Moreover, the study's success in demonstrating the feasibility and effectiveness of immersive learning lays the foundation for future research and development in this dynamic and rapidly advancing field.

Limitations

Although the 'Wegfest' study provides evidence for the potential benefits of VR-based mobility training for seniors, several limitations must be taken into account when interpreting the results and planning future research. These limitations underscore the challenges of transferring behavioral improvements observed in a controlled VR environment to real-world outcomes.

A major limitation lies in the difficulty of replicating the complexity and subtlety of real-world environments within a virtual setting. Although the computer-generated street scenarios in 'Wegfest' strive for realism, they inevitably shape users' perceptions of the simulation. As Benoit et al. (2015) emphasize, the design of VR applications significantly influences the sense of presence, which in turn can impact user behavior. Heightened curiosity about the immersive VR environment and the novelty of interacting with new technology may prompt participants to take greater risks, potentially leading to an overestimation of their abilities within the protected virtual space and resulting in negative consequences in real-world contexts. Additionally, the Hawthorne effect—where participants modify their behavior simply because they are being observed—may have contributed to behavioral changes during the study.

Although 'Wegfest' focuses on VR-based training, it remains unclear how comparable applications developed in augmented reality (AR) might impact training outcomes. AR could potentially enhance haptic feedback and auditory realism—such as the perception of surface textures and environmental sounds—which are critical for simulating real-world conditions and may facilitate a more effective transfer of skills to everyday environments.

From a methodological standpoint, a major limitation of the study is its reliance on a relatively small sample size ($n = 20$) combined with a considerable dropout rate of 31%. This raises concerns about potential selection bias, as participants who completed the study may have been more motivated, physically capable, or technologically proficient than the broader senior population. Consequently, the findings may not be fully generalizable, particularly to older adults with lower physical abilities or limited technological experience. Although the inclusion and exclusion criteria ensured thorough screening of the 29 seniors initially recruited, the results must be interpreted with caution due to the small sample size. The development of specific assessments to evaluate participants' suitability for VR, though necessary given the limited existing literature, may have further shaped the sample composition. By excluding individuals with cognitive or physical impairments to create an appropriate cohort for this pilot study, the research focused on a relatively high-functioning subgroup of seniors, which limits the transferability of the results to populations with greater health challenges.

The observation that some participants encountered more hazardous situations or accidents in later training sessions suggests that excessive difficulty levels, fatigue effects, or a decline in perceived realism and presence over repeated sessions may negatively affect performance.

The absence of significant changes in Montreal Cognitive Assessment (MoCA) scores between measurement points raises questions about the intervention's impact on cognitive performance. The lack of effect in the MoCA may be explained by ceiling effects and the instrument's limited sensitivity to subtle or short-term cognitive changes, potentially missing small improvements. Theoretically, the absence of significant changes does not necessarily indicate a lack of effect but may also reflect methodological limitations or insufficient statistical power. For future studies, the use of more specific cognitive tests is recommended to more precisely capture training-induced changes.

This study was designed as a pilot (exploratory) investigation to assess the feasibility and potential effects of the VR intervention 'Wegfest' on physical function, fall-related confidence, and cognitive status in older adults. Given the small sample size, a relatively high dropout rate (31%), and the absence of behavioral measures from the VR sessions, the findings should be interpreted with caution. The results provide initial insights but cannot be generalized to the broader population of older adults. Future studies with larger, more representative samples and the inclusion of behavioral outcome measures are necessary to confirm and extend these preliminary findings.

It remains unclear whether VR training directly leads to improved street-crossing performance or a reduction in accident risk in real-world scenarios, underscoring the need for further validation in real environments.

Future directions

Building on the results of the "Wegfest" study and taking into careful account the identified limitations, several important avenues for future research emerge. These future research directions should aim to enhance the rigor, generalizability, and practical applicability of VR-based mobility training interventions for older adults. A primary focus should be the investigation of the transfer of VR experiences to real-world behavior, with particular emphasis on understanding the mechanisms underlying skill transfer. For instance, analyzing movement patterns during street crossing in "Wegfest"—including sequences of body rotations (eyes, head, trunk)—could yield valuable insights into the cognitive and motor processes involved in safe street crossing. These findings could be compared with those of Kim, Fricke, and Bock (2020), who examined movement behavior during street crossing in a similar context. Such comparisons may inform optimal approaches for the development of mixed reality (MR) solutions. MR, in which virtual and real elements blend seamlessly, could be a particularly promising approach to bridge the gap between the controlled environment of VR and the complex realities of real-world traffic scenarios.

In line with the design implications described by Bitkom (2021), the integration of remote rendering technologies enables AR, VR, and MR applications to more effectively meet real-world demands by allowing real-time visualization and manipulation of highly complex 3D models—such as detailed engines or entire vehicles—without compromising on detail or performance. This technological advancement not only enhances the quality and expressiveness of digital prototypes but also ensures data security, as sensitive design data remain on secure servers and are streamed to end devices only as needed.

Future research should also explore how different parameter weightings influence training effectiveness. Given the observed rise in hazardous situations and accidents during later 'Wegfest' sessions, it is essential to examine the impact of challenging difficulty levels on participants' performance and motivation. An alternative strategy could involve gradually increasing scenario complexity by incrementally introducing new elements while maintaining a consistent overall difficulty, thereby minimizing frustration and enhancing engagement. Incorporating personalized feedback mechanisms tailored to individual performance and learning styles could further improve training outcomes. From a methodological standpoint, addressing limitations related to sample size and participant selection remains a critical priority.

To minimize selection bias and improve the generalizability of results, future studies should focus on the use of randomization, stratified sampling, and transparent study designs, increase sample sizes, and ensure diversity within the participant pool. Strategies to reduce dropout rates are also essential for strengthening data integrity. "Additionally, it is important to clarify how various parameters of VR training can be effectively transferred to real-world situations. A deeper investigation into individual mobility factors is essential for developing evidence-based care approaches that promote mobility behavior in older adults and establish higher quality standards in care. Empirical research is needed to validate frameworks such as CAMIL (Cognitive Affective Model of Immersive Learning), EFiL (Educational Framework for Immersive Learning), and M-iVR-L (Meaningful-Immersive Virtual Reality-Learning Framework) across diverse educational contexts and age groups. The necessity for empirical validation becomes particularly evident when examining the interaction between technological and pedagogical parameters. Future studies should explore how different VR visualization technologies (e.g., head-mounted displays versus laptop-based VR) and instructional methods (e.g., exposure versus exploration) directly influence cognitive and evaluative learning outcomes. It must be considered that these effects are often non-linear and moderated by learning process variables such as sense of presence, cognitive load, and flow (Cabrera Duffaut et al., 2024; Mulders, 2022). For instance, future research could investigate whether laptop-based VR is comparable to head-mounted displays in promoting perspective-taking, an important affective objective in many applications (Mulders, 2022).

Conclusion

The increasing digitalization of healthcare offers innovative opportunities, particularly in the areas of prevention and therapy, thereby making a significant contribution to society. Technological advancements continuously drive the development of tools aimed at enhancing quality of life. In this context, virtual reality (VR) technology is gaining recognition as a valuable resource across a range of applications, including the promotion of health behaviors among older adults (Hajder et al., 2025; Chan et al., 2021). The VR application 'Wegfest,' developed as part of this research project, serves as a prime example of this progress.

VR applications for senior citizens must be tailored to their specific needs. A participatory approach to development ensures the usefulness and accessibility of such applications (Napetschnig et al., 2023). The quality criteria core set for senior-friendly VR applications (Napetschnig, 2024) provides a valuable foundation by outlining specific requirements for designing VR tools for this demographic. In recent years, numerous VR applications have been developed to positively impact the quality of life of senior citizens (Bayshore Healthcare, 2020). Orsolits and Lackner (2020) predict that mixed reality technologies will become ubiquitous across application areas in the future. This trend, coupled with an increasing number of scientific publications on the topic (Diemer and Zwanzger, 2019), suggests that future research will continue to explore and evaluate new fields of application for VR among seniors. Particular attention should be paid to practical suitability and potential long-term effects.

While many use cases have already been established in practice (Orsolits and Lackner, 2020), it remains essential to evaluate the individual suitability of VR technology and analyze its benefits for heterogeneous target groups such as senior citizens. Although initial studies indicate positive long-term effects of VR on seniors (Seifert and Schlomann, 2021; Dermody et al., 2020), further research is needed to adequately address diverse subgroups within this population. This includes investigating the effects of VR applications on real-world behavior.

The exploratory nature of this study highlights both the potential and the limitations of VR-based interventions for older adults. The present results are intended to inform future, more definitive trials and to guide the development of robust evaluation protocols for VR applications in geriatric populations.

In summary, VR technology presents promising approaches for improving health behaviors among senior citizens. The "Wegfest" application demonstrates how innovative technologies can be specifically utilized to promote mobility in older adults. Future research should focus on how different parameters of VR training can be applied to real-life situations and explore evidence-based care models that leverage these technologies effectively.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Ethic Committee at Deutsche Sporthochschule Köln. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

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