# Evacuating in Virtual Reality: Advancing Insights into Individual Behavior at Crowded Events

**Leonie Terfurth***
Technische Universität Braunschweig
leonie.terfurth@tu-braunschweig.de

**Simon Burkard**
Fraunhofer FOKUS
simon.burkard@fokus.fraunhofer.de

**Lars Gerhold**
Technische Universität Braunschweig
Fraunhofer FOKUS
lars.gerhold@tu-braunschweig.de

## ABSTRACT

Knowledge of human behavior is essential to ensure evacuation efficiency at large-scale events. However, gaining necessary understanding of individual behavior in security-related events is challenging due to ethical and logistical constraints in real-life studies. Although virtual reality (VR) simulations are used as a flexible alternative, more research on the applicability of immersive virtual environments for evacuation studies is necessary. This work-in-progress paper presents preliminary results from a project featuring (1) the development of a highly immersive, adaptable VR-based simulation to study behavior and perceptions during evacuations of an open-air event and (2) initial findings on how a virtual crowd influence evacuation route choices and perceptions focusing on herding behavior. The current state suggests strong potential of the environment for evacuation research. Future comparisons of behavior and perceptions in less complex environments will provide further insights into the transferability of results to real-life behavior.

### Keywords

Evacuation, Behavioral Analysis, Virtual Reality, Herding, Exit Choice

## INTRODUCTION

Evacuations of large-scale events, such as concerts, sports games, or open-air festivals may be necessary for various reasons including weather changes, fires, or terrorist threats. Ensuring that such evacuations are conducted safely and efficiently is critical to protecting public safety during emergencies.

However, the behavior of individuals in crisis situations often remains unclear because decision-making in the event of evacuation is complex and influenced by a variety of individual and social-psychological factors, e.g., the behavior of other participants or the way warning messages are communicated (Gao et al., 2023). Consequently, the prediction of actual evacuation patterns and routes of evacuations is a major challenge. Gaining more empirical insights to understand human behavior in crowded evacuation events is crucial to better design evacuation plans and to optimize crowd behavior models for virtual evacuation simulations (Haghani & Sarvi, 2018).

Although empirical studies in real world settings focussing on evacuation behaviors are possible, they present logistical and ethical challenges. The chance of accompanying large-scale evacuations scientifically in real time is low, hence many insights are based on post-event reporting. High-fidelity field simulations of such scenarios are costly and may subject participants to undue levels of stress. Immersive Virtual Reality (VR) simulations have therefore emerged as suitable and cost-effective alternatives to real-world experiments (Feng et al., 2021; Gao

*corresponding author

et al., 2023; Moussaïd et al., 2016). However, the virtual environments that have been used in recent research projects strongly vary in level of immersion, realism of environments, selected evacuation scenarios, and type of stress inducement. Hence, the transferability of results to real-world evacuation behavior in general, and specifically to large-scale open-air event evacuations, remains uncertain. Further studies are essential in this context to analyze whether and to what extent (highly immersive) virtual environments are suitable for reproducing real-world evacuation scenarios. This research is important in order to be able to use VR environments on a valid basis as a low-cost and effective evaluation tool in the future.

This work-in-progress paper reveals the first results of an ongoing research project aiming to advance the capabilities and the understanding of the applicability of virtual environments for evacuation research. First, we present a novel technical solution depicting a highly immersive, virtual open-air evacuation environment. The designed application can be used for evaluating a variety of research questions related to crowd evacuation, e.g., concerning the perception of visual and acoustic warning messages, or experiments on individual evacuation behavior. Second, we describe the procedure and preliminary results of an initial experiment to validate this virtual environment for research on evacuation behavior. Here, we focus on perception of the virtual environment and the virtual crowd, as well as the influence of the virtual crowd on the individual evacuation behavior (herding behavior). Although further investigation is necessary, the results underline potential and usefulness of highly immersive environments for evacuation research.

## RELATED WORK

### Individual Behavior in Crowd Evacuation

Human behavior in crowded evacuation scenarios has been analyzed and discussed in several studies and real-world observations. Their different findings show that human behavior during evacuations is complex and difficult to predict (Haghani & Sarvi, 2018). The specific factors that influence evacuation decisions involve the type of hazard, the scale, and type of the area to be cleared. In scenarios involving crowd evacuations, such as the urgent clearing of a densely packed festival ground, herding behavior is a frequently reported phenomenon (Fagel et al., 2013). It describes the tendency to copy the behavior of others. People observe others and believe that their actions represent a good alternative, leading them to follow (Van den Berg et al., 2018). However, looking deeper into research results, the evidence on the herding influencing behavior of evacuees is diverse and highly depends on the scenario. Some authors found evidence for herding as a strong influencer of exit choice scenarios (Feng et al., 2021; Liu & Mao, 2022; Lovreglio et al., 2016; Moussaïd et al., 2016; Ni et al., 2024; Van den Berg et al., 2018). Other researcher found no tendency of following or even avoiding the crowd (Bode et al., 2014; Haghani & Sarvi, 2019; Li et al., 2019). Gaining deeper insights into human behavior during evacuations is therefore still an important and crucial research question.

### Behavior in Virtual Crowded Environments

While many empirical studies in the past have been based on data collection after real-world evacuation cases, either after actual events or in planned field experiments, VR technology has gained popularity as a powerful cost-effective tool for investigating human responses and behaviors. The VR environments used in these works differ significantly in level of immersion and selection of evacuation scenario.

Li et al. looked at effects of crowdedness on human way finding in a virtual shopping mall. Without focussing on evacuation tasks, they found that visitors tend to avoid virtual crowds (Li et al., 2019). Trivedi and Mousas found that variations in agents' avoidance proximity influenced perceived interaction realism as well as walking trajectories (Trivedi & Mousas, 2023). Also, they showed that additional tactile feedback simulating collisions with virtual crowds influenced participants' movement behavior. The results strongly highlight the influence of design details of virtual agents on behavior and, consequently, emphasize the importance of carefully designing virtual crowds when aiming to gain insights being transferable to real-world behavior. However, these works do not focus on the human behavior in critical situations in the event of disaster or evacuation order.

Further work specifically focuses on virtual evacuation scenarios. For example, Gao et al. compared the factors influencing exit choice in a virtual environment with those observed in field experiments (Gao et al., 2023). They conclude that their virtual environment is a feasible tool for assessing factors affecting exit choice during building evacuations. However, they did not focus on impacts of virtual crowds and herding behavior.

Other studies specifically examine human decision responses and behavior in crowds during virtual evacuation scenes. Bode et al. conducted extensive experiments regarding movement decisions in crowds during virtual evacuation scenarios concluding that people did not have a strong tendency to follow the simulated crowd (Bode

et al., 2014). Notably, they used a simple 2D top-down view of a virtual room with dot-shaped agents and no immersive 3D environment.

In contrast to that, Moussaïd et al. found signs of mass herding and overcrowding in their stress-induced virtual evacuation experiments (Moussaïd et al., 2016). Interestingly, they worked with a small-scale indoor escape experiment in which each virtual agent was controlled by a real participant. However, they also did not use a fully immersive 3D environment with VR headsets and controllers, but instead a virtual environment with uniformly modeled crowds, controlled with mouse and keyboard. Underlining the diversity of results, Zhang et al. examined to what extent evacuees tend to change their initial route choice decision in virtual crowd evacuations depending on the crowd flow (Zhang et al., 2023). They stated that crowd flow modes significantly affect the evacuation performance of the participant, but does not dominate participants' route choices in a single decision. Likewise, Lin et al. investigated the influences of crowd flow and herding effects on route choice during emergency evacuations in virtual metro stations. They found out that participants under mental stress are motivated to follow the majority of the crowd at wayfinding decision points (Lin et al., 2020).

As shown, there are several existing research projects in the field of behavioral analysis in crowd evacuation scenarios using VR technology. However, these works vary significantly in several aspects, for example with regard to level of immersion, realism of environments, selected evacuation scenario, or type of stress inducement. In order to validate the universal applicability of virtual simulations for real-life evacuations, further studies are advisable. In this context, our work brings in some innovative and novel aspects, separating it from existing research: existing studies examine evacuations in buildings (corridors and rooms) and indoor spaces (e.g., subway stations). There is no known work that examines human evacuation behavior in large crowds at large-scale outdoor events using state-of-the art VR technology. In addition, the level of immersion and realism is limited in existing studies. Either, the scenarios cannot be received fully immersive at all (Bode et al., 2014), or are subject to severe technical limitations with regard to the degree of realism, e.g., sparsely modeled virtual agents (e.g., (Moussaïd et al., 2016)) or very limited number of virtual agents (Lin et al., 2020). In contrast, our research work realizes a highly immersive environment with several hundred high-quality textured and animated agents.

## IMMERSIVE OPEN-AIR ENVIRONMENT

For our research work, an open-air music concert was created as a three-dimensional environment characterized by a high degree of realism. The scene includes a large illuminated stage with a music band featuring a singer and groups of dancers, as well as a virtual crowd represented by 250 virtual people (agents) arranged in front of the stage as a crowd of visitors (see Figure 1). Two large digital video screens are located to the left and right of the stage. In addition, two caravans and a construction container are positioned at the rear of the site as additional landmarks. The entire scene is surrounded by trees and fences, interrupted only by two large exits clearly marked with the word *EXIT*. All major structural elements (fences, exits etc.) are mirrored along the center line of the scene, i.e., the left and right sides of the environment are designed analogously to each other. A meeting point in the center of the scene marks the starting point for the participants (see Figure 2).

The virtual agents (visitors, music band) are represented by textured 3D characters with different appearances (in terms of clothing, age, hairstyle, etc.), enhanced with different animations that are randomly assigned to the visitors with pre-defined probabilities. These animations include various active movements (dance movements, clapping, cheering, discussing, walking, running) and quiet animations (idle standing, listening). The scene furthermore contains acoustic elements (music, babble of voices, shouting). In this way, a realistic virtual representation of a typical music festival situation can be achieved, both on a visual and acoustic level.

The virtual open-air environment is implemented using the 3D development platform Unity3D. The animations are realized with the help of the Adobe Mixamo online service, whereas the movement of the virtual agents towards defined target points (e.g., exits) is controlled using an additional Unity asset for crowd navigation. The environment is adapted and graphically optimized for immersive use of virtual reality technology, with the VR user acting as own virtual agent who can move freely around the festival site while experiencing the festival from the visitor's perspective. This VR experience also includes collision handling with other virtual visitors and virtual objects. The integration of VR hardware is realized by the OpenXR plugin.

Based on the open-air festival scene described above, various empirical studies are plausible and technically feasible to analyze human behavior in large crowds through the use of VR headsets. Possible experiments can address the analysis of perception, visibility, and effectiveness of visual or auditory warning messages, the investigation of subjective stress perception in dense crowds, or - as in this paper - how the behavior of other visitors influences one's own escape behavior during evacuations.


**Figure 1. Design of the open-air music festival environment used for the virtual evacuation experiment. (a) Top view highlighting the mirrored layout of the scene with music stage, meeting point (start point) and two exits. (b) Virtual crowd and music band, animated with high degree of realism.**

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## EVALUATION METHODOLOGY

In this work, we use the developed VR environment to empirically investigate the potential and applicability of the virtual solution to realistically depict real evacuation scenarios. For this purpose, we examine the perception of the virtual crowd by the VR participants and the influence of the virtual crowd on the individual evacuation route, focusing on herding behavior. The design of this experiment is described in the following chapter.

### Evacuation Task

The VR experiment was conducted using a Meta Quest 3 device as VR headset (Figure 2c). At the beginning of the immersive scenario, participants were positioned at the central meeting point in the virtual environment. Following a task introduced by the experimenter before the start of the VR experiment, the participants walked to the stage, turned around, and walked to the back end of the area. Here, they scanned the area for two caravans placed in front of the two exits and reported their colors to the experimenter. Afterward, they returned to the meeting point. This training phase was implemented to promote participants' ability to move within the environment and to ensure adequate spatial knowledge, including the awareness of the two festival exits. Up to this point, participants were not aware that an evacuation was about to take place.

Triggered by the arrival of participants at the meeting point, a visual evacuation message was displayed on the two stage screens and played acoustically via virtual loudspeakers, calling for immediate evacuation of the area (*"Emergency situation - please leave the festival area immediately"*, see Figure 2a). Divided into eight virtual groups of people randomly distributed around the site, the virtual crowd gradually started to evacuate the environment through the two available exits (Figure 2b). Targeting an unevenly perceived use of the exits, 80 % of the virtual crowd used one exit (the *crowded exit*), while the remaining 20 % used the other (the *uncrowded exit*). This 80/20 split has also been employed in other studies (Lin et al., 2020). The side of the crowded exit was counterbalanced between participants. The gradual evacuation of the entire virtual mass required around 90 seconds. The VR experiment ended when the participants reached an exit. An exemplary walking trajectory of a single participant is shown in Figure 2d.

### Data Collection

Using event data and motion trajectories extracted from Unity, we examined the objective exit choices of participants, determining whether they evacuated through the *crowded* (used by 80 % percent of virtual agents) or *uncrowded* exit (used by 20 % percent of virtual agents). Also, we compared evacuation durations, measured from the time the evacuation message appeared until the time the participant reached the exit.

Using a questionnaire, we gained insights into subjective exit choices by asking questions on the influence of the virtual crowd (Lovreglio et al., 2016). In addition, we assessed general experience in the virtual world using a visual


**Figure 2. Procedure of the evacuation experiment. (a) Visual warning messages calling for immediate evacuation. (b) Inside VR view of virtual agents leaving the area via exit. (c) Outside view of VR participant. (d) Example trajectory of participant in training and evacuation phase.**

analogue stress scale (pre- and post-evacuation task) and the physical and social presence subscales (Makransky et al., 2017; Volkmann et al., 2018). We measured crowd awareness (related to the concept of situational awareness) by asking participants to estimate the ratio of the agents exit choice (Exit A vs. Exit B). In order to explore subjective differences from real-life evacuation scenarios, we used a semi-structured interview.

The questionnaire was hosted on Lime Survey. Python 3.11.9 was used for data analysis. The plotting of trajectories was done with the geopandas package. Due to the preliminary state of the research and limited amount of data, no inferential statistics were applied. We report descriptive data and tendencies. Advanced analysis will be published at a later stage of the project.

### Participants

We recruited 20 participants (65 % female, mean age 21.6 years) via local listings. Data collection took place in December 2024 at Technische Universität Braunschweig. Psychology students were reimbursed with course credit.

## RESULTS

### Exit Choice and Influence of Virtual Crowd

The analysis of the motion trajectories of the participants did not show relevant differences in exit choice by side (55 % Exit A, 45 % Exit B). We observed that 65 % of participants chose the exit crowded by virtual agents, thus 35 % used the uncrowded exit (see Figure 3a). On average, the participants needed 57.4 s (SD = 12.67 s) to evacuate. We see a small difference in evacuation duration between participants who evacuated with the majority of

the virtual crowd and participants who evacuated through the uncrowded exit (crowded: M = 59.69 s, SD = 14.31 s; uncrowded: M = 53.21 s, SD = 8.20 s). However, participants who used the crowded exit spent more time during the evacuation not moving (crowded: M = 10.43 s, SD = 14.86 s; uncrowded: M = 4.04 s, SD = 2.50 s).

Looking at the reported exit strategy, 30 % percent stated that they intentionally used the crowded exit, whereas 10 % of participants reported the intentional use of the less frequented exit. The remaining persons mentioned other reasons for their exit choice, including choosing the exit they saw first and the one that appeared closer. In general, the virtual crowd was reported to be only partly influential on the exit choice (see Figure 3b).The influence of the virtual crowd looks notably higher for participants who chose the crowded exit (overall: M = 3.05, SD = 1.28; crowded: M = 3.38, SD = 1.26; uncrowded: M = 2.42, SD = 1.13) on a scale from 1 (not at all) to 5 (completely).

### General Experience

The comparison of pre- and post-stress ratings did not reveal a clear pattern. The participants indicated that they felt moderately present in the virtual environment (physical presence: M = 3.26, SD = 0.75, on a scale from 1 = not at all to 5 = completely, see Figure 3c). Regarding social presence, they reported only limited experiences of interacting with virtual agents as if they were actual humans (M = 2.11, SD = 0.97). Interestingly, participants who evacuated through the crowded exit appeared to perceive their interactions with the virtual agents as more human-like (crowded exit: M = 2.34, SD = 1.09, uncrowded exit: M = 1.69, SD = 0.51).

It is also noticeable that participants generally struggled to estimate the distribution of virtual agents between exits (see Figure 3d). In contrast to the actual distribution of 80 % to 20 %, participants reported a distribution of 61.40 % (SD = 18.52 %) to 38.60 %. This perceptual difference appears to be stronger for participants who used the uncrowded exit (54.86 %, SD = 14.62 %) compared to participants who used the crowded exit (64.92 %, SD = 19.95 %).

### Differences to Real-Life Evacuation

Clustering the insights of the interviews, we focused on the expected differences in participants' behavior in comparable real-world situations to find out about possible limitations of the developed virtual environment.

Interestingly, the participants reported a range of different perspectives. Some noted that in real evacuation scenarios, they would not have simply chosen the first available exit, but would have thought longer about the choice of exit. Others, however, reported that they would not have taken the time to think about their decision in a real-world scenario, but did so in the virtual simulation. This was related to the observation that they would have acted under panic in real-life situations, whereas they did not experience such emotions in the virtual environment.

Another key aspect raised was that they would not have made decisions on their own in real-world scenarios. Instead, they would either consult the people around them in general or the persons they were attending the festival with. This aspect is related to the most frequently mentioned technical limitation: the inability to exchange information with others, as well as the lack of social connection with some agents. Other areas for improvement included the limited field of vision and the request to adjust the walking speed.

Some participants also reported struggling with the instructions. We suggested following the flow of the environment after completing the training tasks. However, some were unsure whether they were supposed to wait for further instructions from the experimenter when the evacuation message was displayed asking the participants to leave the festival ground.

## DISCUSSION

### Exit Choice and Influence of Virtual Crowd

With only a few more participants using the crowded exit, our data does not present a clear picture of herding (with virtual agents) leading to an increase in participants choosing the crowded exit. This is consistent with the contradictory findings of previous research (Haghani & Sarvi, 2018; Liu & Mao, 2022). Since it is known that herding is influenced by factors such as crowd density (Liu & Mao, 2022), further experiments are necessary here to gain insights on of generalizable effects of virtual crowds.

Interestingly, when looking at the reported reasons for exit choice, our participants frequently reported that they did not intentionally follow the crowd or chose the uncrowded exit. Such statements regarding the irrelevance of the virtual crowd did not arise so frequently in previous studies (Lovreglio et al., 2016). The lower levels of realism and immersion in this previous work may be an indicator that high realism and immersion are relevant factors when

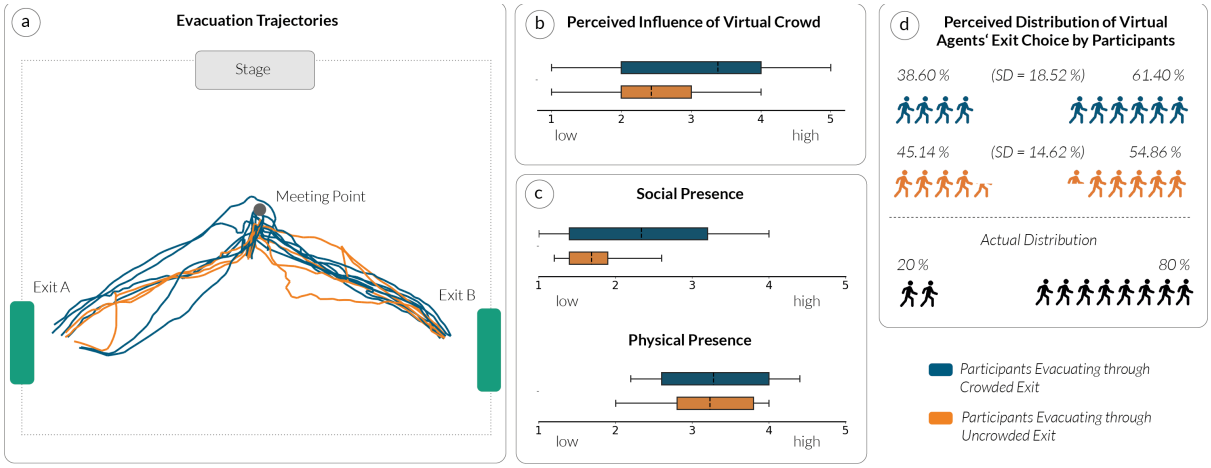


**Figure 3. Overview of key experimental results. In all figures, orange depicts participants that chose the crowded exit, blue depicts participants that chose the uncrowded exit. (a) Evacuation trajectories of all participants. (b) Box plots for reported influence of the virtual crowd. (c) Box plots for presence scales. (d) Pictographic visualization of perceived distribution of exit choices of the virtual crowd.**

aiming for results that can be transferable to real-life behavior. Here, we suspect the first-person vs. 2D bird's eye perspective to have major influence.

Similarly, it is not surprising that the participants struggled to correctly estimate the distribution of virtual agents between exits. In order to assess this distribution accurately, it would be necessary to closely observe the behavior of the other visitors over the entire evacuation period. However, the immersive first-person view does not allow a clear strategic overview of the behavior and routes of the other agents. Most of the participants made their own way to the exit immediately after the evacuation order without actively studying the behavior of the other visitors in detail. Interestingly, this tendency to misjudge the agent distribution seemed to be stronger when the uncrowded exit was chosen. This is in line with the false consensus effect (Ross et al., 1977), that causes people to see their own behavioral choices and judgments as relatively common and appropriate to existing circumstances.

No relevant behavioral conclusions can be drawn with regard to the time required by the participants to successfully evacuate. As we limited participants' walking speed to avoid simulator sickness, the small differences in duration are explainable by a ceiling effect in walking speed. Similarly, for the participants who chose the crowded exit, we observed longer periods in which they did not move. However, this is likely due to situations in which they bumped into other agents. Thus, both are likely to be not the result of cognitive processes, but technical aspects.

Overall, it can be stated that certain differences in behavior between participants were recognizable with regard to the choice of crowded and uncrowded exit. This suggests that the virtual crowd influences individual behavior to some extent. Taking the subjective explanations of the participants into account, this is in line with Li et al. stating that virtual agents either drew the participants to a space or compelled them to avoid it (Li et al., 2019). However, this being a WiP research work, we can not yet make conclusions about the validity and transferability of results to real world behavior.

## General Experience of Virtual Environment

Unfortunately, quantitative measures of presence are rarely included in evacuation research, making direct comparisons between studies difficult. When such measures are used, the PQ (Presence Questionnaire (Witmer & Singer, 1998)) is commonly employed, which focuses on physical presence. Although the scale differences should be acknowledged, our participants reported a higher physical presence as previously observed (Feng et al., 2021; Lin et al., 2020).

To our knowledge, none of the virtual environments used in evacuation research has been evaluated for social presence. Therefore, we cannot make direct comparisons, but acknowledge that the reported results are relatively low. This result is not surprising, considering that some social presence items address features that were clearly not implemented, i.e., responsiveness or awareness of own presence, and interaction (Makransky et al., 2017). However, that people who chose the crowded exit scored higher on perceived social presence may indicate that more contact with the agents increases the perception of interaction with them as with real people.

There were no significant differences in the perception of personal stress levels before and after the VR experiment. This may be due to the unspecific stress measurement method, or due to increased stress levels of the participants before the start of the experiments (e.g., due to the unknown environment or time pressure reaching the lab). In addition, the VR environment was not designed to promote an increased stress level (e.g., no simulation of the exact cause of the evacuation, for example due to a strong explosion).

## CONCLUSION & OUTLOOK

The paper presented the preliminary results of our experimental research work to investigate the applicability of highly immersive VR environments for evacuation research. For this purpose, an initial experiment was designed that investigates influence and perception of the virtual crowd by VR users during evacuations. The experiment examines the behavior of participants in a music concert in relation to the influence of the virtual crowd, using a novel, high immersive virtual open-air environment. The preliminary results provide an inconclusive picture of the influence of the virtual crowd on individual evacuation behavior, being in line with previous empirical research studies.

Although further work is necessary to ensure the validity and transferability of the results to real world evacuations, the quick and straightforward nature of the data collection, the quality of the data, and positive feedback from the participants support the impression of the great potential and the usefulness of highly immersive VR environments for evacuation research in open-air scenarios.

Future work will therefore extend the data collection and examine the validity and significance of the data collected in more detail and provide insights into the transferability to real-world evacuations by comparing the results with evacuation behavior in less immersive and less realistic virtual scenarios. Further improvements and enhancements are also feasible regarding the development of the immersive environment presented here. Firstly, we want to address the limitations identified in the evaluation in terms of degree of reality and social interaction. This includes the integration of adjustable walking speed and improved field of view. In addition, we plan to investigate the possibilities for social grouping by adding interaction options with virtual agents.

Secondly, we want to expand our data collection capabilities to gain more insight into the behavior patterns and experiences of our evacuees. For example, adding eye tracking technology provides great potential for evaluating the modality and design of warning messages. Furthermore, additional biophysiological measurements, such as electrodermal activity and electrocardiography, can provide further objective insights into the experience of stress.

In this context, the use of the developed VR simulation environment is also plausible for other research questions related to open-air evacuations (e.g., in terms of the perception and effectiveness of different types of warning messages). With regard to the application scenario, it is furthermore imaginable to design more complex evacuation environments and scenarios, for example in urban streets or road networks from a traffic safety perspective. In any case, the great potential of high-immersive VR environments already indicated in this preliminary study highlights the wide range of possible application scenarios of such technical solutions for future evacuation research.

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