Crowdsourced Virtual Reality-based Experimental Approach in Pedestrian and Evacuation Dynamics

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Abstract

Virtual reality (VR) technology has been increasingly used in investigating pedestrian behaviors in normal and emergency scenarios. However, traditional VR experiments are confined to lab settings, limiting the number of participants coexisting and interacting in immersive virtual environments (IVEs) due to space and device constraints. We propose a novel approach - crowdsourced virtual reality (CVR)-based experimental approach, which expands traditional lab-based VR experiments to an online environment and allows to access participants in a crowdsourced manner. The proposed approach contains a web-based platform and a process model. A classic experiment on unidirectional pedestrian flow was conducted to validate the CVR experimental approach. The widely-recognized characteristics of pedestrian dynamics were successfully reproduced in the experiment. The first of its kind, the proposed approach enables researchers to access participants across barriers of geography, culture, age, and social identity, and yield representative and generalizable behavior data for pedestrian and evacuation dynamics (PED) research.

Keywords: Crowdsourcing, virtual reality, pedestrian and evacuation dynamics

1 Introduction

The emergence of virtual reality (VR) technology has reshaped the way researchers construct and conduct scientific experiments on pedestrian behaviors in normal and emergency scenarios, due to VR's inherent advantages in facilitating human-computer interactions and simulating complex disaster scenarios. Previous studies utilizing VR experiments have explored a broad spectrum of topics in the area of pedestrian evacuation and dynamics. In normal conditions, researchers have explored aspects such as pedestrians' local interactions with neighbors (Rio et al., 2018; Warren, 2018) and inter-person distance and walking speed (De Schot et al., 2023). In emergency conditions, investigations encompass psychological and physiological response, cognitive process (Chen et al., 2023b), exit and route choice (Lovreglio et al., 2016), spatial knowledge and navigation (Cao et al., 2019; Chen et al., 2023a) during evacuations, as well as evacuation training and education (Feng et al., 2020). However, previous VR experiments conducted within laboratory settings faced several limitations: (1) the sample representativeness and the external validity of research may be influenced by the biased participant recruitments in the traditional laboratory experiments (Henrich et al., 2010); (2) the research reproducibility and generalizability may be impaired by the considerable time and transportation costs associated with laboratory experiments; and (3) investigations on human interactions within large crowds may be impeded by the constrained number of participants that can coexist and interact in the immersive virtual environment (IVE).

To overcome the above limitations, this study proposed a novel approach for conducting experiments using crowdsourced virtual reality (CVR). This approach collects behavioral data from a diverse group of participants through an open call or invitation extended to the public, which allows researchers to expand lab-based VR experiments to an online environment and involve participants in a crowdsourced manner. The CVR experimental approach consists of a web-based platform and a process model, which provide the technical and methodological supports for researchers to conduct CVR experiments. The CVR experimental platform was developed based on Hubs (Mozzila community, 2024), which can run online crowdsourced experiments, and record various types of experimental data related to the system and network performance, as well as participants' movements, interactions, and fields of view. The CVR experimental process model is proposed to help manage participants remotely and yield high-quality experimental data. To validate the proposed CVR experimental approach, a classic pedestrian dynamic experiment on unidirectional pedestrian flow through bottleneck was conducted. The results showed that the CVR experiment successfully reproduced the key characteristics of pedestrian flow widely recognized in the pedestrian dynamics field. The first of its kind, the CVR experimental approach enables researchers to access participants in IVEs across barriers of geography, culture, age, social identity and so on, and yield representative and generalizable behavior data for pedestrian and evacuation dynamics (PED) research.

2 The CVR experimental approach

The proposed CVR experimental approach expands traditional lab-based VR experiments on PED to an online environment in a crowdsourced manner, which is expected to be an effective tool for crossing the barrier of sample bias in lab experiments and increasing external validity (Draschkow, 2022). To provide technical and methodological support for researchers, a platform and a process model were developed for the CVR experimental approach.

2.1 The CVR experimental platform

Recently, the Metaverse has experienced rapid development, with the emergence of social VR platforms, which enable geographically separated participants to co-exist and interact in a virtual shared space (Koshnicharova et al., 2022). However, existing social VR platforms (e.g., VRChat (VRChat, 2024), Rec Room (Rec Room, 2024)) do not meet the requirements for a CVR experiment with restrictions in their extensibility to future requirements, level of customization in interaction design, and data collection permissions (Cheng et al., 2022; Radiah et al., 2021; Saffo et al., 2021, 2020). Thus, a new CVR experimental platform is needed to address the technical challenges for the CVR experimental approach.

The CVR experimental platform in this study was developed on an open-source project called Hubs (Mozzila community, 2024), encompassing both the back-end and front-end components, as shown in Figure 1. The back-end server provides essential services, including the synchronization of scenario information and data transfer. Real-time synchronization of events within the IVE, such as avatar movements, voice interactions, and room host operations, is facilitated through a WebRTC-based technique over the Internet. The database management system is designed to store and manage two categories of data. The first category is scenario data, which includes avatar figures, animations, 3D models, and interaction events. The second is experimental records generated by clients, which include log data and behavioral data. Log data records device ID and types, login/logout time, and network performance metrics. Behavioral data captures VR headset and controller coordinates from participants' terminals, sampled at the VR terminal refresh rate.

Within the front end, two distinct user roles are designed, namely admin and visitors, contingent on whether the user logs in with a researcher account. Room visitors can join the rooms created by the host, talk and text with other participants, and navigate and interact with the VE upon obtaining permission from the host. Additionally, the room host owns higher privileges on experimental room creation, participant management, scene changes, experimental process control and full data access. For an immersive experience, participants are recommended to log in with a head-mounted display (HMD), while the researcher can use a personal computer interface for the additional functions.

As for the platform's interaction design, the first aspect pertains to locomotion methods. For VR devices, three locomotion methods are pre-defined including walking in the physical space, moving at a constant speed using a joystick, and the ArmSwinger technique (Keller, 2016). Under the ArmSwinger mode, participants' movement speed in the VE is determined by the arm swing speed of the controllers they hold, with the relationship controlled by a configurable parameter. Researchers can choose any of the three locomotion methods based on the specific demands of their experiment. For PC users, avatar movements are controlled by the keyboard. Second, the collision simulation among participants is achieved by equipping each avatar with a built-in collider with a configurable radius. Third, vocal communication utilizes spatial audio techniques, by which the voice volume dynamically changes based on the distance between two avatars.

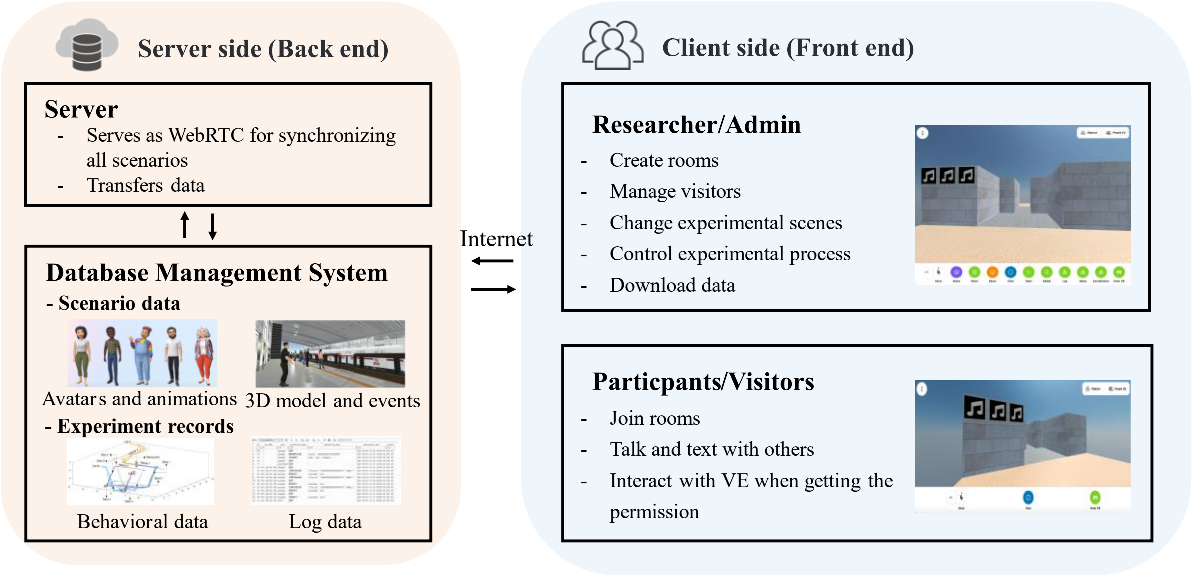


Figure 1. The CVR experimental platform and its interfaces.

2.2 The CVR experimental process model

A structured and well-organized workflow is crucial to ensure that CVR experiments are conducted in a scientific manner, thus improving the data quality and overall research validity. To solve the methodological challenges, a CVR experimental process model, as shown in Figure 2, is proposed based on (1) references to the process model specifically for extended reality-enabled experimental research (Li et al., 2022); (2) references to the best practice and lessons derived from the unsupervised and remote VR research (Mottelson et al., 2021; Radiah et al., 2021); (3) the recommended guidelines for social VR studies including ethics approval, recruitment, participant privacy, platform technical challenges, experimental design and data retrieval (Saffo et al., 2021). The CVR experimental process model is structured into four sequential phases, including experimental design, participant crowdsourcing, remote training and experiment, and data collection and analysis. It should be noted that the process model by Li et al. (2022) has fully explained how VR-enabled research should be planned, designed, implemented, analyzed, verified, and validated. Consequently, the proposed CVR experimental process model focuses less on the VR aspects and primarily addresses the specific concerns and considerations arising from the challenges inherent in crowdsourced and remote experimentation.

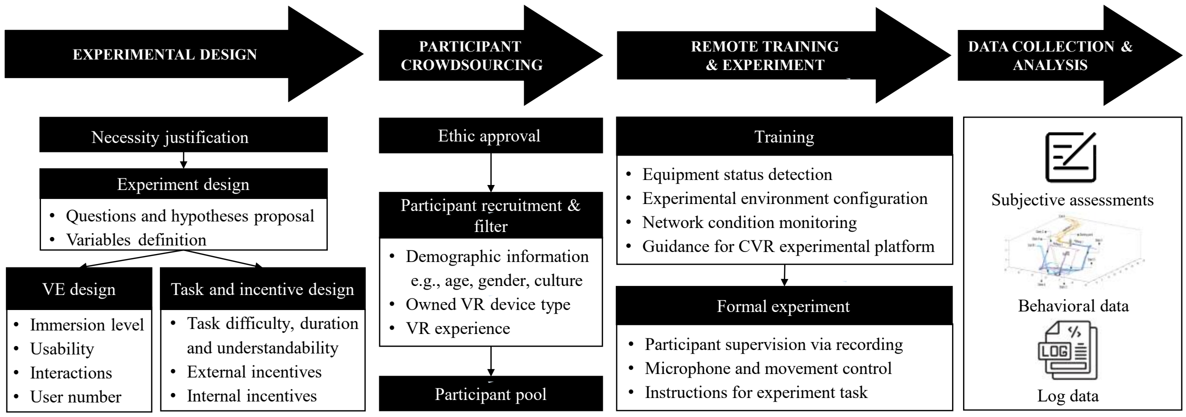


Figure 2. The CVR experimental process model.

2.2.1 Experimental design

Researchers should first deliberate on the necessity of conducting the research in a crowdsourced manner, trading off experimental controllability and generalizability. More importantly, researchers must prioritize aligning the research purpose with the primary advantage that CVR experiments can offer - a shared virtual space facilitating interactions among a diverse crowd of participants. Then, specific research questions and hypotheses should be carefully developed. For the detailed experimental design process, refer to (Li et al., 2022). Next, considering the rendering capabilities and affordances of the experimental platform, a trade-off between the operation smoothness, immersion levels, and the user number should be made when designing the VE and interactions. Additionally, the experimental task and interaction method should be easy enough for participants to understand. Lastly, to avoid participants being distracted from the experiment, both external incentives (e.g., rewards and penalties) and internal incentives (e.g., task interest) should be involved in the experiment. For instance, researchers could fully explain the research purpose and value to the participants to induce their interests and responsibilities.

2.2.2 Participant crowdsourcing

The first step is to ask for ethics approval. Researchers must ensure that their research design minimizes the risks to participants and aligns with the Belmont Report's principles of beneficence, respect, and justice (*The Belmont Report*, 1979). Data privacy issues should be seriously addressed. Researchers can consider a higher compensation rate for participants due to the overhead of setting up their own HMD equipment. Secondly, participants can be recruited from various sources, such as social media, VR-related forums, university email lists, and friend recommendations. It is crucial to obey forum rules during recruitment. Questions about demographic information, VR device ownership, and VR experience should be included in the registration questionnaire to help filter qualified participants. Due to the lower controllability of remote participants, stricter rules than lab experiments should be established for their participation. For example, participants breaking instructions may not receive rewards or be eligible for further experiments. Lastly, it is recommended to establish a participant pool to retain individuals interested in the research and facilitate participant recycling, considering the challenge of recruiting qualified participants.

2.2.3 Remote training and experiment

The effectiveness of training highly determines the success of the formal experiment. During the training phase, participants should be asked to carefully check their equipment and experimental environment configurations on their own devices. This includes ensuring that the VR devices, including the helmet and controllers, have sufficient power to complete the experiment, microphones are active, and time zones align with experimental requirements. The checking process should be recorded by participants' own VR devices and uploaded to the cloud for the researcher's verification. The researcher should also examine participants' network conditions by accessing log data from the CVR experimental platform. Guidelines should be provided in various formats, including text, video, and vocal instructions through virtual meetings to help participants become familiar with the CVR experimental platform. Additionally, unqualified participants in the training phase should not be permitted to participate in the subsequent formal experiment.

Participants are required to use the same device and network utilized in the training phase and set experimental environment configurations in advance. For experiments with a strict requirement on a fixed sample size, researchers should emphasize the importance of punctuality, and penalties may be imposed for late attendance. To create a supervised environment in the remote experiment, the whole experimental process should be recorded by participants and then uploaded to the cloud. Throughout the task instruction process, researchers should turn off participants' microphones and movement functions to maintain their focus on the instructions.

2.2.4 Data collection and analysis

Subjective assessments, behavioral data and log data are collected by the CVR experimental platform. The design of subjective assessments should prioritize simplicity for easy completion; otherwise, items for distraction detection need to be set in the questionnaire. Meanwhile, considering the slight lags among different devices and time delays between local clients and the cloud server, meticulous preprocessing is essential to ensure the alignment of all objective data in the same timeframe.

3 Experiment and results

Bottlenecks are a critical element that determines the evacuation performance of building layout designs. The pedestrian flow through bottleneck has been one of the most investigated topics in the PED area over the past years (Haghani, 2020). The phenomenon where flow increases linearly with bottleneck width (Kretz et al., 2006; Seyfried et al., 2009) has become a fundamental rule in the latest pedestrian dynamics models. Therefore, as the first step in validating the proposed CVR experimental approach, we conducted a classic bottleneck experiment following the CVR experimental process model. The experimental design and results are described in detail below.

3.1 Experiment design and procedure

The experiment is a replication of a real-life classic experiment on unidirectional pedestrian flow through the bottleneck in the field of pedestrian dynamics (Hoogendoorn and Daamen, 2005; Kretz et al., 2006; Seyfried et al., 2009). As shown in Figure 3, participants are initially located in a large orange space with a distance of 0.7m between each other. Considering the difference between the rigid collision in the VE and the flexible squash in real life, the radius of each avatar is set at 0.2 m, slightly smaller than half of one's shoulder width. The ArmSwinger locomotion method was used in this experiment with a ratio of 2:1 of the movement speed in the VE and the arm swing speed at the y-axis. In the formal experiment, participants are instructed to walk through the bottleneck (length = 4 m) in front of them after the starting signal to the other orange area on the other side of the bottleneck. Once participants arrive at the end of the bottleneck, they will be teleported to the initial orange space immediately and be required to walk through the bottleneck again. This process repeats until an end signal appears. This design generates continuous pedestrian flow during the experiment despite the limited group size of the participants. The bottleneck width (b) varied from 0.8 m to 1.8 m at an increment of 0.2 m. A total of 6 trials were performed, one for each bottleneck width. Each trial lasts around 4 to 5 minutes. Both the different bottleneck widths and the initial positions of participants for each bottleneck width were arranged in a random order.

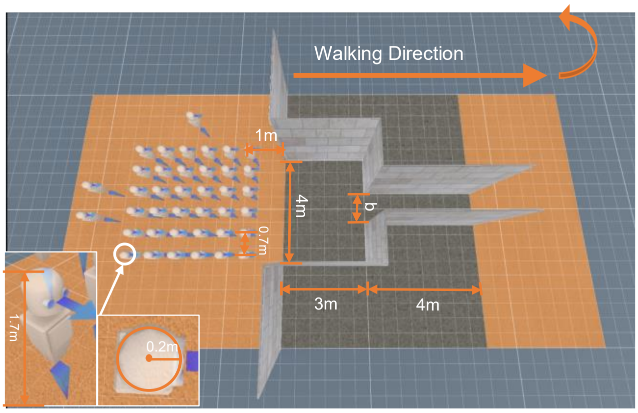
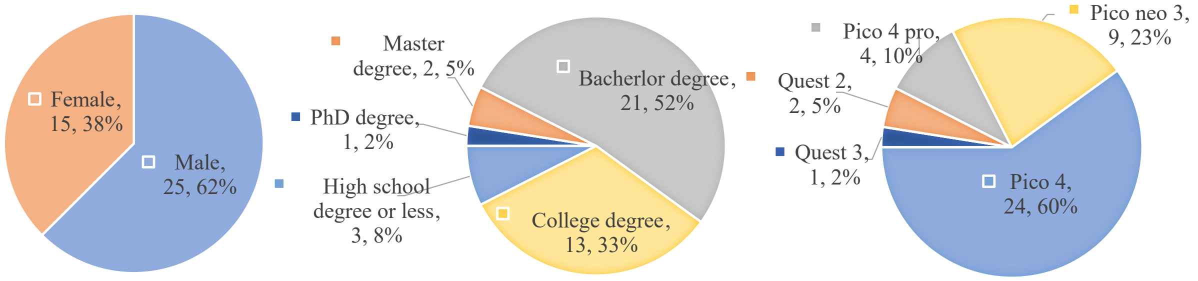


Figure 3. The experimental layout.

The experiment was conducted in December 2023. An online social media group was created to manage all participants, including making announcements and distributing and collecting the informed consent and the pre- and post-questionnaires. All the participants were well-trained and qualified for the formal experiment. At the beginning of the experiment, a pre-recorded vocal instruction was played to all participants. After ensuring all participants fully understood the instructions, the researcher conducted all the trials by changing the scene with different bottleneck widths. This experiment was approved by the Institutional Review Board of Tsinghua University. All participants received monetary compensation for their participation.

3.2 Results

We recruited 40 participants (25 males and 15 females) from various social media platforms, spanning 16 provinces in China, with ages ranging from 21 to 66 years old (*M* = 34.5, *SD* = 8.82). All participants possessed considerable VR experience (*M* = 2.36, *SD* = 1.16, in years) and self-evaluated their skill level as exceptionally high (*M* = 9.05, *SD* = 1.58, on a 10-point scale). The majority of participants had bachelor's degrees, and the primary VR device utilized in the experiment was Pico 4 (Pico 2024), as shown in Figure 4. The experiment, which involved multiple trials for multiple bottleneck widths, was conducted over two days. During each day, 35 participants showed up for the experiment.



(a) (b) (c)

Figure 4. Distribution of participants' (a) gender; (b) education level; (c) HMD devices.

The experimental server was equipped with 2 CPUs and 8GB of RAM, boasting a 200Mbps public network bandwidth. The round-trip times (RTTs) of the platform, hosting 37 users (35 participants plus two researchers) for each trial, are depicted in Figure 5. The RTTs were observed to be relatively low and stable, which indicated the feasibility of conducting CVR experiments over the Internet.

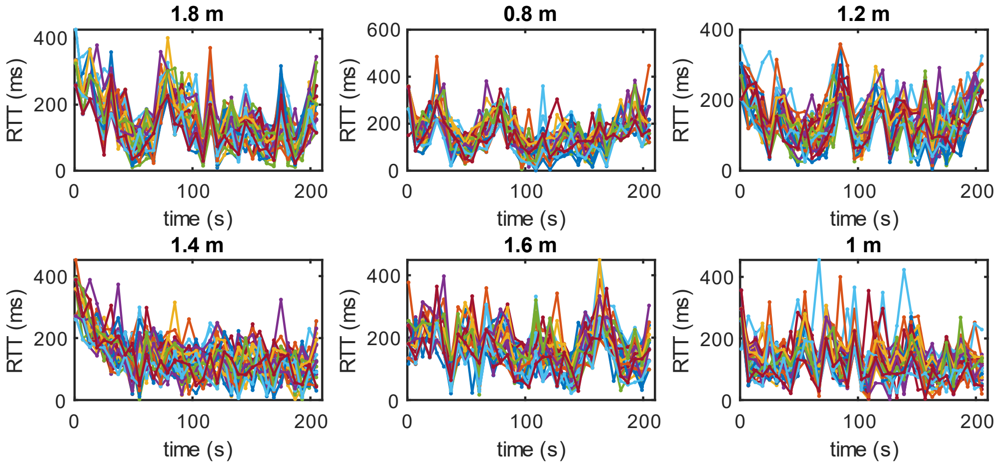
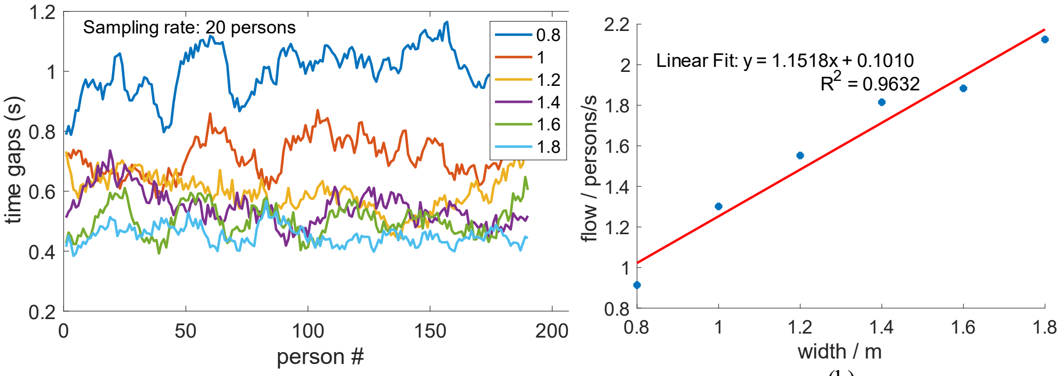


Figure 5. RTTs (ms) for each trial.

To validate the CVR experimental approach, the most fundamental quantitative relationship tested in all bottleneck experiments, namely pedestrian flow increases with the bottleneck width (Hoogendoorn and Daamen, 2005; Kretz et al., 2006; Moussaïd et al., 2016; Seyfried et al., 2009) was selected to be verified in this study. First, to estimate the time dependence of the time gaps, the evolution of the average time gap between two consecutive persons was calculated with a sampling rate of 20 persons, as shown in Figure 6 (a). The time gaps for each width demonstrated relative stability over time. Then, the flow was calculated as the number of pedestrians who enter the bottleneck per unit of time. The relationship between the flow and the bottleneck width was analyzed, as shown on Figure 6 (b). The result successfully replicated the findings in prior empirical studies that showed the flow increased linearly with the bottleneck width (Hoogendoorn and Daamen, 2005; Kretz et al., 2006; Moussaïd et al., 2016; Seyfried et al., 2009).



(a) (b)

Figure 6. (a) The average time gap over time; (b) flow through the bottleneck.

4 Conclusions

In this study, we proposed and validated a groundbreaking CVR-based experimental approach for PED research. A CVR experimental platform and a process model were developed and applied in a classic experiment on unidirectional flow through a bottleneck. The diverse participant pool demonstrated that the CVR experimental approach effectively transcends geographical, educational, and age-related barriers. The stable network conditions affirmed the feasibility of conducting crowdsourced experiments using VR over the Internet. Furthermore, the results from the bottleneck experiment successfully replicated the fundamental findings from the field experiments in previous research, indicating that the flow is independent of time and increases linearly with bottleneck widths. The CVR experimental approach, as the first of its kind, can be a powerful tool for yielding representative behavioral data and generalizable findings for empirical

PED research. In the future, the CVR experimental approach will be further validated and then applied to conducted experiments in PED research.

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