Personal Protection Equipment Training as a Virtual Reality Game in Immersive Environments: Development and Pilot Study

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Abstract

Background: Proper donning and doffing of personal protection equipment (PPE) and hand hygiene in the correct spatial context of a health facility is important for the prevention and control of nosocomial infections. On-site training is difficult due to the potential infectious risks and shortages of PPE, whereas video-based training lacks immersion which is vital for the familiarization of the environment. Virtual reality (VR) training can support repeated practice of PPE donning and doffing in an immersive environment that simulates a realistic configuration of a health facility.

Objective: The aim is to develop and evaluate a VR simulation focusing on the correct order of PPE donning and doffing in an immersive environment that replicates the spatial zoning of a hospital. The VR method should be generic and support customizable sequencing of PPE donning and doffing.

Methods: An immersive VR PPE training tool was developed by computer scientists and medical experts. The effectiveness of the immersive VR method versus video-based learning was tested in a pilot study as a randomized controlled trial (N=32: VR group N=16, video-based training N=16) using questionnaires on spatial-aware order memorization questions, usability, and task workload. Trajectories of participants in the immersive environment were also recorded for analysis.

Results: The analysis of the study data showed that the VR group had significantly better usability in the System Usability Scale (VR: $\mu=74.78,\ \sigma=13.58$ vs. Video: $\mu=57.73,\ \sigma=21.13,\ p=0.009$) than the video group. Comparable sequence memorization scores (VR: $\mu=\ 79.38,\ \sigma=12.90$ vs. Video: $\mu=74.38,\ \sigma=17.88,\ p=0.372$) as well as NASA-TLX scores (VR: $\mu=42.9,\ \sigma=13.01$ vs. Video: $\mu=51.50,\ \sigma=20.44,\ p=0.168$) were observed. The analysis and visualization of trajectories revealed a positive correlation between the length of trajectories and the completion time, but neither correlated to the accuracy of the memorization task. Further user feedback indicated a preference for the VR method over the video-based method. Limitations of and suggestions for improvements in the study were also identified.

Conclusions: A new immersive VR PPE training method was developed and evaluated against the video-based training. Results of the pilot study indicate that the VR method provides comparable training quality to the video-based training with better usability. In addition, the immersive experience of realistic settings and the flexibility of training configurations make the VR method a promising alternative to video instructions. Clinical Trial: Our pilot study was a randomized controlled trial involving University students. It was not a clinical trial and did not involve patients or patient data. Therefore, it was not registered as a clinical trial

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A new immersive VR PPE training method was developed and evaluated against the video-based training. Results of the pilot study indicate that the VR method provides comparable training quality to the video-based training with better usability. In addition, the immersive experience of realistic settings and the flexibility of training configurations make the VR method a promising alternative to video instructions.

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Keywords: virtual reality training; nosocomial infection control; visualization; human computer interaction.

Introduction

Nosocomial infections are infections acquired within healthcare facilities. Such infections not only extend hospital stays and treatments of a patient but can also result in severe complications and even death [[CITATION Kirkland:1999 \l 1033][1],[CITATION Haque:2018 \l 1033][2]][1, 2]. Moreover, healthcare workers face an increased risk of infection due to cross-contamination that can escalate workload and disrupt healthcare services. Implementing preventive measures such as proper hand hygiene, disinfection protocols, appropriate PPE usage, and clean environment maintenance can significantly reduce the risk of such infections [[CITATION Pittet:2006 \l 1033][3],[CITATION Stone:2014 \l 1033][4],[CITATION John2016 \l 1033][5]][3, 4, 5]. Notably, the availability, selection, and proper training of PPE is critical for reducing the risks of nosocomial infections [[CITATION John2016 \l 1033][5],[CITATION Haegdorens2022 \l 1033][6]][5, 6]. The order of and the correct handling during donning and doffing of PPE is critical for reducing infections. It is known that a high risk of contamination exists during doffing[[CITATION Saraswathy2021 \l 1033][7]][7].

On top of that, infection control protocols of a healthcare facility often involve spatial division for different protection and disinfection levels, for example, the operation room requires a higher PPE protection level than that of the outpatient building. In the case of a pandemic, for example, COVID-19, the “three areas and two corridors” division is used for healthcare facilities [[CITATION NHCPR \l 1033][8],[CITATION Chang2024 \l 1033][9]][8, 9]. There, PPE donning and doffing have to be done in specific orders in specific regions to ensure the isolation of contaminated regions from clean regions.

PPE Training in Health Facilities

PPE training is typically organized by each health facility with in-person demonstrations and lecturing. A major benefit of in-person training in a health facility is that personnel can be trained in a real spatial context. However, training in the real environment has severe shortcomings: First, the risk of the trainee being infected and the contamination of the uninfected regions; second, the lack of repeated practice due to the potential shortage of PPE. To reduce differences in training and infectious risks, standardized PPE training videos are available. Participants passively acquire the information as the trainer presents lecture slides or demonstrates the procedure, and need to practice on their own with real PPE equipment that is sometimes in shortage. Simulation-based education is an alternative to lectures as it is effective for PPE training with reduced cognitive load [[CITATION Mumma2018 \l 1033][10],[CITATION DiazGuio2020 \l 1033][11]][10, 11].

Infection Control Training in Virtual Reality

VR and augmented reality (AR) are extensively used in medical training for a wide range of procedures, for example, surgery [[CITATION Yu2023 \l 1033][12],[CITATION Chheang2024 \l 1033][13]][12, 13], needle insertion [[CITATION Heinrich2019 \l 1033][14],[CITATION Heinrich2020 \l 1033][15]][14, 15], and ultrasound [[CITATION Allgaier2023 \l 1033][16]][16]. Compared to AR, VR provides a more immersive experience, saves training costs, and avoids exposure risks and resource consumption in real environments [[CITATION zhao:2021 \l 1033][17],[CITATION kavanagh:2017 \l 1033][18]][17, 18]. Therefore, we decide to devise our training method in VR.

VR methods are available for infection control training for various scenarios [[CITATION Birrenbach2021 \l 1033][19],[CITATION Buyego2022 \l 1033][20],[CITATION Yu2021 \l 1033][21],

[CITATION Yu2022 \l 1033][22],[CITATION Masson2020 \l 1033][23],[CITATION Omori:2023 \l 1033][24]][19, 20, 21, 22, 23, 24]. A VR infection control simulation program is available for training nurses to help children patients with COVID-19 [[CITATION Yu2022 \l 1033][22]][22]. There, donning and doffing of PPE, and the treatment of patients are simulated. However, the immersive environment does not focus on the spatial arrangements of zones of a real hospital; furthermore, the control group of this study did not receive video-based or conventional training but only did a questionnaire survey. For the management of COVID-19 patients, VR methods are developed for the infection control and diagnosis process [[CITATION Birrenbach2021 \l 1033][19]][19] and proper case handling [[CITATION Buyego2022 \l 1033][20]][20].

VR is also used for infection control for operations in specific areas of a healthcare facility, such as preventing surgical-site infections in the operating room [[CITATION Masson2020 \l 1033][23]][23], and in neonatal intensive care units [[CITATION Yu2021 \l 1033][21]][21]. Hand hygiene and PPE donning are taught through 360-degree videos in VR for infection control training which is shown to be superior to traditional slideshow lecturing [[CITATION Omori:2023 \l 1033][24]][24]. However, no work is currently available for interactive training of PPE donning and doffing embedded in an immersive environment with a spatial division for infection control that simulates a real healthcare facility.

Our VR Method for PPE Training in a Spatial Context

In this paper, we propose an immersive PPE training method in VR with simulated spatial division of a hospital for nosocomial infection prevention to address this issue. Our work is a close collaboration with medical professionals who provided healthcare support for the Winter Olympic Games 2022 during the COVID-19 pandemic. Our immersive training method involves the modeling of virtual workspace, the avatar, PPE donning and doffing logic based on the actual setting of the supporting hospital of the Winter Olympic Games. In a pilot study of 32 participants, we compared our new method to traditional video-based instruction learning. Results demonstrate that our VR method has a comparable training quality in terms of memorizing PPE donning and doffing orders with better subjective evaluations.

The main benefit of our method is that it allows the practice of PPE donning and doffing according to the infection prevention and control protocols immersively in a virtual environment that resembles the actual zoning of a hospital without wasting PPE which can be potentially scarce. Another benefit is that our method allows for easy and flexible editing of the donning and doffing sequence with a spatial context that adapts to the actual situation of a health facility.

Methods

Methods of this study mainly involve the collaborative development of the immersive VR training method and a pilot study as a controlled randomized trial.

Immersive VR PPE Training Method

An immersive PPE training method as a mini VR game was developed as a collaboration between computer science experts and medical experts. Based on the requirement analysis, we designed the generic donning and doffing sequence model, the virtual environments, the avatar, and the training logic. Our VR training method was implemented by computer scientists in our group as a Unity application

Requirement Analysis

The requirements were initially proposed by medical experts who took the PPE training in a support hospital for the Winter Olympic Games 2022, and finalized through iterative discussions between computer science experts and medical experts. The hospital was under a high infection prevention and control level to ensure the safety and high-quality healthcare services of the Games. Medical experts identified two challenges: first, PPE includes many items and they have to be donned and doffed properly in the correct order; second, the doffing has to be done in the correct zones that need to be familiarized. Specifically, in this case, PPE includes medical masks, N-95 masks, protection suits, gowns, inner gloves, outer gloves, goggles, face shields, and shoe covers. The hospital was spatially divided using the “three zones and two corridors” protocol and several rooms were allocated for different steps of doffing.

After discussions, both the medical and computer science experts agreed that an interactive VR method should be designed as it can support the repeated practice of donning and doffing and an immersive experience in an environment that simulates the hospital. The requirements of the VR method are as follows.

- R1. Focuses on the practice of PPE donning and doffing sequence.
- R2. Simulates the spatial division of the hospital relevant to PPE donning and doffing.
- R3. Configurable donning and doffing order for flexibility and extensibility.

Therefore, we conceptualized the VR method as a mini-game that guides users to learn the correct ordering. The trainee starts from the donning zone, and s/he has to follow the correct donning and hand sanitation order to get access to the work zone. The door unlocks only after the prescribed donning sequence is successfully performed without any error. Next, in the same fashion, the trainee has to correctly
follow the doffing order with thorough hand sanitation to proceed to subsequent doffing zones to finish the game.

Generic donning and doffing sequence modeling

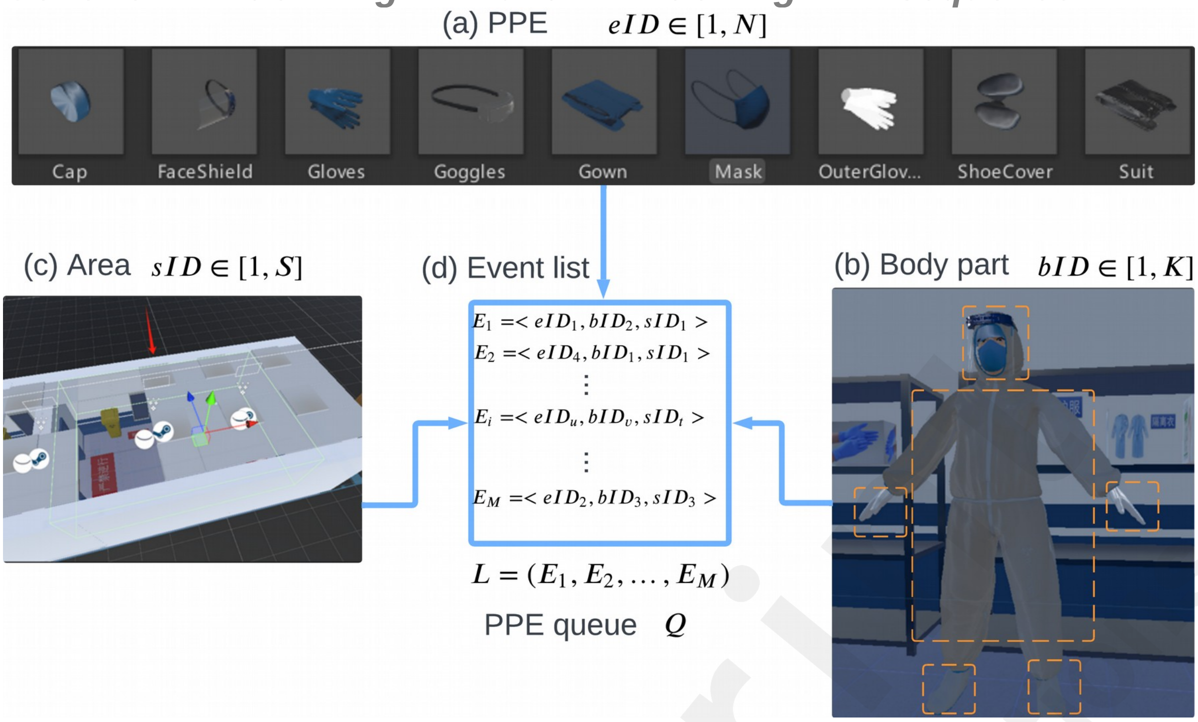


Fig 1: The generic donning and doffing sequence model.

A generic donning and doffing sequence model is devised to enable flexible customization of PPE simulation training (R3). As shown in Fig. 1, each PPE is associated with an eID, body part identifier bID, and region identifier sID. The donning and doffing event triples E_i are recorded in a list L:

$L = (E_1, E_2, \ldots, E_M)$,

$E_i = < eID_u, bID_v, sID_t >$,

where $i \in [1, M], u \in [1, N], v \in [1, K], s \in [1, S]$.

Here, M, N, K, and S are the total steps of donning and doffing, the number of types of PPE, the number of body parts, and the number of zones, respectively. To ensure that all PPE is properly doffed, a queue Q is used to record the PPE status. If a piece of equipment is donned, it is enqueued into Q, and is dequeued if the equipment is doffed, and Q should be empty at the end of the training. The eID and bID in an event was pre-bounded so that the PPE can only be put on or removed when correctly corresponds to the body position and the collision detection has been passed. Therefore, the trainer only needs to set the sequence of events in corresponding areas to create a customized donning and doffing sequence according to the actual situation. The sequence in this paper follows the actual order in the supporting hospital during the 2022 Winter Olympics Games.

Virtual Environment Modeling

Fig 2: Photos of the PPE donning and doffing areas of the hospital. The overview (a) of the donning area with (b) details of the PPE on shelves. The three doffing areas are shown in (c---e).

Based on photos and videos of the environments of the actual hospital as shown in Fig. 2, we create a virtual environment by reconstructing the rooms, items, and their arrangements (R1, R2). Four rooms are created: one for donning (Fig. 3(a)) and three for doffing (Fig. 3(b–d), and the rooms are divided by doors. Other areas including the work zone of the hospital are omitted. In the donning room, PPE is placed on shelves in the order of the actual placement in the real hospital. Hand sanitizers, mirrors, and trash bins are placed at their corresponding locations. Indication signs (in Chinese), for example, floor signs “to the work zone” in the donning area (Fig. 3(a)), “doffing zone” and instructions of doffing orders on the walls of doffing areas (Fig. 3).

Teleportation zones are designated to facilitate moving to specific areas and prevent participants from accidentally exiting the room boundaries. To make the teleportation more effective, anchor points are placed in front of hand sanitizers and shelves so that users can conveniently reach target areas and items (semi-transparent circles with arrows in blue off Fig. 3).

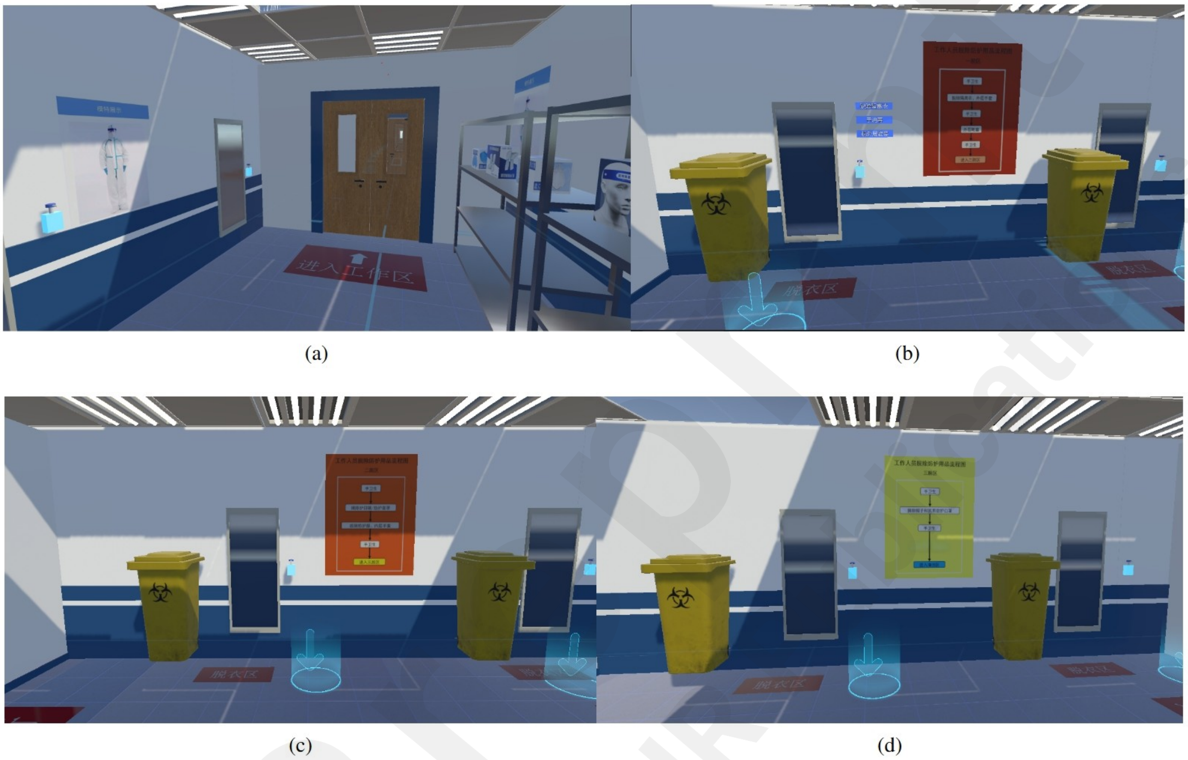


Fig 3: Virtual scenes of (a) the donning area, and (b--d) three doffing areas.

PPE Donning and Doffing Design

Mechanisms are designed for practicing the PPE donning and doffing ordering (R1) which can be conveniently configured according to actual situations of hospitals (R3).

Donning

The donning order is shown as an item checklist in a user interface (UI) above the left-hand controller model (Fig. 4). This UI displays the sequence for donning or doffing gear within this zone using checkboxes: the box in white that the action is pending, blue signifies a completed action, and red indicates that the action was performed incorrectly as shown in Fig. 4(a). In the donning zone, interactable boxes

of PPE are distributed on shelves. The trainee uses the controller to touch a box and presses the trigger button to grasp the PPE from the box. PPE model must be brought close to the relevant body part to simulate the donning process: for example, goggles must be near the head, while a protective suit near the torso. When sufficiently close, the material of the protective item turns green, indicating correct placement. Releasing the trigger button causes the item to automatically adhere to the designated position on the body.

Following the correct donning, the indicator on the left-hand UI panel is updated to blue (Fig. 4(a)). The right-hand UI tracks each action taken during the donning and doffing process, including any erroneous movements. After the entire donning process is complete, the door of the donning zone opens, allowing the user to proceed to the next section. Note that the work zone is omitted as it is irrelevant to our training.

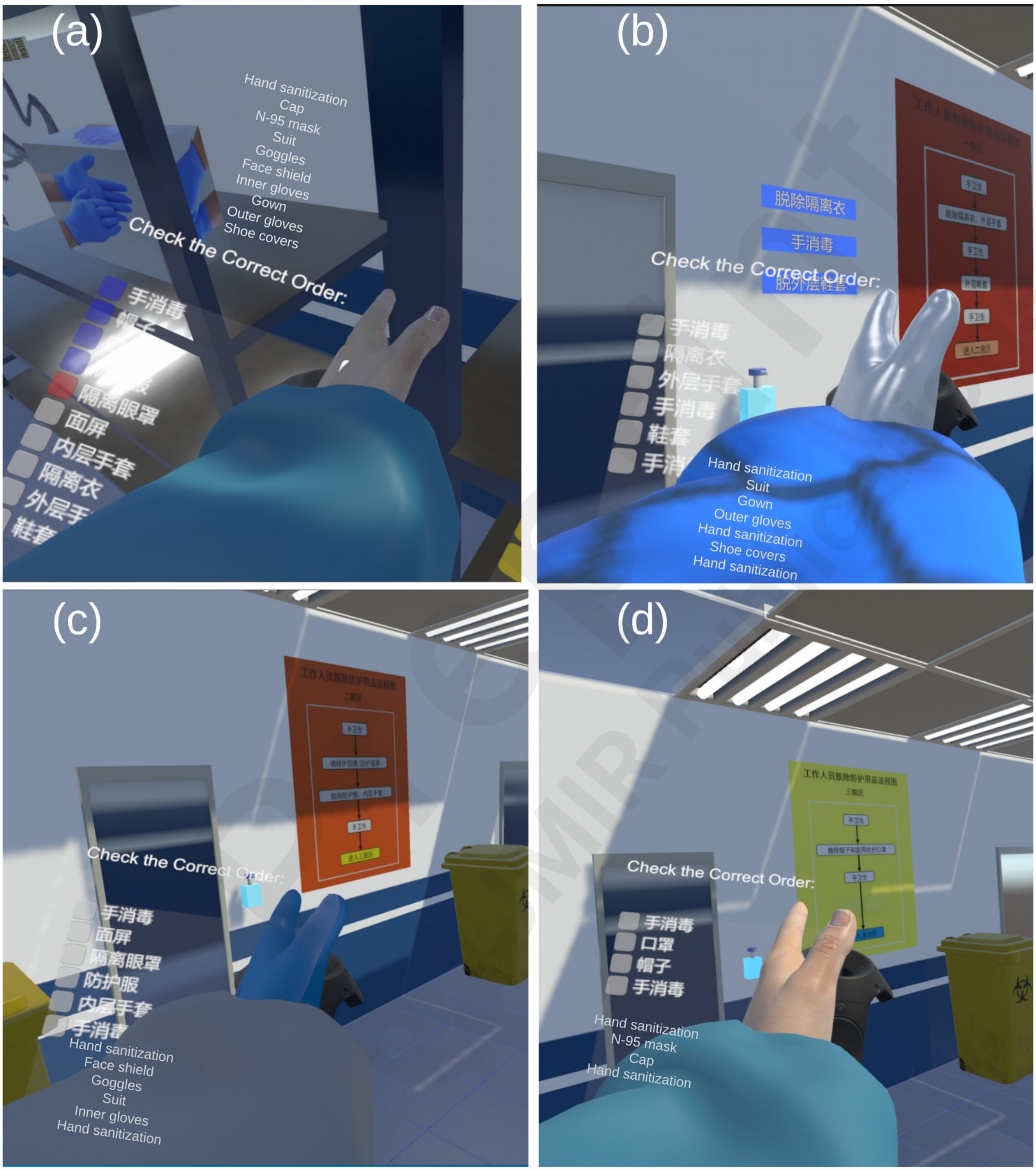


Fig 4: The UI instructions of (a) the donning area, and (b--d) three doffing areas.

Doffing

Similar to the donning section, upon entering the doffing zones, the UI on the left controller shows the sequence for removing protective gear, along with indicative markers (Fig. 4(b–d)). In this zone, users are required to follow the displayed instructions carefully, removing the protective items from specified parts of the body. For example, by approaching the head with the controller, the face shield can be grasped and lifted off; by approaching the torso, the protective suit can be taken off. The instruction flowchart placed on the wall within each doffing zone provides participants with guidance on the correct order for removing protective equipment as in the real hospital.

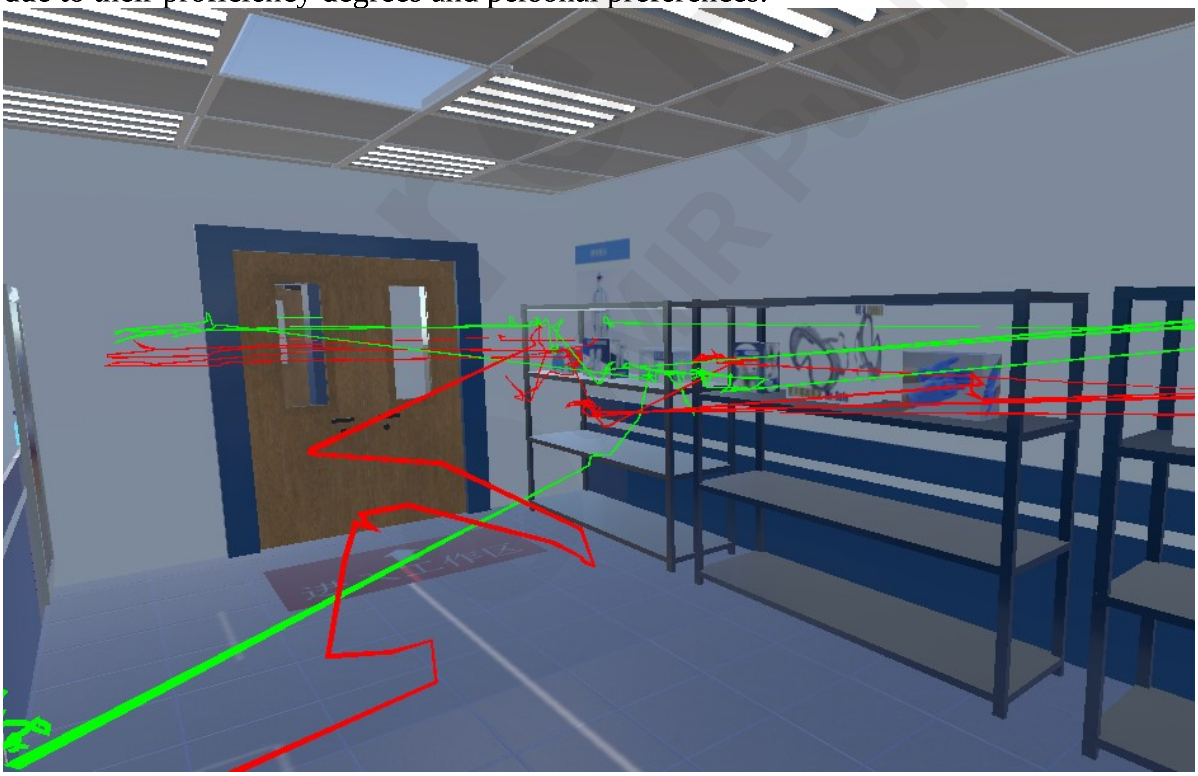
Avatar

To increase the realism of the training, an avatar is designed (R2). The camera associated with the virtual reality headset is aligned with the eye position of the avatar for a synchronized first-person perspective. Hand controllers are bound together with the hands of the avatar, facilitating an intuitive representation of hand movements. The avatar is skeletal rigged and inverse kinematics is used to simulate human movements, for example, the movements of the whole arms when PPE is picked up, being donned, or doffed. Upon equipping and removing each PPE item, the avatar is updated visually as shown in Fig. 1(b).

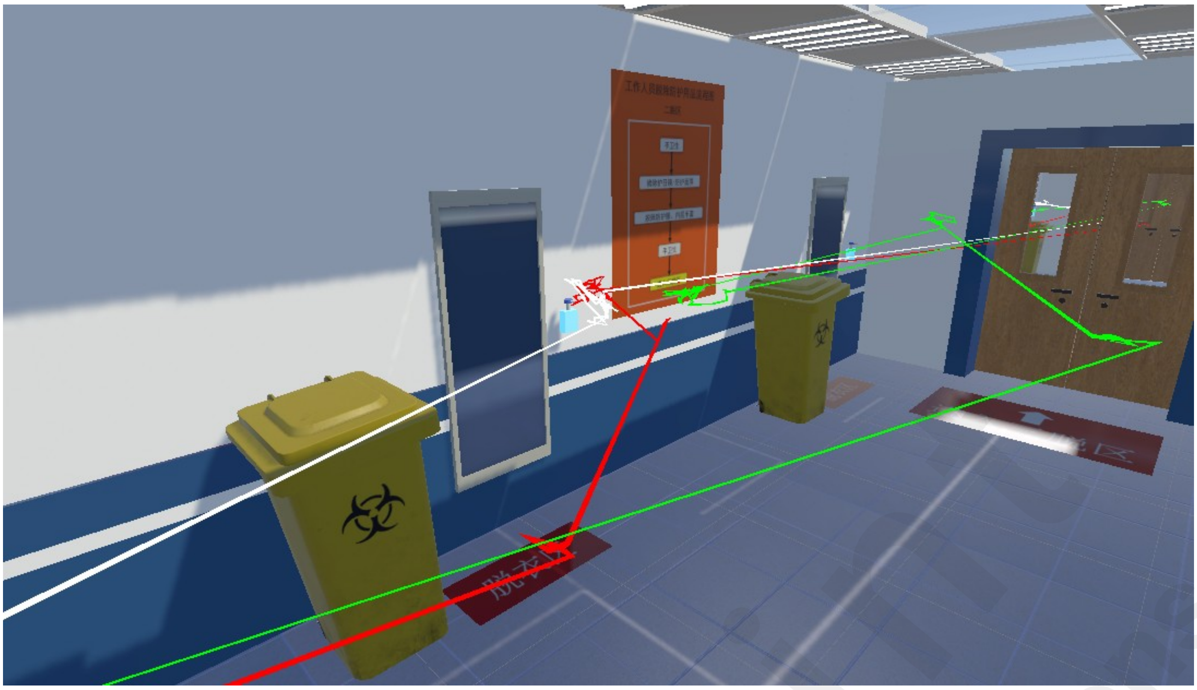
Trajectory Recording and Visualization

To support the analysis of the proficiency of trainees and also potential improvements in the placement of items in the hospital, our VR method supports the recording of trajectories and the visualization thereafter. Trajectories of the user's head, left hand, and right hand are recorded during the entire duration of use. Furthermore, the time spent by the user in each designated area, as well as the total time consumed, are also recorded.

After the training session, the recorded trajectories of head positions can be visualized for analysis as shown in Fig. 5. It can be seen that trajectories vary for different users quite a lot. This is probably due to their proficiency degrees and personal preferences.



(a)



(b)

Fig 5: Visualization of trajectories of users in (a) the donning zone, and (b) the first doffing zone after a training session.

Pilot Study

We evaluated the effectiveness of our method in a controlled randomized trial.

Study Design

We used a between-subject design to test two training conditions: our immersive PPE training (VR group), and the instructional video training (video group). To compensate for the weight and experience of an HMD, both training methods are tested through HMDs [[CITATION Skreinig2023 \l 1033][25],[CITATION Haltner2023 \l 1033][26]][25, 26].

We hypothesize that *the VR group has a comparable accuracy of memorizing the PPE donning and doffing orders to the video group, but the usability and subjective ratings of the VR group are higher than the video group.*

Ethical Approval

The study was approved by the ethics review board of the institute of the first author under the approval number of IRB00001052-23206.

Stimulus and Apparatus

We created an instructional video of approximately 5 minutes as no instructional video was readily available for the PPE training in the hospital of the 2022 Winter Olympic Games. We edited parts of a PPE donning and doffing training video released by the National Health Commission to the same order as the VR group; PPE doffing zoning was instructed using the flowcharts that are identical to those on walls in the virtual and real environments. An HTC VIVE Pro Eye HMD and an accompanying PC with Intel i9 3.5GHz CPU, NVidia RTX 3080 GPU, and 64GB RAM were used for the study.

Tasks

The task for participants was to memorize the orders of donning and doffing and answer a questionnaire about details of the ordering after the training with the assigned condition. Subjective evaluations of the test condition were acquired through the NASA Task Load Index (NASA-TLX) [[CITATION Brooke1996 \l 1033][27]][27], and the System Usability Scale (SUS) [[CITATION Hart1988 \l 1033][28]][28] questionnaires.

To assess memory of the sequence, the questionnaire contains 10 multiple-choice questions on the order of PPE and hand hygiene operations as follows.
1. Which item of protective equipment should be donned first?
2. After donning the inner gloves, what is the next piece of equipment to wear?
3. What is the next step after donning the suit?
4. In which area does the process of doffing the suit commence?
5. At which stage in the donning process are goggles worn?
6. When are boot covers typically donned in the sequence?
7. What is the last PPE to be removed within the first doffing area?
8. Which piece of equipment is typically removed first in the first doffing area?
9. Which item is removed in the final doffing area?
10. After removing the goggles and the face shield in the second doffing area, which piece of equipment should be doffed next?

Each question is of 10 points and has four choices: one correct answer and three distractors, and the total score of the memorization questionnaire is 100.

Study Procedure

Before the study, each participant received a comprehensive overview of the project and provided informed consent. The participants had to sign the consent to confirm their willingness to participate in the experiment. Participants were told that they could quit the study at any time, but none of them did.

Upon agreeing to participate, each participant was randomly assigned to either the VR group or the video group. The study began with an introductory training session of approximately 10 minutes for participants to familiarize themselves with the necessary user interactions. Those in the video group were instructed on how to control video playback, pause, and adjust the progress bar using the controllers while wearing the HMD, ensuring they completed the entire instructional video. For participants in the VR group, initial guidance via a slideshow presentation was given, followed by hands-on training within the VR setting, where they learned to navigate spatially with the controllers and perform the motions of donning and doffing PPE. A researcher offered on-site direction to assist participants through the entire sequence of the experiment—from entering the donning area to exiting the doffing zones.

Next, a free practice session of 10 minutes began, and participants were told to practice and memorize the sequence of handling PPE as well as they could. The video learning group was granted the ability to rewatch instructional videos to reinforce their retention. In contrast, the VR group was engaged in interactive "think-aloud" exercises within the immersive environment, where they independently carried out the PPE donning and doffing, but could ask any questions to the researcher.

Next, participants were asked to complete one objective questionnaire and two subjective questionnaires to evaluate the effectiveness of the training. Finally, a brief interview session was conducted to elicit authentic feedback and valuable suggestions from the participants regarding their experience. The average completion time of the study by a participant was 30 minutes. Each participant was compensated with approximately $4.

Participants

Participants were recruited via posters published on online forums of the institute (the medical campus of a University) of the first author. Participants were required to be medical students who had no previous experience with PPE training and be able to perform actions as directed by the research team. Additionally, they were required to have normal or corrected-to-normal visual acuity and adequate head and body mobility, ensuring that physical conditions did not adversely affect the experimental process.

A total of 32 volunteers (16 females) aged between 18 to 30 (μ=22.53, σ =2.65) were recruited for the study.

Data Collection

We collected the trajectory data, questionnaires, and useful comments from the participants. The positional data of the HMD and both hand controllers of each user were recorded to construct trajectory profiles, at a sampling rate of 2 Hz to prevent latency during the VR training session. In addition to the questionnaire, we collected basic demographics of participants and their prior experience with VR.

Results

The performance of the PPE order memorization task, usability, task workload, and virtual trajectories are analyzed for the study. Results of the study are summarized in Tab. 1 and visualized as boxplots as shown in Fig. 6.

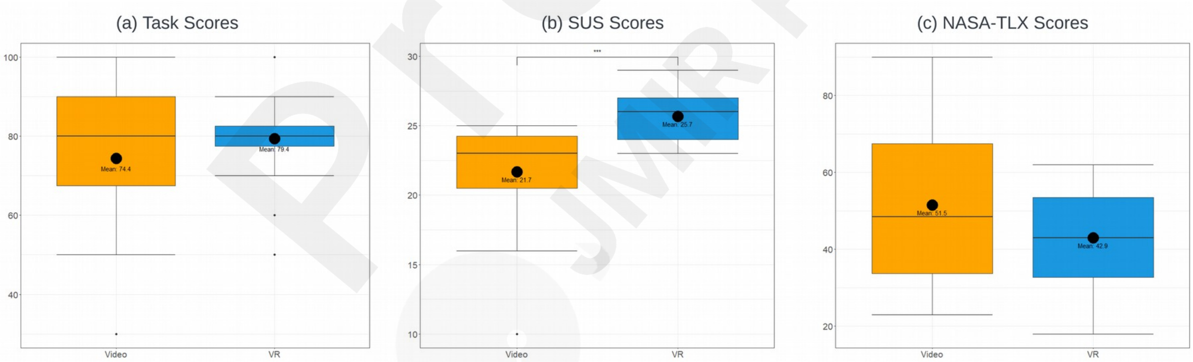


Fig 6: Boxplots of (a) the task scores, (b) SUS scores, and (c) NASA-TLX.

Tab 1: Results of questionnaires of the pilot study. Mean scores and standard deviations (in parentheses) are documented for the VR group
(VR) and the video group (Video). P values of Student's t-test between the two groups are also reported.

	VR (N=16)	Video (N=16)	P value (t-test)
Task scores	79.38 (12.89)	74.38 (17.88)	0.372
SUS	74.78 (13.58)	57.37 (21.13)	0.009*
NASA-TLX	51.50 (20.44)	42.94 (13.01)	0.168

Order Memorization

Descriptive statistics of the order memorization questionnaire are shown in the boxplot in Fig. 6(a). The VR group has a higher mean, equal median, and lower variance compared to the video group.

A Shapiro-Wilk normality test shows that both groups follow the assumption of normality ($p=0.172$ for the VR group, $p=0.079$ for the video group). Levene's test ($p=0.143$) shows that the equal variance assumption is met. The intergroup differences are then tested with a Student's t-test that shows no significance (p = 0.372).

System Usability Scale

The boxplot of SUS scores can be seen in Fig. 6(b): the VR group has a higher mean and median, and a smaller variance, compared to the video group.
Both groups satisfy the normal distribution criteria with the Shapiro-Wilk test ($W(16)=0.961, p=0.672$ for the VR group, and $W(16)=0.926, p=0.209$ for the video group). Levene's test demonstrates no significant disparity between the two groups ($F=2.990, p=0.094$), therefore, it is reasonable to deduce that variances are equivalent across the groups. A subsequent t-test shows a statistical significance
($p=0.009$) between the two groups.

NASA-TLX

The NASA-TLX result is shown in Fig. 6(c): the VR group has a lower mean and median, and a smaller variance compared to the video group. The NASA-TLX scores of both groups follow the normal distribution criteria after the Shapiro-Wilk test ($W(16)=0.956, p=0.595$ and $W(16)=0.962, p=0.693$, for VR and video groups, respectively), and show no significant differences in variance with the Levene's test
($F=2.990, p=0.062$). No significant difference between the groups is found with the t-test ($p=0.168$).

Trajectory Analysis

For quantitative analysis, we calculate the sum of the gradient magnitude of a trajectory as the total variance (var) to describe the degree of fluctuation. A scatterplot of total variance versus task completion time (time) is shown in 7, where the user ID is drawn on data points. A positive correlation (Pearson correlation coefficient = 0.47) is observed between the variance and time as shown in the blue fitted line in Fig. 7.

Moreover, we visualize the actual trajectory of each user within the Unity scene, as shown in Fig. 8. It can be seen that the trajectories are more cluttered in the donning area (Fig. 8(a)) than in the doffing areas (Fig. 8(b--d)). We identified some trajectories that are long and with few fluctuates (colored), and these correspond to participants who were fluent in VR.

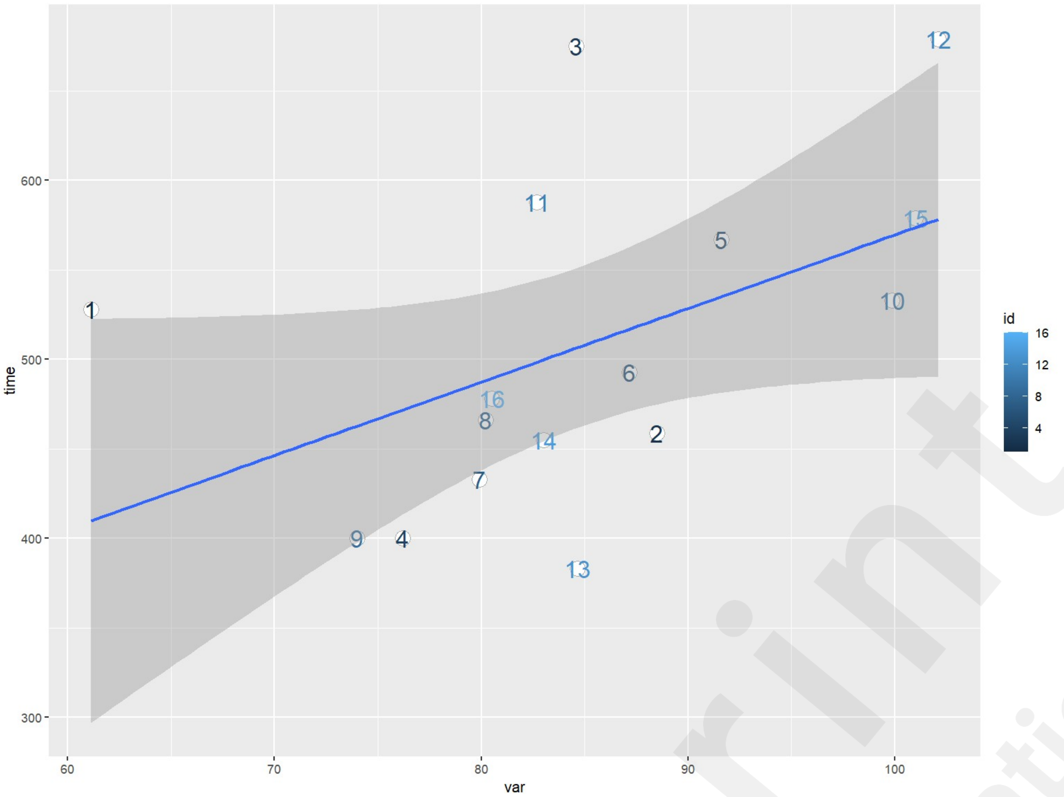
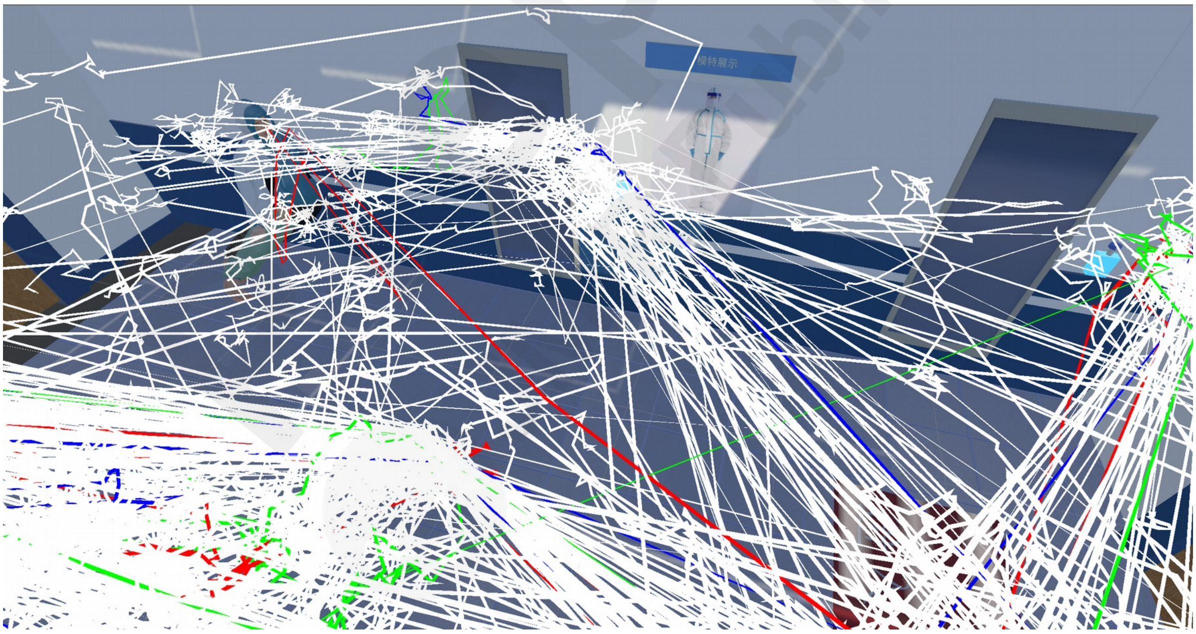
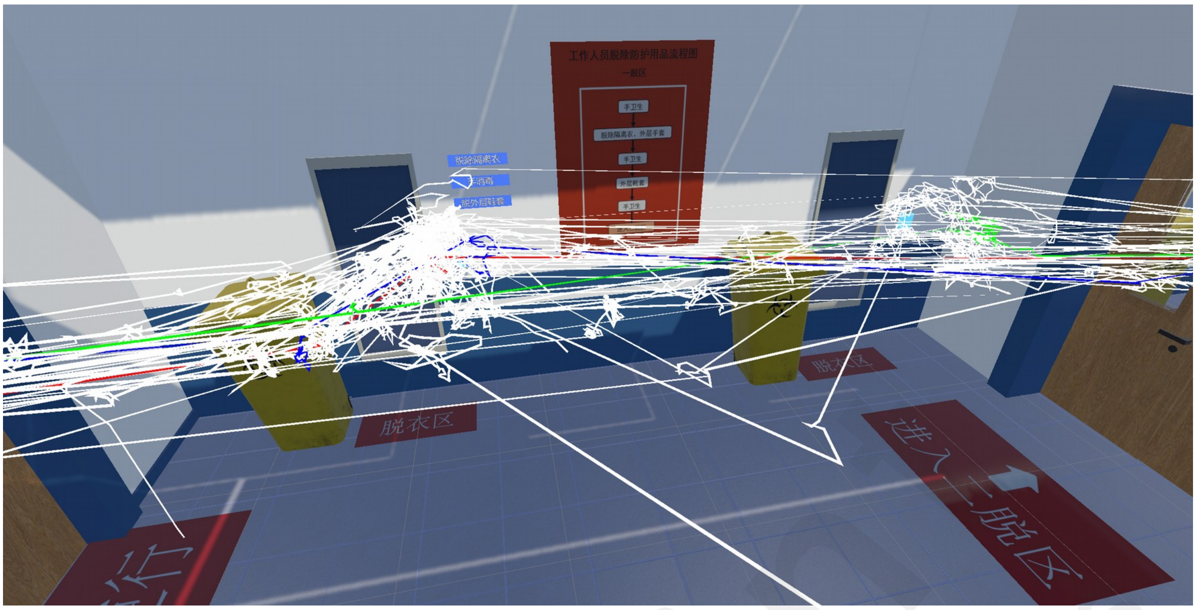


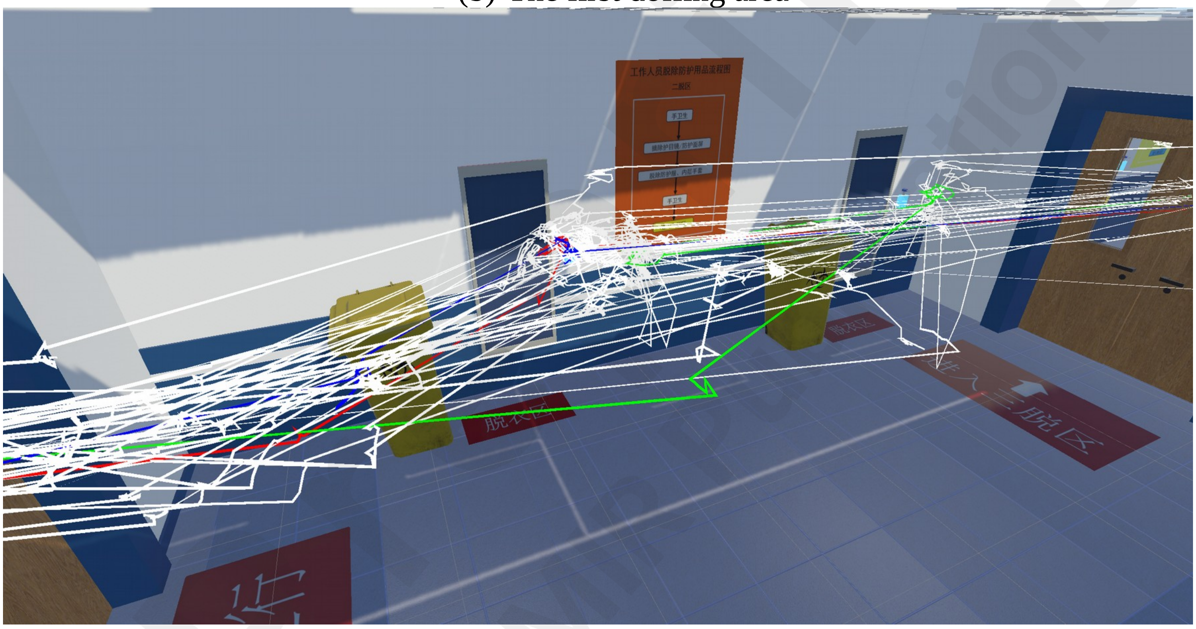
Fig 7: The scatterplot of the total variance (var) of trajectories and task completion time (time) with the linearly fitted trend.



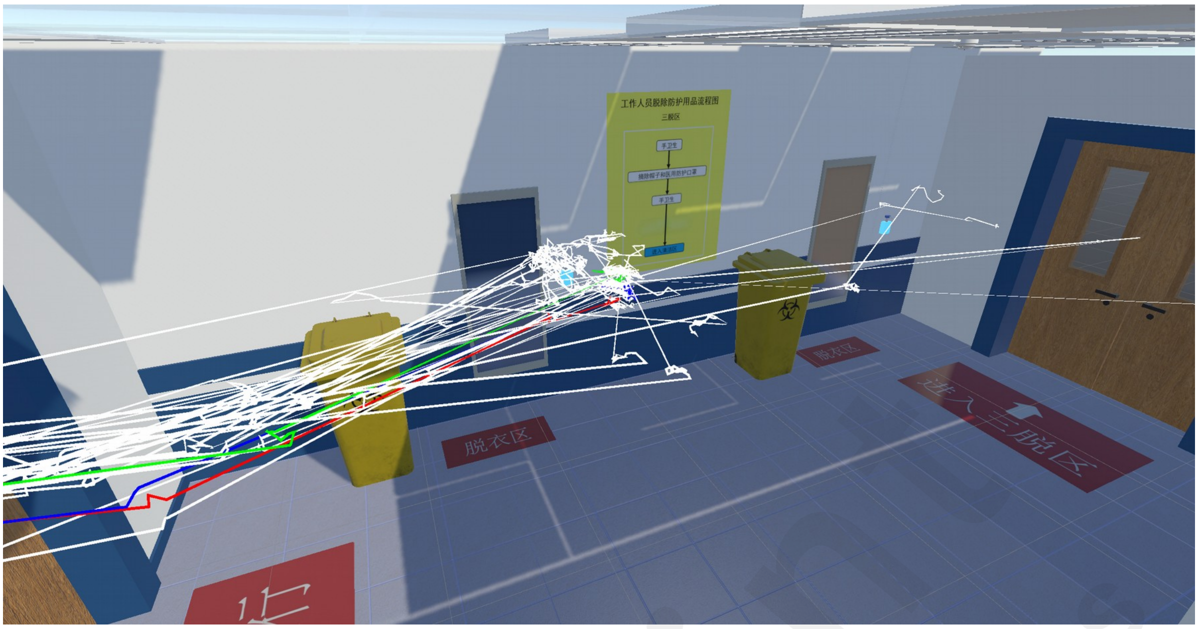
(a) The donning area



(b) The first doffing area



(c) The second doffing area



(d) The third doffing area

Fig 8: Visualization of trajectories of the participants as spaghetti plots.

Discussion

We discuss the findings of our pilot study, useful feedback from the participants, and limitations.

Main Findings

The t-test on order task scores of the two groups is not significant indicating that the order memorization outcomes between the VR group and the video group are not significantly different. The significantly better SUS scores of the VR group over the video group indicate that our method provides better usability than the video group. It is further evident by the SUS of the VR group exceeding the generally accepted threshold of 68 points, which suggests an above-average usability. With the NASA-TLX scores, it can be inferred that the psychological workload or task load required by participants for both training methods was roughly equal for the case of memorizing donning and doffing orders. The smaller variance suggests that the VR experience was more consistent across participants compared to the video group.

For the analysis of trajectories of the VR group, the positive correlation between total variance and time suggests that participants who tended to move around spent more time to complete. The visualization of trajectories reveals that participants took a relatively long time to get familiar with the environment, and searched for PPE items and donned them.

Given the study results and the analysis, we conclude that the VR group has an above-average usability which is significantly better than the video group, and both groups have comparable donning and doffing order memorization task scores, and task workload. Therefore, our hypothesis can be accepted.

Feedback

During the training, all participants noted that their initial focus was on familiarizing themselves with the interactions. It was only during the free practice phase that they shifted their attention to memorizing the sequence of donning and doffing. This suggests a need to reinforce operational guidance in the early training phase and to emphasize memory training exercises in the subsequent practice sessions. Most VR participants (14/16) indicated that they relied on the left-hand UI guidance bar to remember the sequence of steps. However, two participants suggested that providing a flow diagram in the donning area, similar to that in the doffing areas, could potentially improve the efficiency of memorization.

The majority of participants in the VR group reported a superior experience to those of the video group, highlighting increased engagement, satisfaction, and interest provided by this gamification method. They agreed that the spatial context in the virtual environment can improve their confidence in task performance and reduce the adaptation time in a real hospital. They also commented that the customizable donning and doffing order makes our VR method a generic and flexible tool that can adapt to a wide range of PPE training scenarios of varying prevention levels.

Limitations

Several limitations are identified for this study. The use of hand-held controllers instead of hand-tracking added to the overhead of the VR method and reduced its efficiency. The allocation to different groups may potentially introduce a bias in the satisfaction, and performance of participants. Our VR method does not currently support the creation of a customizable immersive space with room modules, for example, having fewer or more doffing areas. Simulating key steps during donning or doffing PPE with high-precision tracking of movements is not possible with our method. Finally, our method does not yet simulate emergent contamination situations for more comprehensive PPE training.

Conclusions

We have presented a PPE training method in VR with a flexible donning and doffing ordering and spatial context. In immersive virtual environments that resemble the relevant configurations of an actual hospital, trainees can practice customized PPE donning and doffing in the corresponding zones to aid the memorization of the sequence and familiarize them with the hospital settings. With a pilot study ($N=32$), the method is compared against the video-based training in a randomized controlled trial. Results suggest that our new method yields a comparable memorization performance and cognitive load to the video training, but higher SUS scores, satisfaction, and engagement. Our method provides an immersive experience that is not possible with video training. It is important to note that our work does not intend to replace but to complement the existing training. Hands-on PPE donning and doffing in the real world is irreplaceable for successful infection prevention and control.

Acknowledgements

The information will be added if the paper is accepted.

Conflicts of Interest

None declared.

Abbreviations

PPE: personal protective equipment
VR: virtual reality
AR: augmented reality
NASA: National Aeronautics and Space Administration
NASA-TLX: NASA-Task Load Index
SUS: System Usability Scale

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