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Human-virtual crowd interaction: Towards understanding the effects of crowd avoidance proximity in an immersive virtual environment

Hritik Trivedi | **Christos Mousas**

Department of Computer Graphics Technology, Purdue University, West Lafayette, Indiana, USA

Correspondence
Christos Mousas, Department of Computer Graphics Technology, Purdue University, West Lafayette, IN 47907, USA.
Email: cmousas@purdue.edu

Summary

This paper focuses on understanding how study participants interact and perceive a virtual crowd in an immersive virtual environment. Specifically, our within-group exploratory study investigated how avoidance proximity variations (i.e., low, medium, and high avoidance proximity [defined as avoidance radius]) assigned to crowd agents impacted participants' interaction with the virtual crowd. During the study, we instructed our participants to walk in a virtual environment. At the same time, we had a virtual crowd scripted to walk toward the start position of the participant following a straight path. During the participants' walking task, we collected movement data (i.e., trajectory length and completion time) and immediately after each experimental condition, we asked participants to self-report their experience (i.e., co-presence, behavioral independence, crowd realism, crowd interaction realism, perceived politeness, and emotional reactivity). Based on the collected data, we found that when we exposed our participants to the high avoidance proximity condition, they: (1) followed longer paths, (2) spent more time reaching the target goal, (3) rated the virtual crowd less polite, (4) rated the virtual crowd and their interaction with the virtual crowd less realistic, (5) rated the behavior independence of the virtual crowd lower, and (6) self-reported higher emotional reactivity. We discuss our findings and suggestions for further research on human-virtual crowd interaction.

KEYWORDS

avoidance proximity, crowd interaction, immersive interaction, virtual crowd, virtual reality

1 | INTRODUCTION

The field of crowd simulation has been evolving since the 1980s, and there has been considerable progress in simulating the behaviors of crowds in a computer environment.[1] Crowd simulations have been used in various domains, such as video games, building analysis, and emergency evacuation studies.[2] The use of virtual reality (VR) is a new

tool that is increasingly being employed for the research of crowd simulations. Studies have been conducted to determine the effectiveness of VR in simulating crowds, and positive results have been obtained in terms of collision avoidance and user experiences.[3,4] The avoidance behavior displayed by an individual crowd agent can affect the behavior of the overall crowd by making it feel more realistic to the participant.[5] The avoidance proximity or avoidance radius of a crowd agent is defined as the agent's "personal space" through which obstacles and other agents should not pass.[1]

Understanding the impact of virtual crowds on human behavior can be beneficial to developing more immersive applications in the future.[5] These applications can help in simulating situations that might not be possible with a real crowd due to costs, practicality, or ethical constraints.[6] Our work focuses on understanding how participants interact and perceive their interaction with a virtual crowd population in an immersive environment. For our study, we asked participants to walk from a starting position to a given target in the virtual environment. We also scripted the agents of a virtual crowd to move toward the start position of the participants and avoid them based on predefined avoidance proximity conditions (i.e., low, medium, and high avoidance proximity). We collected logged movement data and self-reported ratings for each examined condition to study how participants interacted with and perceived the virtual crowd.

The study was structured based on the assumption that changing the avoidance proximity of crowd agents will elicit different reactions from the participants when traversing the immersive virtual environment. The results of this study can be beneficial for understanding the design considerations involved when creating an immersive environment and virtual reality experiences in which humans interact with virtual crowd agents. Based on our study, we aim to answer the following research questions:

1. **RQ1:** How do avoidance proximity variations assigned to virtual crowd agents impact the study participants' task execution?
2. **RQ2:** How do avoidance proximity variations assigned to virtual crowd agents impact the study participants' perception of that virtual crowd?
3. **RQ3:** Can we use movement data to predict self-reported responses?

The remainder of this paper is organized as follows. We present related works in Section 2. In Section 3, we provide the methodology and implementation details. We present our results in Section 4 and discuss them in Section 5. In Section 6, we describe the limitations of our study, and in Section 7, we address the conclusions and potential for future research.

2 | RELATED WORK

Crowd simulations can be designed using either a macroscopic approach, which views a crowd as a single unit with properties related to fluids, or a microscopic approach, which involves modeling the behaviors of individual agents and their local interactions.[3,7] In designing virtual crowds, an essential requirement is to create human-like steering behaviors to maintain realism, which can be achieved through either algorithmic simulation or animation.[8] In general, crowd movements emerge from a combination of local interactions between neighboring agents in a crowd.[9] These local interactions give rise to the concept of interaction neighborhoods, which can take the form of formalized neighbors that are likely to influence an agent's path.[10] This concept can be used to model and understand how humans behave during local interactions under fixed conditions. With regard to simulating a crowd's behaviors, the literature indicated that a polite crowd can improve a human's ability to navigate through it by creating an open space when it is approached[11] and that the lack of collision among crowd agents increases human comfort when they are walking through this multitude.[12] Such crowd behaviors, therefore, enhance the naturalness of an agent's movements and improve a human's overall experience.

Thus far, researchers have examined human movement behaviors in either real or virtual environments or both.[13-16] Virtual environments can evoke responses similar to those occurring in the physical world,[17-19] and understanding the influence of virtual crowds on the manner by which humans conduct themselves can be beneficial in the development of more immersive applications in the future.[5] Furthermore, virtual environments are safe for participants and advantageous to simulations of the same condition for each participant in a controlled laboratory environment.[20]

Several studies have been conducted to understand the movement behaviors of humans according to the walking conditions present in virtual environments.[14,15] For instance, researchers have explored collision avoidance between humans

[1] https://docs.unity3d.com/ScriptReference/AI.NavMeshAgent-radius.html.

and virtual characters[21-23] or virtual crowd agents.[12,14,24] The study conducted by Olivier et al.[3] demonstrated the effectiveness of using virtual reality in crowd simulations, where users can walk in virtual environments. The authors found that collision avoidance behavior in virtual environments is similar to that occurring in actual experiences. In another study, the authors developed a situation-based environment where a participant is asked to cross a road when being in a crowd.[8] They discovered that a virtual crowd population's density, speed, and direction affect individuals' movement behaviors.

Several explorations have also been directed toward human perceptions of groups of virtual characters and crowds[5,25] to understand how humans regulate their movement behaviors during interactions with virtual characters. Specifically, researchers reported that interactions in which virtual characters violate participants' personal space induce negative reactions from the latter.[18,26] Scholars also indicated that when humans walk alongside virtual characters, they tend to keep a safe distance from such figures.[27] Similarly, Bruneau et al.[10] inquired into how a virtual crowd's relative motion and visual aspects (characters' appearance) can affect participants' avoidance decisions. The results revealed that humans follow longer paths when surrounded by a highly populated virtual crowd and that the appearance and motion of the crowd affect the chosen paths traversed by a user-controlled virtual character.

Researchers also showed that the tendency of participants to try to maintain distance from virtual agents that move into their personal space is similar to real-world reactions.[17,18] Participants interacting with virtual agents also display behaviors that echo those observed in the real world.[19] Another study showed that the avoidance behavior of humans when interacting with crowds depends on factors such as distance, target position, and angle.[28] Generally, researchers have reported that humans use anticipatory locomotor adjustment behaviors to adjust their steps before maneuvering around a crowd.[8] Others have found that people tend to stay in a straight line with little deviation when avoiding collisions with other humans in an orthogonal direction.[29]

The results discussed so far can be used by virtual reality developers and researchers to grasp human decision-making processes in virtual crowds better. However, although scholarship has been devoted to human-virtual crowd interactions, no examination has been directed toward the impact of the avoidance proximity assigned to virtual crowd agents on users' movement behaviors and perceptions of virtual crowds. In this study, therefore, we endeavored to provide additional insights into this matter. Our results can help us further understand human interactions in virtual environments with virtual crowds.

3 | MATERIALS AND METHODS

In this section, we discuss the implementation of our application and the methodology of the study.

3.1 | Participants

We conducted an *a priori* power analysis to determine the sample size using G*Power v.3.10 software.[30] Based on a medium-effect size of .30,[31] one group with three repeated measures, and a non-sphericity correction of $\epsilon = .70$, to achieve 80% power ($1 - \beta$ error probability), the analysis recommended a minimum of 25 participants. For our within-group study, we recruited 27 participants, which included undergraduate and graduate students from our university. Of the sample, 21 participants were male (age: $M = 23.57$, $SD = 3.07$), five participants were female (age: $M = 24.40$, $SD = 2.30$), and one participant identified as other/third gender (age: $M = 21.00$, $SD = .00$). Participants were from various departments of our university, with two participants having no previous VR experience, 17 participants having less than one hour per week of VR experience, two participants with less than five hours per week of VR experience, and five participants with more than 5 h per week of VR experience. No participants reported musculoskeletal disorders that would prevent them from walking in the virtual environment. All participants completed the study without reporting motion sickness. The Institutional Review Board of our university approved this study. All participants volunteered for this study and agreed to participate in the study by giving their consent before the beginning of the study.

3.2 | Virtual reality application and hardware

We developed an application for our study using the Unity game engine (version 2020.3.20). We used the HTC Vive Pro head-mounted display (HMD) with SteamVR Base Station 2.0 trackers for deploying the project to virtual reality. The

FIGURE 1 A participant walking in the motion capture studio while observing the virtual environment on the HMD.

headset was connected to an MSI VR One backpack computer (Intel Core i7, NVIDIA GeForce GTX1070, 16 GB RAM), allowing the participants to walk and have a room-scale VR experience (see Figure 1).

We used the Amazon Lumberyard Bistro[2] as the virtual environment in which to immerse our participants (see Figures 2 and 3). We made several modifications to reduce the number of surrounding buildings and improve visibility for the user. We downloaded the virtual characters we used from the Microsoft Rocketbox library to resemble the virtual crowd.[32] Our virtual crowd consisted of 30 virtual characters (see Figure 3)—17 were male, and 13 were female. We simulated our crowd's movements by developing several scripts in Unity. Specifically, each crowd agent had a `NavMesh` agent script for avoidance proximity (radius), steering, and pathfinding; a custom target script for their target position; and a collider to detect collisions with the user. We assigned different walking motions to each crowd agent, which we downloaded from Adobe Mixamo, to enhance the movement realism of the virtual crowd. We set the average speed of all crowd agents to equal the normal walking speed of humans. Researchers estimated this speed to be 1.20 m/s, according to the U.S. Manual on Uniform Traffic Control Devices.[33]

We set up the virtual environment in sunny afternoon weather. The participant stood near the entrance of the café and had to walk towards two light poles in front of them (see Figure 2). We scripted the crowd to walk toward the start position of the participant and stop after the participant crossed the light poles. At that time, the application ended, instructing the participant to stop walking in the real environment. All the crowd agents had their height set up according to the average height of humans (1.65 m).[3] We decided to keep the same height for our virtual characters in each developed condition to standardize our experiment across participants.

3.3 | Conditions of the experiment

We developed three conditions for this study to explore how different avoidance proximity variations assigned to virtual crowd agents could impact our participants. The examined avoidance radius is only toward the user and not toward inter-agent interactions. However, we scripted our agents to prevent other agents from disrespecting an agent's personal space. For the avoidance proximity of the virtual agents toward the user, we used the proxemics model[34,35] to develop the following three conditions:

1. **Low avoidance proximity (LAP)**: We used the upper boundary of the close phase of the personal space (.76 m) as the avoidance proximity for this condition (see Figure 4).

[2] http://developer.nvidia.com/orca/amazon-lumberyard-bistro.
[3] https://ourworldindata.org/human-height.

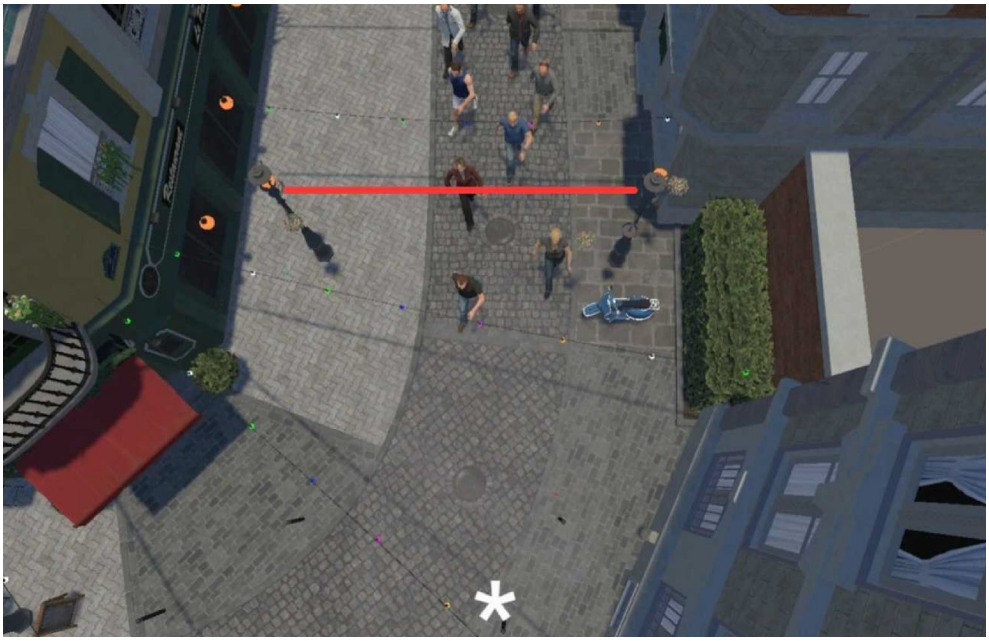

FIGURE 2 A top view of the virtual environment. The participants were placed at the position of the white asterisk and walked toward the red line. We did not render the asterisk and the red line in the scene.

FIGURE 3 A perspective view of the virtual environment and the virtual agents that compose the virtual crowd.

2. **Medium avoidance proximity (MAP)**: We used the upper boundary of the far phase of the personal space (1.22 m) as the avoidance proximity for this condition (see Figure 4).
3. **High avoidance proximity (HAP)**: We used the upper boundary of the close space of the social space (2.10 m) as the avoidance proximity for this condition (see Figure 4).

3.4 | Measurements and ratings

We collected both logged movement data and questionnaire responses for each condition to assess our participants' movement behavior and perceptions of the virtual crowd. We collected the trajectory length and completion time from the

(a) LAP (b) MAP (c) HAP

FIGURE 4 The three conditions (LAP, MAP, and HAP) for this study to explore how different avoidance proximity variations assigned to virtual crowd agents could impact our study participants.

participants' movements. From the questionnaire responses, we collected data on co-presence and behavioral independence following Biocca et al.,[36] and emotional reactivity following Mousas et al.,[37] and we developed the crowd realism, crowd interaction realism, and perceived politeness scales. We should mention that the "politeness" in our study did not refer to agents expressing certain emotions by means of facial expression and body posture, such as in Volonte et al.,[38] but to the perceived friendliness in terms of avoiding or making suitable space similar to Bönsch et al.[39,40] We provide all the questions we used in our study in Appendix A. Note that we adapted the questionnaires to match the scope of our study.

3.5 | Procedure of the experiment

To begin, we asked each participant to follow the guidelines by reading, agreeing to, and signing the consent form for the study. Next, we informed participants about the study's procedure and how we planned to conduct the experiment. The first step after this was completing the demographics questionnaire, after which we assigned participants to one of the conditions of the study. We ordered the conditions using the Latin Squares ordering method[41] to ensure an equal balance across participants. Each participant repeated each condition twice, a common human movement analysis research practice.[42-45]

Before the experiment began, we helped the participants to put on the HMD. We then asked them to walk in the virtual environment we used in our study to ensure they could walk freely while wearing our equipment. We should note that in this part of our study, we did not place virtual characters in the environment. Next, we initiated our experiment. Once our participants finished each condition, we helped them remove the headset and told them to complete the post-condition survey. Then we asked them to return to the original position and continue with the following condition. This was repeated for all three conditions of our study. Once our participants had completed all three conditions, we asked them to complete the final survey form, which consisted of open-ended questions about their experience. We informed participants that they could terminate the experiment at any time. All of our participants completed the study. Moreover, none of our participants took more than 30 min to complete the study.

4 | RESULTS

To analyze our data, we used one-way repeated measures analysis of variance (ANOVA) using the three experimental conditions as independent variables, and the collected movement measurements and the self-reported ratings from the questionnaire as dependent variables. We assessed the individual differences using post-hoc Bonferroni corrected estimates if the ANOVA was statistically significant ($p < .05$). We screened the avoidance movement behavior and the self-reported data for correlations using the bivariate Pearson product-moment correlation coefficient. We screened the normality of the collected data graphically using Q-Q plots of the residuals and with Shapiro-Wilk tests at the 5% level. Both analyses indicated that the obtained data fulfilled the normality criteria. We provide boxplots of the movement data in Figure 5 and of the self-reported ratings in Figure 6.

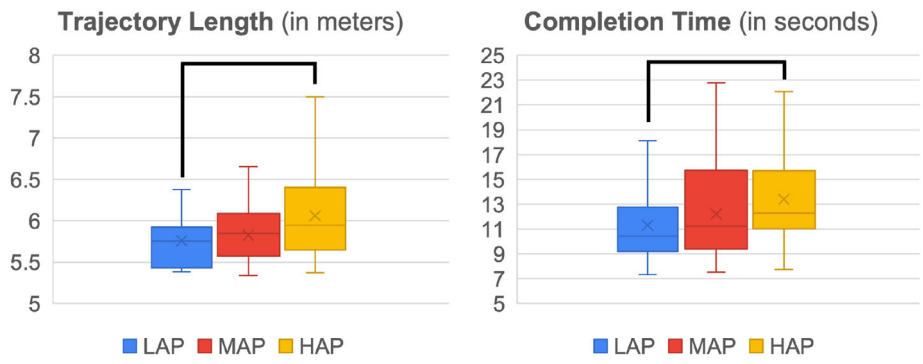

FIGURE 5 Boxplots of the movement data. Boxes enclose the middle 50% of the data. A thick horizontal line denotes the median. The thick black line(s) denoted the significant differences between the conditions of our experiment.

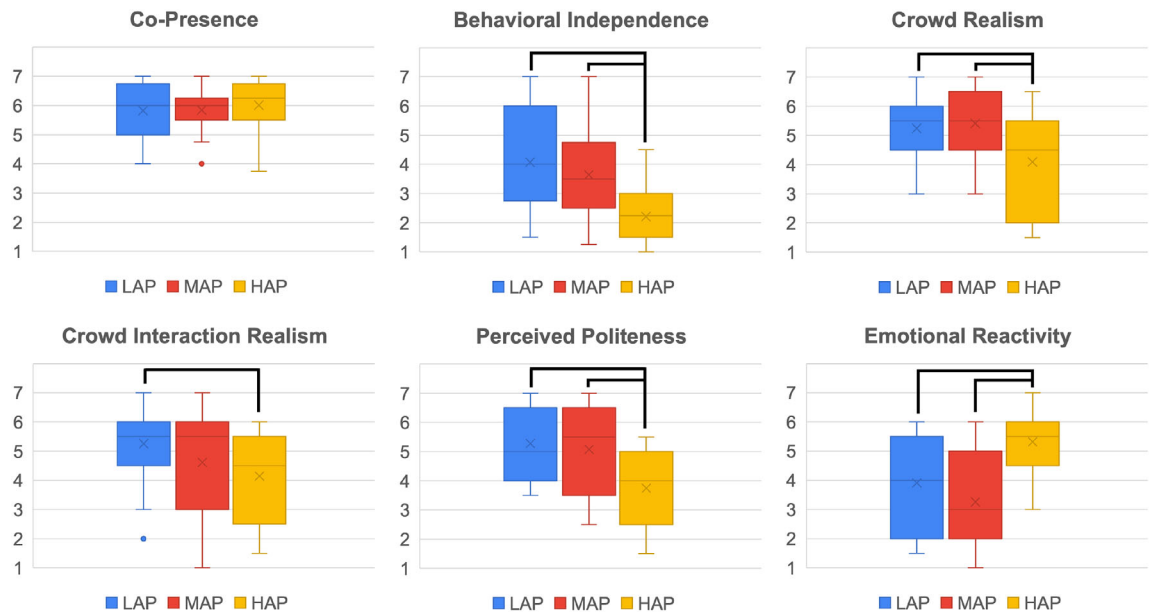

FIGURE 6 Boxplots of the self-reported data for all the examined concepts. Boxes enclose the middle 50% of the data. A thick horizontal line denotes the median. The thick black line(s) denoted the significant differences between the conditions of our experiment.

4.1 | Movement data

We identified a statistically significant result for the **trajectory length** measurement (Wilks' $\Lambda = .698$, $F[2, 25] = 5.409$, $p = .011$, $\eta_p^2 = .302$). The post-hoc analysis revealed that the participants in the LAP condition ($M = 8.06$, $SD = .42$) traveled less than those in the HAP condition ($M = 8.42$, $SD = .83$) at $p = .024$. We also found a statistically significant result for the **completion time** measurement (Wilks' $\Lambda = .770$, $F[2, 25] = 3.739$, $p = .038$, $\eta_p^2 = .230$). The results of the pairwise post-hoc analysis revealed that the participants in the LAP condition ($M = 11.29$, $SD = 2.97$) spent less time to reach the target position than those in the HAP condition ($M = 13.40$, $SD = 3.53$) at $p = .035$. We did not find significant results between the LAP and MAP and between the MAP and HAP conditions for either **trajectory length** or **completion time** measurements.

4.2 | Self-reported ratings

The analysis of the **co-presence** ratings were not statistically significant (Wilks' $\Lambda = .948$, $F[2, 25] = .686$, $p = .513$, $\eta_p^2 = .052$). We found a statistically significant result for the **behavioral independence** rating (Wilks' $\Lambda = .476$, $F[2, 25] =$

13.735, $p = .000$, $\eta_p^2 = .524$). The results of the pairwise post-hoc comparison indicate that the participants in the HAP condition ($M = 2.21$, $SD = .95$) rated the crowd's independence lower than when we exposed them to the LAP condition ($M = 4.07$, $SD = 1.65$) at $p = .000$ and the MAP condition ($M = 3.63$, $SD = 1.41$) at $p = .001$.

For the **crowd realism** rating, the statistical analysis revealed a significant result (Wilks' $\Lambda = .734$, $F[2, 25] = 4.527$, $p = .021$, $\eta_p^2 = .266$). The pairwise post-hoc comparison indicates that when we exposed participants to the HAP condition ($M = 4.09$, $SD = .95$), they rated the crowd's realism lower than when we exposed them to the LAP condition ($M = 5.24$, $SD = 1.17$) at $p = .049$ and the MAP condition ($M = 5.40$, $SD = 1.25$) at $p = .017$.

We also found a statistically significant result for the **crowd interaction realism** rating (Wilks' $\Lambda = .738$, $F[2, 25] = 4.449$, $p = .022$, $\eta_p^2 = .262$). The results of the pairwise post-hoc comparison indicate that the participants in the LAP condition ($M = 5.25$, $SD = 1.28$) rated the realism of their interaction with the virtual crowd higher than when we exposed them in the HAP condition ($M = 4.14$, $SD = 1.60$) at $p = .026$. We did not find significant results between the LAP and the MAP conditions, or between the MAP and the HAP conditions.

The **perceived politeness** rating is also statistically significant (Wilks' $\Lambda = .536$, $F[2, 25] = 10.839$, $p = .000$, $\eta_p^2 = .464$). The pairwise post-hoc comparison indicates that when we exposed our participants to the HAP condition ($M = 3.74$, $SD = 1.17$), they rated the crowd's politeness lower than when we exposed them to the LAP condition ($M = 5.28$, $SD = 1.18$) at $p = .000$ and the MAP condition ($M = 5.07$, $SD = 1.57$) at $p = .003$.

Lastly, the **emotional reactivity** rating is also statistically significant (Wilks' $\Lambda = .496$, $F[2, 25] = 12.684$, $p = .000$, $\eta_p^2 = .504$). The pairwise post-hoc comparison indicates that when we exposed our participants to the HAP condition ($M = 5.31$, $SD = 1.14$), they rated their emotional reactivity towards the virtual crowd higher compared to when we exposed them to the LAP condition ($M = 3.90$, $SD = 1.59$) at $p = .004$ and the MAP condition ($M = 3.25$, $SD = 1.55$) at $p = .000$.

4.3 | Correlations

Since we collected both movement data and self-reported ratings, we also explored correlations (cumulative for the three conditions) between the different data sets and, more specifically, between the two movement features and the six self-reported scales (12 combinations in total). We found a weak positive correlation [$r = .347$, $n = 81$, $p = .001$] between the **trajectory length** and **crowd interaction realism**, a weak positive correlation [$r = .285$, $n = 81$, $p = .010$] between the **trajectory length** and **behavioral independence**, and a moderate positive correlation [$r = .516$, $n = 81$, $p = .000$] between the **completion time** and **perceived politeness**.

5 | DISCUSSION

We conducted a virtual reality study to understand how participants interact with a virtual crowd population in an immersive virtual environment. We explored two things. First, we explored how the avoidance proximity assigned to agents of a virtual crowd could impact how study participants move toward a target when surrounded by a virtual crowd population moving in the opposite direction. Second, we explored how our study participants perceived the variations of the virtual crowd based on the assigned avoidance proximity. To do so, we collected and analyzed both logged movement data and self-reported ratings of participants.

Regarding the movement data (**RQ1**), we found that the avoidance proximity impacted both the **trajectory length** and **completion time** measurements. In the low avoidance proximity condition, participants followed shorter paths and needed less time to reach the target position in the virtual environment compared to the high avoidance proximity condition. We interpret these findings as follows. In the low avoidance proximity condition, we placed our participants in a highly constrained virtual environment where the virtual crowd population closely surrounded them and did not allow them to easily find and follow an alternative sub-optimal path to reach the target position. The opposite happened in the high avoidance proximity condition. In this condition, the participants were free to move around the environment. Based on our observations, several also tried to explore the environment when moving toward the target position; therefore, they followed longer paths and needed more time to reach the target spot. Considering previously conducted research on human-virtual crowd interaction[8,20] that discusses how crowd density could impact study participants' coordination behavior and research on avoidance behavior with virtual characters,[14,43,46] we can say that our participants felt safe walking in the virtual environment. They were aware that in a high avoidance proximity condition, they would have enough space to perform the task without risking potential collisions with the virtual characters.

Our statistical analyses of the self-reported data also reveal several interesting findings (**RQ2**). **Co-presence** ratings do not differ significantly across the three conditions. We think this finding is due to the indirect interaction with the agents of the virtual crowd and the missing communication component with the virtual agents. According to previously published research, communication channels can enhance how study participants perceive the other avatars in a virtual environment.[47,48] The lack of direct interaction and communication with the virtual characters was something that study participants also mentioned in the comments they left: "I didn't feel like the crowd noticed me because they were all walking in one direction and didn't make any eye contact."

The **behavioral independence** findings show that our participants clearly stated that the virtual crowd was perceived as less independent when they were exposed to a high avoidance proximity condition. Our participants reported the opposite when we immersed them in the low and medium avoidance proximity conditions. According to our results, the low and medium avoidance proximity conditions caused the crowd to be perceived as more responsive to our participants when they were closer to a virtual agent; thus, they realized that the virtual agents were directly responding to their movement behavior. By contrast, when we immersed the participants in the high avoidance proximity condition, the agents' response toward our participants started when they were far from each other; thus, it was less obvious. The literature also partially confirms this, which tells us that proximity to a virtual character could change participants' perceptions toward them.[49,50]

The **crowd realism** and **crowd interaction realism** results indicate that when we placed our participants in the low avoidance proximity condition, they felt that the crowd exhibited a more realistic behavior toward them. We see, for example, participants stated that "The third one [high avoidance proximity] had completely weird reactions and threw me off." Based on our findings, being in a crowd that alleviated congestion among the participants made the crowd less realistic. This could have happened because of our participants' prior knowledge when interacting with real crowds. They expected that the crowd would have a more uniform density. In addition, participants commented about the virtual crowd's realism: "If possible, I think when crossing the crowd, if the people in the crowd can give me a second eye peek it would make the crowd in the virtual world even more realistic;" "Add greetings and hand gestures [to the virtual crowd] to make it more realistic;" "I think it would be more realistic if the crowds were talking or made eye contact before avoiding you;" and "They seem a little robotic. Adding sound might also help make it more realistic." When being in a crowd in a city environment, one also expects to hear some background noise, which research has demonstrated to increase interaction realism.[51,52]

Our participants also rated the **perceived politeness** of the virtual crowd lower when we exposed them to the high avoidance proximity condition compared to when we exposed them to the low and medium avoidance proximity conditions. In our discussions with participants, some stated they felt the crowd was not polite toward them when assigned a high avoidance proximity, since they thought the agents were trying to avoid them. This created an unpleasant experience for our participants. Our participants felt intimidated or isolated or that they were not part of the virtual crowd population. We also think that perceived politeness also contributed to how our participants reacted emotionally, since when we exposed them to the high avoidance proximity condition, our participants provided high **emotional reactivity** ratings.

The last issue we investigated in our study (**RQ3**) was whether there were possible correlations between the movement and self-reported data. We found that participants' task execution and perceptions of the virtual crowd indeed did correlate. However, although we have seen similar results between movement and self-reported data in previously published work,[43,53] we cannot argue that the task execution of our participants can, in fact, predict their perceptions of and interaction with the virtual crowd. We say this due to the nature of the correlations (weak and moderate), since there is a chance that the significant correlations that we found might be random instead of regular. We think this because the task and the environment in which participants interacted can strongly impact their behavior.[53] Thus, even though the current study found some evidence of correlations, we argue that such correlations demand further investigation.

6 | LIMITATIONS OF THE STUDY

This section discusses the limitations of our study. First, the crowd did not fully represent a real crowd, as all the crowd agents had fixed behavior scripts assigned to them. The crowd agents also did not look at the participants, which might have alienated some participants while traversing the environment. Second, the application did not have any sounds integrated into the environment. Furthermore, some participants were expecting virtual hands in the environment, but

we did not assign a self-avatar to the participants in the application. Third, the HMD did not support eye-tracking, so we could not capture eye-gaze data for the participants to understand better how they were observing the virtual crowd and the virtual environment when executing the walking task.

Despite the limitations mentioned above, we would like to state that such limitations do not invalidate our findings regarding the effects of a virtual crowd's avoidance proximity on study participants' movement and self-reported data. We think that future researchers should address such limitations to advance the understanding of avoidance movement behavior in the presence of virtual crowds.

7 | CONCLUSIONS AND FUTURE RESEARCH

In this study, we focused on understanding the movement and perception of study participants towards virtual crowd agents exhibiting different avoidance behaviors in an immersive virtual environment. We found that the low avoidance proximity assigned to crowd agents caused our participants to follow shorter paths and finish the task faster. Also, the high avoidance proximity made the crowd look less polite, less realistic, and perceived as less independent, and caused higher emotional reactivity.

As our research on the avoidance proximity in crowds was exploratory, future research could study in-depth the factors impacting human movement and perception in relation to a virtual crowd. Investigating the correlation between the movement data and participants' perceptions of the virtual crowd is also important. Such findings could provide VR developers with information on how to use virtual crowds in immersive environments. We also suggest investigating participants' responses by adding more features to the VR experience (e.g., sounds, crowd acknowledgment, self-avatar representation). Lastly, including participants with mental and behavioral disorders (e.g., agoraphobia, depression, and social anxiety) could provide a new understanding of human behavior and perception in relation to human-virtual crowd interaction.

ORCID

Hritik Trivedi https://orcid.org/0009-0007-7203-9720
Christos Mousas https://orcid.org/0000-0003-0955-7959

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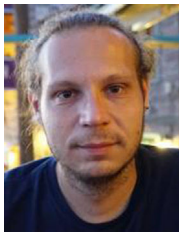
APPENDIX A. QUESTIONNAIRE

#	Question/Statement	Anchors of the scale
Co-presence		
1	I noticed the virtual crowd.	1: Not at all; 7: Totally
2	The virtual crowd noticed me.	1: Not at all; 7: Totally
3	The virtual crowd's presence was obvious to me.	1: Not at all; 7: Totally
4	My presence was obvious to the virtual crowd.	1: Not at all; 7: Totally
Behavioral independence		
5	My behavior was often in direct response to the virtual crowd's behavior.	1: Not at all; 7: Totally
6	The behavior of the virtual crowd was often in direct response to my behavior.	1: Not at all; 7: Totally
7	The virtual crowd's behavior was closely tied to my behavior.	1: Not at all; 7: Totally
8	My behavior was closely tied to the virtual crowd's behavior.	1: Not at all; 7: Totally
Crowd realism		
9	I found the virtual crowd behaving realistically.	1: Not at all; 7: Totally
10	The virtual crowd's behavior resembled a real crowd.	1: Not at all; 7: Totally
Crowd interaction realism		
11	How realistic were your interactions with the virtual crowd?	1: Not realistic at all; 7: Very realistic
12	I felt like walking in a real crowd.	1: Not at all; 7: Totally
Perceived politeness		
13	How polite was the virtual crowd?	1: Not polite at all; 7: Very polite
14	Do you think the virtual crowd was more polite than you?	1: Not at all; 7: Totally
Emotional reactivity		
15	I felt calm walking in a virtual crowd.	1: Not at all; 7: Totally
16	I felt comfortable walking in the virtual crowd.	1: Not at all; 7: Totally

AUTHOR BIOGRAPHIES

Hritik Trivedi is currently pursuing his MS in Computer Graphics Technology at Purdue University (West Lafayette, IN). His research interests include virtual and augmented reality, game development, level design, and user experience design. He completed his B.Tech. in Computer Science and Engineering at Charusat University (Anand, India).



Christos Mousas is an Assistant Professor at Purdue University (West Lafayette, IN). His research revolves around virtual reality, virtual humans, computer graphics & animation, and human-computer interaction. He has previously been affiliated with the Department of Computer Science at Dartmouth College (Hanover, NH) as Postdoctoral Researcher, and with the Department of Cultural Technology and Communication of the University of the Aegean (Mytilene, Greece) as a Research Assistant. He holds a PhD in Informatics and an MSc in Multimedia Applications and Virtual Environments, both from the School of Engineering and Informatics of the University of Sussex (Brighton, UK), and an integrated Master's degree in Audiovisual Science and Art from Ionian University (Corfu, Greece). He is a member of ACM and IEEE, and has been a member of the organizing and program committees of many conferences in the virtual reality, computer graphics/animation, and human-computer interaction fields. Mousas has received a Best Paper Award from ACM SIGGRAPH VRCAI 2022, and Honorable Mention Awards (top 5% of all accepted papers) from ACM CHI PLAY 2021 and ACM CHI 2022.