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Immersive walking in a virtual crowd: The effects of the density, speed, and direction of a virtual crowd on human movement behavior

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Abstract
We investigated the movement behavior of participants walking within a virtual crowd in an immersive virtual environment. We investigated three different parameters that characterize a moving virtual crowd: *density*, *speed*, and *direction*. An immersive road-crossing scenario that took place in a virtual metropolitan city was created. In this scenario, the participants were instructed to walk toward the opposite sidewalk. Three measurements (speed, deviation, and trajectory length) were used to evaluate the impact of the parameters assigned to the virtual crowd on the movement behavior of the participants. Significant results were found for both the main and interaction effects. The results suggested that the high density, low speed, and diagonal direction situations associated with the virtual crowd had the greatest impacts on the speed, deviation, and trajectory lengths of participants when they walked in a virtual environment and were surrounded by a moving virtual population.

KEYWORDS
human–crowd interaction, movement behavior, virtual crosswalk, virtual crowd, virtual reality

1 | INTRODUCTION

A number of real-world human–crowd interactions and experiences can be transferred to virtual ones.[1] For example, one might want to virtually travel to a metropolitan city and take a walk on a sidewalk to explore the surroundings. During this experience, the users of such an application might be surrounded by a virtual population. Similarly, users could learn how to evacuate a building while surrounded by a crowd when immersed in a virtual environment. Finally, in a digital film production, the actor might be asked to walk with a virtual crowd while performing a part of the script. In all the above examples, it is quite likely that the users of such virtual reality experiences might be surrounded by virtual populations that are moving in the same or different directions and most likely doing so at different speeds and with varying levels of density.

Although a significant amount of research has been conducted on the analysis, modeling, and simulation of crowds and crowd dynamics,[2-9] and a number of published articles have examined interactions with individual and groups of virtual characters, a limited number of studies have examined how humans walk along with virtual crowd populations surrounding them.[10,11] Therefore, there are no conclusive results regarding whether a moving virtual crowd population affects the movement behavior of humans or how such an effect would materialize.[12,13] Consequently, an understanding of how a moving virtual crowd might or might not affect the movement behavior of humans could be beneficial for

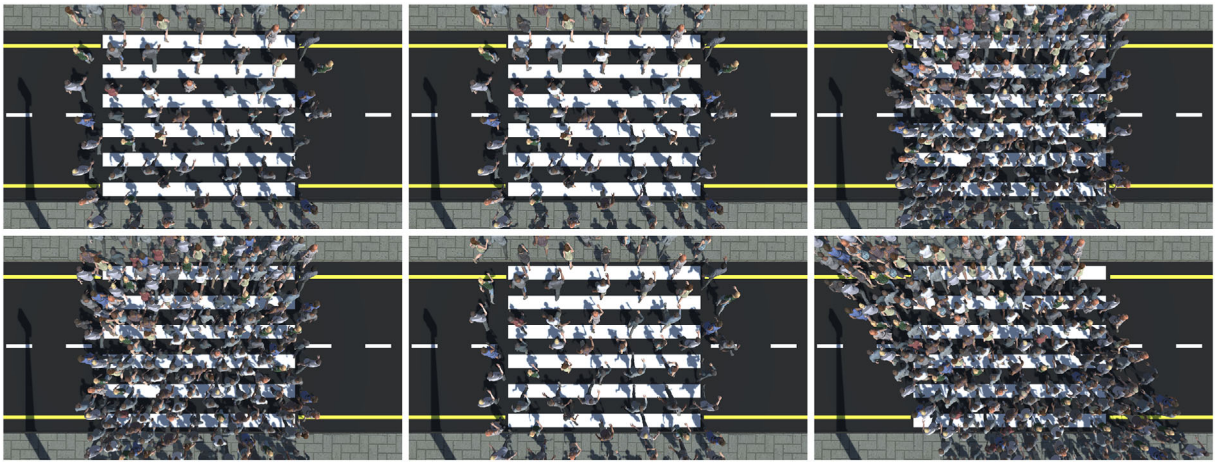

FIGURE 1 The parameters of the virtual crowd that were examined in this article. Left: low density (top) versus high density (bottom) situations. Middle: low speed (top) versus high speed (bottom) situations. Right: straight direction (top) versus diagonal direction (bottom) situations

virtual reality developers, as it would allow them to more precisely and effectively develop the aspects of virtual reality experiences that include immersive interactions with moving virtual crowds.

To understand how human movement is or is not affected by a moving virtual crowd population, the present study investigated three parameters (see Figure 1): *density*, *speed*, and *direction*.[14] The study participants were asked to cross a virtual crosswalk while surrounded by a virtual crowd population that was scripted to move toward the opposite sidewalk. For each examined condition, the participants were asked to perform a simple walking task, during which their motions were captured, and three measurements (speed, deviation, and trajectory length) were extracted to explore the effects of crowd movement on the participants' movement behaviors.

This article is organized as follows: Section 2 presents research related to this project; the methodology is outlined in Section 3; the results are described in Section 4 and analyzed in Section 5; and, finally, the conclusion and future research directions are addressed in Section 6

2 | RELATED WORK

Studies concerning interaction between humans and virtual characters have interested the virtual reality community for the past few decades.[15-17] To understand interactions with virtual characters, subjective data may be collected using questionnaires, or objective data may be collected using various types of sensors (e.g., electroencephalograms, electrodermal sensors, eye-tracking sensors, and motion capture sensors). Such methods have been employed efficiently to understand such interactions.[18,19] Previous studies have indicated that both objective and subjective measurements collected during interactions with virtual characters tend to match those that are collected in the real world with humans,[20,21] even though the participants were aware that the virtual interactions involved virtual rather than human characters.[22] This finding is important, especially because previous studies of human movement have indicated that humans' avoidance behavior is qualitatively similar in virtual and real conditions.[23] Additionally, in cases of unconstrained, goal-specified walking tasks, the trajectories of humans in virtual environments tended to match those of humans in the real world when the virtual and real-world spaces were identical.[24] Therefore, such studies could provide valuable information that is applicable not only to video games and virtual reality but also to human behavior research and real-world interaction scenarios.

In addition to studies on single-character interaction,[20,25] several have explored interactions with small groups of virtual characters and crowds.[9,11,18,26-28] To further investigate how humans regulate their movement behaviors during interactions with virtual characters, previous studies have explored the following:[29,30] side-by-side[31] and face-to-face walking[32] behaviors, group formations,[33] and collision avoidance tasks.[34,35]

The aforementioned studies yielded a number of interesting results that are applicable in numerous different domains of virtual reality. It was found that interactions in which virtual characters violated humans' personal space resulted in negative reactions on the part of the human participants.[36,37] As a result, humans walking alongside virtual characters tend to keep a safe distance, especially when the latter are considered to be realistic.[38] In a similar context, it was found that humans tended to keep more distance when moving toward virtual characters from the front than from behind.[39] Bruneau et al.[13] investigated the relative motion and visual aspects of a virtual crowd, and in their study, the motion of a user-controlled character was captured; however, the participants were asked to use a joystick to control the virtual character instead of performing a walking task. The results revealed that humans follow longer paths when surrounded by a highly populated virtual crowd. Moreover, Bruneau et al.[13] also found that the appearance and motion of the crowd affected the chosen paths that the user-controlled virtual character followed.

Other studies have investigated the movement coordination of participants. Such studies have included real[40-42] and virtual reality[43-45] scenarios in which people coordinated their movements while crossing an intersection in the presence of either a human or virtual character. It has been found[46-48] that two humans tend to become more sensitive to each other's presence and to simultaneously change their decisions or actions when crossing a road as part of a group, compared with when doing so on their own. In a human-virtual crowd interaction study, Warren[49] found that participants (followers) tended to match the crowd leader's velocity rather than keeping a constant distance from the leader. Rio et al.[50] investigated interaction within a crowd in a neighborhood to determine which neighbors influence pedestrian behavior, how this is affected by neighbor position, and how the influences of multiple neighbors combine. They found that neighbor influence is combined in a linear fashion and decreases with distance but not with lateral position.[50] Nelson et al.[12] investigated individually the density, speed, and direction variations of a virtual crowd and found that its speed affected human movement. In the present study, Nelson et al.'s[12] research was extended in two directions. First, a different study design was considered to investigate the interaction effects between the different parameters that can be assigned to a moving virtual crowd. Second, a higher number of participants were recruited to ensure the validity and reliability of the results. We believe that both the study design and the increased number of participants are sufficient to differentiate this article from the previously conducted study.

The present study aimed to investigate whether the parameters of a moving crowd population impacted the movement of participants within a virtual environment. More specifically, we attempted to investigate whether human movement is affected by the movement parameters assigned to a virtual crowd population within a virtual reality crosswalk scenario taking place in a virtual metropolitan city. Due to the nature of this study, human motion data were captured. Note that various other studies that have attempted to assess virtual reality interaction by capturing and analyzing human movement behavior.[13,34,35] This study can be considered an extension of previous research that examined interactions with virtual crowd populations[11,12,26,51] while analyzing and attempting to understand human movement behavior.[12,13,24,34] Finally, it should be noted that this article does not focus on movement coordination. Rather, it goes a step further by exploring movement manipulation and, more specifically, examining whether a moving crowd can change the speed, deviation, and trajectory lengths (total distance traveled) of participants who have been instructed to simply cross a road and reach the opposite sidewalk and have not been instructed to follow the movement of the virtual crowd.

3 | MATERIALS AND METHODS

The following subsections provide details of the materials and methods used in this study.

3.1 | Participants

Eighty healthy individuals ($M = 22.51, SD = 3.02$)were recruited from a university setting. Of this sample, 22 were female and 58 were male. The participants were recruited through class announcements, emails, and posters placed on notice boards in our department. All participants were volunteers, and no compensation was offered. None of the participants reported motion sickness or any other types of cyber sickness. All participants were exposed to all examined conditions, and each performed a single-walking task for each condition.

3.2 | Conditions of the experiment

Based on the *density*, *speed*, and *direction* that characterize a virtual crowd, we developed and tested eight experimental conditions. We chose a 2×2×2within-group study design to directly compare the different parameters of a crowd across the examined conditions of this study. The eight conditions were formed in three pairs: low density versus high density (*density*), low speed versus high speed (*speed*), and straight direction versus diagonal direction (*direction*). Each parameter is shown in Figure 1.

For the *density* parameter, the low density situation simulated a virtual crowd with one pedestrian for every square meter, and the high density situation simulated a virtual crowd with 2.5 virtual characters per square meter. For the purposes of this study, the density model proposed by Still[3] was considered and implemented to deal with the *density* parameter of the virtual crowd and to specify the number of pedestrians for every square meter.

For the *speed* parameter, for the low speed situation, a normal walking speed was assigned to each character in the virtual crowd according to the US Manual of Uniform Traffic Control Devices,[52] which states that humans' normal walking speed has been estimated to be 1.2 m/s. For the high speed situation, each character was assigned a running motion of 3.8 m/s, according to the estimations of Miller et al.[53]

For the *direction* parameter, each virtual character crossing the road in the straight direction situation was assigned a 0° angle. For the diagonal direction situation, a 30° angle was assigned to each character crossing the road. Therefore, in contrast to the straight situation, each character in the diagonal crowd simulation reached the opposite sidewalk with an offset distance. Various other directions could have been applied to our crowd, including the opposite (i.e., crowd moving against the participant) and perpendicular ones. In this study, we examined whether a crowd that is moving to the opposite sidewalk (the crowd is moving along with the participants and not against them) could affect the participants' movement behavior. We decided to explore a 30° angle, as a previous study conducted by Nelson et al.[12] found no significant effects of crowd direction on participants' movement behavior when 2°, 4°, 6°, 8°, and 10° angles were examined. Therefore, we decided to examine whether a direction that can easily be perceived by the participants could affect their movement behavior.

3.3 | Measurements

To determine how participant movement was affected by each experimental condition, we recorded the participants' motions using a motion capture system. The trajectory of the root was later extracted from the full-body motion sequence, and the data were down-sampled in 100 equidistant points,[54] as was done in previous studies.[12,34] The following three measurements were extracted:

- *Speed:* The average speed of the participants walking toward the opposite sidewalk. This was measured in meters/second.
- *Deviation:* The x-axis deviation (absolute value) of the participants upon their arrival at the opposite sidewalk. Deviation was computed using the difference between participants' initial x-axis positions (initial positions at the sidewalk) and final x-axis positions (final positions at the opposite sidewalk). Deviation was measured in meters.
- *Trajectory length:* The participants' total trajectory length (total distance covered to reach the opposite sidewalk). The length of the captured trajectory was measured in meters.

3.4 | Experimental setup, equipment, and virtual reality application

The motion capture studio was used to conduct this study. The motion capture studio is 8 m long and wide and has a ceiling height of 4 m. The studio was almost free of obstacles, with only a desk, a computer, and a couple of chairs on one side of the room. For the purposes of this study, our participants were asked to walk 7 m, leaving some space to avoid collisions with the front wall (no collisions occurred over the course of the study).

The following equipment was used for this study. The HTC Vive Pro head-mounted display was used to project and immerse the participants in the virtual environment. The Xsens inertial motion capture system was used to capture participants' motions. We also used a backpack computer—the MSI VR One—to run the virtual reality application and a Dell Alienware Aurora R7 desktop computer to remotely control the backpack computer and switch between conditions. Figure 2 shows a participant walking within the motion capture studio and the content he observed during the walking task.

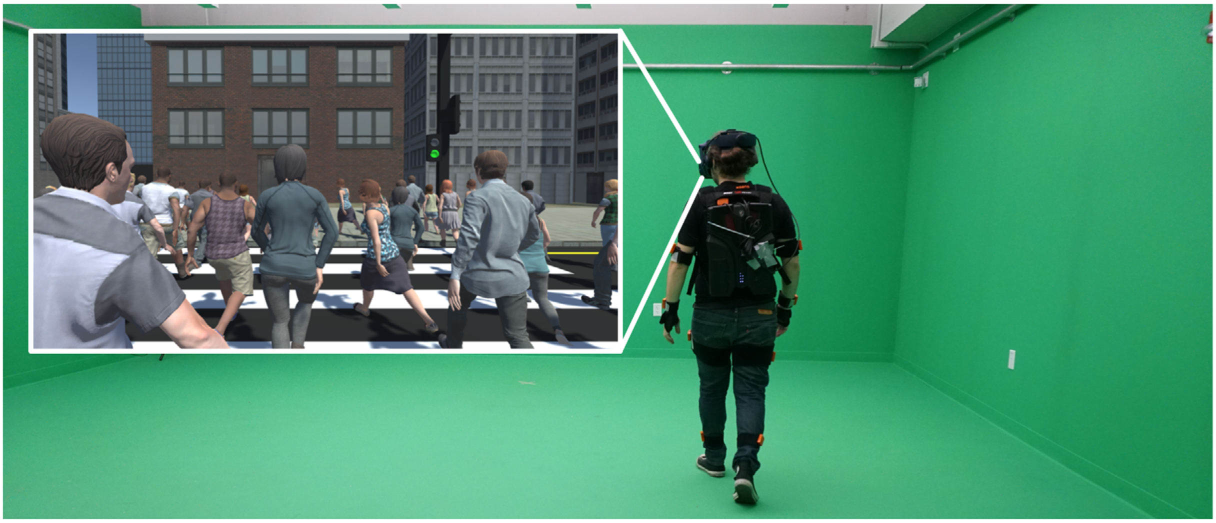

FIGURE 2 A participant walking in the lab and moving toward the opposite sidewalk in the virtual metropolitan city. A third-person view of the virtual environment observed by the participant is also shown. The participant is wearing all the devices used in this study (an MSI VR One backpack computer, an HTC Vive head-mounted display, and an Xsens motion capture system).

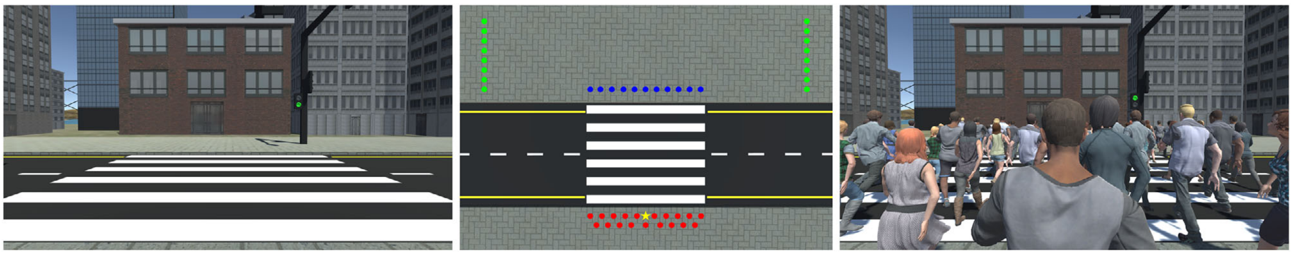

FIGURE 3 Left: The part of the metropolitan city (virtual crosswalk) that was used in our study. Middle: Each pedestrian in the crowd was initialized at the red circles and was asked to first reach the blue circle (target position) on the opposite sidewalk and then one of the green circles on the sides of the opposite sidewalk to alleviate congestion. The participant was initialized at the yellow star position, which means that the participant was surrounded by virtual pedestrians. For the diagonal situation, the target positions were shifted toward the left side. Right: A first-person view of the low speed, low density, and straight conditions of the virtual crowd to which the participants were exposed

The research team designed the virtual metropolitan city, including the crosswalk, using Autodesk 3ds Max. This model was later imported to Unity3D game engine version 2019.1.4, which was used to develop and run the virtual reality application. Figure 3 depicts the part of the metropolitan city in which the participants were placed and instructed to cross the virtual crosswalk. The participants were placed in the middle of the sidewalk so that there would be virtual pedestrians on the right and left sides. Each virtual character belonging to the virtual crowd population was scripted to move toward the opposite sidewalk. It should be noted that the crowd simulation was structured in such a way that the participant was surrounded during the crowd-simulation process (see Figure 3). Each individual pedestrian in the crowd was scripted to avoid the participant's presence in the virtual environment; this was done using the collision avoidance mechanism provided by the NavMesh Agent functionality of Unity3D. Each participant had individual trajectories; therefore, although the simulated crowd was scripted to follow a specific behavior (cross the road and reach the opposite sidewalk), the participants might have experienced small variations of the crowd simulation because each participant's behavior was unique. Considering that such variations would appear in all conditions for all participants and the fact that during the study, the participants were surrounded by a crowd moving with specified parameters, it was determined that such variations would not affect our findings, especially because the scope of the article was to examine whether the virtual crowd—not the individual virtual characters—affected participants' movement behaviors.

Our research team designed 30 virtual characters using Adobe Fuse software. To create a crowd that could be considered realistic, we decided to vary the heights of the virtual characters. More specifically, we created a male character with a height of 1.70 m and a female character with a height of 160 m, which are rounded approximations of the global average height for males and females.[1]This decision helped us standardize our study. If we had included virtual characters with different height, this would have added an additional variable to our experiment. Note that all character designs were repeated multiple times throughout the road-crossing scenario. The virtual characters were rigged using Adobe Mixamo. To animate the virtual characters, various walking motion sequences were downloaded from the Unity3D Asset Store. It should be noted that the NavMesh functionality of Unity3D, along with a target position in the virtual environment, were used to compute the path that each virtual character followed. Once each character reached the opposite sidewalk, the virtual characters were scripted to move to a different position within the virtual environment to free the space at the opposite sidewalk and alleviate congestion. The virtual characters were animated using the Mecanim animation engine of Unity3D. To make our characters move at a specific speed, Unity3D's motion blending functionality was used along with the appropriate blend weight assigned to the motion sequences. Thus, we were able to generate walking and running motions with the aforementioned speed specifications. Finally, all eight conditions were prescribed by the researchers, and the buttons on Unity3D's inspector window were used to control the conditions to which the participants would be exposed.

Sunlight was used to illuminate the virtual metropolitan city, thereby providing participants with the impression that the entire interaction was performed during the daytime. To enhance the immersion and presence of the participants, the research team used audio and sound effects that were relevant to the metropolitan city and crowd-simulation scenario. Previous studies have found that sound related to visual content enhances the immersion and presence of the virtual reality experience.[55,56] Finally, although a motion capture system was used to capture the full-body motions of the participants, the research team decided not to use avatars to represent the participants. A previous study found that the use of virtual avatars to represent participants during a walking task might affect their movement within the virtual environment.[34] This was important to consider because the omission of avatars to represent participants helped in extracting movement behavior that was not influenced by parameters other than those examined, such as a virtual body that does not match the participant's own body in terms of size and appearance.

3.5 | Procedure

Each participant arrived at the motion capture studio after scheduling the day and time that best suited him or her. After arriving at the studio, the participants were instructed to read and sign consent forms indicating their agreement to participate in our study. The study was authorized by the institutional review board of Purdue University (IRB Protocol No. 1905022239). After the consent forms were signed, the experimenter handed a demographics questionnaire to each participant. The research team helped the participants to do all the equipment necessary for their participation in the study. A member of the research team asked each participant to walk within the studio, and then the participant was exposed to a virtual environment that was identical to that of the motion capture studio in which the experimental study was conducted. Thus, the research team ensured that the participants were able to perform regular walking within the virtual environment without experiencing simulation sickness.

Once each participant indicated that he or she was comfortable walking within the virtual environment with all the equipment attached to his or her body, the participant was instructed to remove the head-mounted display, move to a specified position within the lab space, and face the opposite sidewalk. The research team was responsible for checking whether the participant faced the forward direction and ensuring that the participant was always exposed to the condition immediately after facing the forward direction. The research team informed the participants that they would be placed on the sidewalk of a virtual metropolitan city. They were told that they should perform a simple walking task and reach the opposite sidewalk. They were also informed that they would be surrounded by a virtual population that would also be moving toward the opposite sidewalk. Figure 2 shows a participant wearing the devices used in this study and walking toward the opposite sidewalk. No further information regarding the movement of the virtual crowd was provided to the participants. All the participants were told that they should start moving once the traffic light at the opposite sidewalk turned green and that a beep would signal for them to stop walking once they reached the opposite sidewalk. They were also told that a black screen would appear once they reached the opposite sidewalk and stopped. At that time, they were instructed to remove the head-mounted display and walk toward the signed position in the motion capture studio to prepare for the next condition of the experimental study. They were told that the research team would inform them once

[1]https://ourworldindata.org/human-height

the experiment was complete. The participants were aware that they could take breaks between conditions if needed and that they were allowed to withdraw from the experiment at any time.

After the participants completed all eight variations of the experimental study, the research team helped them to carefully remove all the equipment that had been attached to their bodies. They were asked to provide feedback on the experimental study by writing their views on a blank sheet of paper that was handed to them. The research team was also willing to answer any questions that were raised by the participants after the study ended. The Latin squares ordering method[57] was used to ensure a balance of first-order carryover effects between conditions. Finally, it should be noted that each participant spent no more than 30 minutes in the motion capture studio.

4 | RESULTS

The data were analyzed using a three-way repeated measure analysis of variance (ANOVA) with the *density*, *speed*, and *direction* factors. The data were screened for normality using the Q-Q plots of the residuals,[58] which indicated that the assumption of normality was satisfied. A $p < .05$wasused to identify statistical differences, and post hoc corrected estimates using Bonferroni was adopted for cases in which the ANOVA yielded significant results. Finally, to support our results, Figure 4 shows the plots of the participants' trajectories for each of the eight exposed conditions.

4.1 | Speed

Regarding the speed measurement, we found a significant main effect for the *density*, $\Lambda = .076, F(1,79) = 953.875, p < .001, \eta_p^2 = .924$, and *speed*, $\Lambda = .869, F(1,79) = 11.890, p < .01, \eta_p^2 = .131$ parameters; however, no significant results were found for the *direction* parameter, $\Lambda = .998, F(1,79) = 0.195, p = .66, \eta_p^2 = .002$. A pairwise comparison with the Bonferroni correction revealed that the participants' speeds were significantly higher for the low-density crowd situation $(M = 1.38, SD = 0.02)$than for the high-density crowd situation $(M = 1.09, SD = 0.01)$.This pairwise comparison also showed that the participants' speeds were significantly higher for the high-speed crowd situation $(M = 1.24, SD = 0.01)$than for the low-speed crowd situation $(M = 1.22, SD = 0.01)$.

A two-way significant interactions effect was found between *density* and *direction*, $\Lambda = .948, F(1,79) = 4.305, p < .05, \eta_p^2 = .052$. The estimated marginal means showed that the participants' speeds were significantly higher when exposed to low-density and straight direction crowd situations. Additionally, a three-way significant interaction effect between *density*, *speed*, and *direction* was found, $\Lambda = .813, F(1,79) = 18.212, p < .001, \eta_p^2 = .187$. The estimated marginal means showed that the participants' speeds were significantly higher when exposed to low-density, high-speed, and straight direction crowd situations. Figure 5 shows the plots of the estimated marginal means.

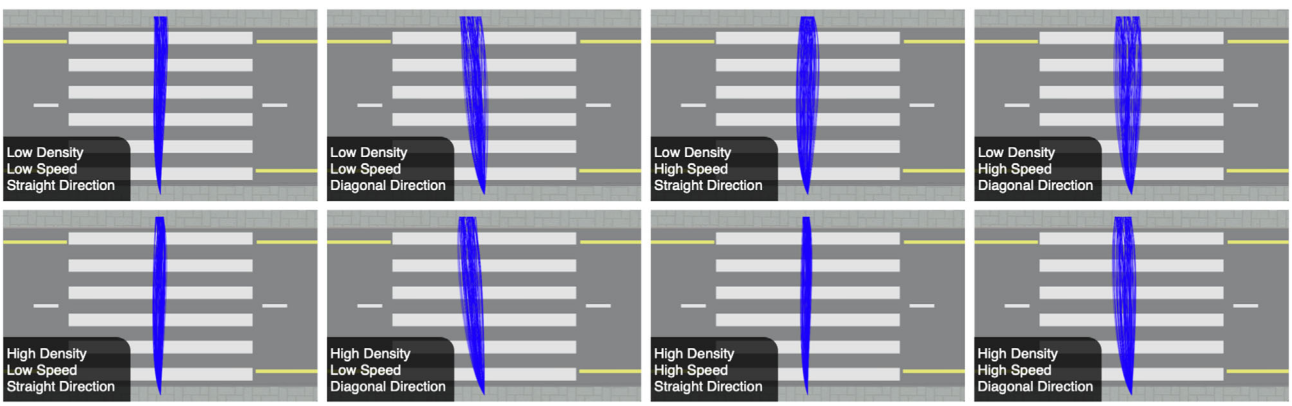

FIGURE 4 The trajectories of participants for each condition (combination of the different *density*, *speed*, and *direction* parameters) to which they were exposed

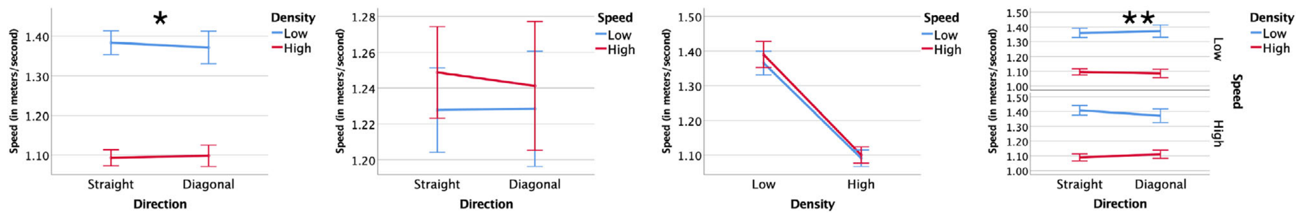

FIGURE 5 The plots of the estimated marginal means of the speed (in meters/second). From left to right: state of *direction* × *density*, state of *direction* × *speed*, state of *density* × *speed*, and state of *direction* × *density* × *speed*. Significant results are indicated with $*p < .05$ and $**p < .001$

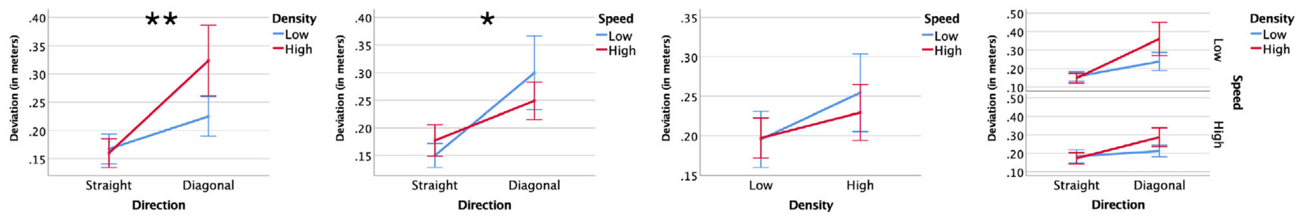

FIGURE 6 The plots of the estimated marginal means of the deviation (in meters). From left to right: state of *direction* × *density*, state of *direction* × *speed*, state of *density* × *speed*, and state of *direction* × *density* × *speed*. Significant results are indicated with $*p < .01$ and $**p < .001$

4.2 | Deviation

When examining the deviation measurement, we found a significant main effect for the *density*, $\Lambda = .857, F(1,79) = 13.169, p < .01, \eta_p^2 = .143$, and *direction*, $\Lambda = .722, F(1,79) = 11.890, p < .001, \eta_p^2 = .278$, parameters; however, no significant results were found for the *speed* parameter, $\Lambda = .994, F(1,79) = 0.491, p = .66, \eta_p^2 = .006$. A pairwise comparison with the Bonferroni correction revealed that the participants' deviation was significantly higher for the high-density crowd situation ($M = 0.24, SD = 0.02$)than for the low-density crowd situation ($M = 0.20, SD = 0.01$).This pairwise comparison also showed that the participants' deviation was significantly higher for the diagonal crowd situation ($M = 0.27, SD = 0.02$)than for the straight crowd situation ($M = 0.16, SD = 0.01$).

We also found significant interaction effects between *density* and *direction*, $\Lambda = .811, F(1,79) = 18.470, p < .001, \eta_p^2 = .189$, and between *speed*and *direction*, $\Lambda = .868, F(1,79) = 12.053, p < .01, \eta_p^2 = .132$. The estimated marginal means showed that participants deviated more when exposed to (1) high-density and diagonal crowd situations and (2) low-speed and diagonal crowd situations. No three-way interaction effects were found. Figure 6 shows the plots of the estimated marginal means.

4.3 | Trajectory length

Regarding the trajectory length measurement, we found a significant main effect for the *density*, $\Lambda = .811, F(1,79) = 7.685, p < .01, \eta_p^2 = .089$, and *direction*, $\Lambda = .737, F(1,79) = 5.347, p < .05, \eta_p^2 = .063$, parameters; however, no significant results were found for the *speed* parameter, $\Lambda = .886, F(1,79) = 0.347, p = .559, \eta_p^2 = .004$. A pairwise comparison with the Bonferroni correction revealed that the participants' trajectory length was significantly higher for the high-density crowd situation ($M = 7.20, SD = 0.04$)than for the low-density crowd situation ($M = 7.12, SD = 0.06$).This pairwise comparison also showed that the participants' trajectory length was significantly higher for the diagonal crowd situation ($M = 7.21, SD = 0.11$)than for the straight crowd situation ($M = 7.05, SD = 0.07$).

We also found a significant interaction effect between *density* and *direction*, $\Lambda = .852, F(1,79) = 3.153, p < .05, \eta_p^2 = .048$. The estimated marginal means showed that participants' trajectory length was higher when they were exposed to high-density and diagonal crowd situations. No three-way interaction effects were found. Figure 7shows the plots of the estimated marginal means.

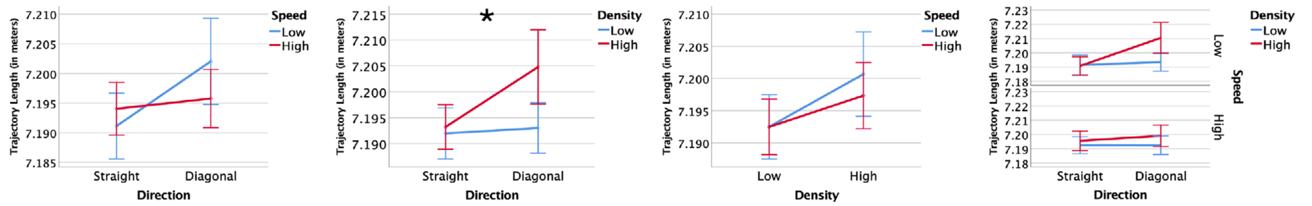

FIGURE 7 The plots of the estimated marginal means of the trajectory length (in meters). From left to right: state of *direction* × *density*, state of *direction* × *speed*, state of *density* × *speed*, and state of *direction* × *density* × *speed*. Significant results are indicated with $*p < .05$

5 | DISCUSSION

The participants in our virtual reality study were asked to cross a virtual crosswalk and reach the opposite sidewalk while surrounded by a virtual crowd performing the same activity. We explored three parameters (*density*, *speed*, and *direction*) that characterize a moving virtual crowd. Eight virtual reality conditions related to the crowd parameters were developed. To understand the effects of the different situations assigned to the virtual crowd on human movement behavior, the speed, deviation, and trajectory length measurements were extracted from the participants' motions, which were captured using a motion capture system. The results obtained from the experimental study indicated that all three parameters (*density*, *speed*, and *direction*) assigned to the virtual crowd did indeed affect participants' movement behavior in the virtual environment.

Considering the results regarding the speed measurement, it can be said that both the *density* and *speed*parameters of the virtual crowd can be used to affect the walking speed of participants, which is also in line with the previously conducted work of Dickinson et al.[27] and Nelson et al.;[12] however, this does not apply to the *direction* parameter of the virtual crowd. Specifically, our results indicated that an increase in the speed of the virtual crowd corresponds to an increase in the participants' speeds. Another result showed that the speed of the participant also increased when a participant was exposed to a low-density virtual crowd. We also found a two-way and three-way interaction effect. Our results indicated that the participants' speeds were significantly higher when they were exposed to low density and straight situations, as well as to low density, high speed, and straight situations.

We interpreted these findings as follows. Humans attempt to secure distance when avoiding virtual characters;[34,38] thus, once the participants became aware of the nearby virtual characters surrounding them, they decided to decrease their speeds to avoid unwanted collisions with them.[36,37] Another interpretation relates to the density of the crowd—that is, how the high density crowd affected the participants' perceptions of their location. Specifically, after completing the study, a few participants reported that due to the limited amount of visual information, they had not been fully aware of their exact distance from the opposite sidewalk. The participants who were exposed to the high density condition were placed in an environment full of virtual characters; therefore, the virtual crowd in front of them blocked the opposite sidewalk. Note that the blocking of the opposite sidewalk affected all participants regardless of their height. Thus, according to the participants' comments, they decided to use care by reducing their speed as they walked to the opposite sidewalk and consequently to the other side of the room without colliding with the front wall.

The results of the deviation measurements suggest that the *density* and *direction* of the virtual crowd were the two parameters that caused the participants to deviate significantly from the exact forward position on the opposite sidewalk. However, no significant results were found regarding the *speed* of the virtual crowd. The results indicated that the participants who were exposed to the high-density virtual crowd deviated significantly more from the exact forward position than they did when exposed to a low-density virtual crowd. Our results also revealed that the deviation of the participants was significantly greater when they were exposed to the diagonal direction of the virtual crowd than to the straight direction. In addition to these one-way effects, we found a two-way interaction effect. Specifically, our results indicated that participants deviated more when exposed to either a high-density virtual crowd that moved diagonally or to a low-speed virtual crowd that moved diagonally. This can be easily understood by observing Figure 4.

Regarding the results of the deviation measurements, it appears that the *density* and *direction* of a virtual crowd can change participants' movement behaviors and, more specifically, the way in which they deviate from the exact straight position on the opposite sidewalk. However, the interaction effects regarding *density* and *direction*, as well as *density* and *speed*, provided even more insights into how the participants decided to regulate their movements within the virtual environment. One interpretation proposes that the participants might have felt trapped within the high density crowd once they were exposed to it. Thus, the participants may have decided to move with the flow of the crowd instead of attempting to free themselves from it,[32,43] as prior studies have shown that humans tend to coordinate with virtual characters when in their presence.[46-48] Moreover, the *direction* and *speed* interaction effect suggests that our participants may have been more willing to follow the virtual crowd when it was moving at a low rather than a high speed. To interpret this result, we recalled our conversations with the participants after they had completed the walking tasks. Specifically, a number of participants stated that they felt less safe following fast-moving virtual characters and that this was why they did not deviate significantly from the forward position on the opposite sidewalk when the virtual characters were running. Moreover, a few participants stated that the high speed motion assigned to the virtual characters was annoying and made it difficult to concentrate on their target destination.

When examining the trajectory length measurement, we found no significant results regarding the *speed*parameters assigned to the virtual crowd. However, we found that the *density* and *direction* parameters assigned to the virtual crowd caused the participants to follow a longer path when crossing the virtual crosswalk. Specifically, our results revealed that the participants who were exposed to the high-density virtual crowd followed longer paths compared with when they were exposed to the low-density virtual crowd. Moreover, our results showed that the length of the participants' trajectories were higher when they were exposed to the diagonal direction of the virtual crowd than when they were exposed to the straight direction. Finally, in addition to the one-way effects, we found a two-way interaction effect between the *density* and *direction* parameters. The results indicated that the participants who were exposed to the high-density virtual crowd moving in a diagonal direction followed longer trajectories than they did when exposed to the low-density crowd moving in a forward direction.

The interpretation of these findings is mainly based on prior work that has addressed virtual crowd density and humans' collective behavior and movement coordination. Specifically, prior work on crowd density[27] has shown that different density conditions affect participants' trajectories. Moreover, considering the interaction effect between *density* and *direction*, it becomes even clearer that this finding could be related to previous studies that examined concurrent and joint human actions;[59-62] such studies have shown that humans tend to coordinate with nearby humans or virtual characters when performing tasks concurrently. The aforementioned research explains why the participants' movements were affected by the virtual crowd population that surrounded them. Additionally, a few participants mentioned that they moved with the flow because they felt suffocated by the virtual crowd around them, especially during the high density situation. This means that the high-density virtual crowd could affect the paths that the participants followed, and as a result, their chosen paths were not based on their intentions but, rather, on the ability of the virtual crowd to manipulate their movements within the virtual environment.

Some additional comments from the participants might help us interpret and understand why they decided to regulate their movement behaviors in certain ways when exposed to the developed conditions. Specifically, a number of participants stated that they were scared that if they moved too fast, they might need more space and time to decelerate and stop upon reaching the opposite sidewalk so as not to collide with the front wall. Moreover, a couple of participants stated that they feared moving fast because they thought they might collide with the virtual characters, thereby generating a domino effect between the characters and destroying the entire simulation process. Note that no physics was applied to the virtual characters; therefore, it would have been impossible for such a domino effect to occur. These comments may partially explain why the participants decided not to run very fast when exposed to the high-speed crowd situations. Finally, a few other participants informed us that they had forced themselves to follow a straight path and avoid deviating from the forward path because they feared they might collide with the side walls. However, we found that the participants' deviation increased when they were exposed to the diagonal crowd situation (see Figure 4); this explains why they did not deviate as much as the crowd did. On average, the characters in the virtual crowd deviated approximately 4 m, while the participants deviated an average of 0.27 m during the diagonal direction situation.

Some reflections on the observations made by the research team over the course of the study are worth noting. The participants were highly immersed within the virtual environment and were focused on accomplishing the given task. As the results revealed, the virtual crowd was entirely responsible for manipulating the participants' movement behavior. We neither asked nor instructed the participants to follow the virtual crowd's movement behavior; rather, we gave them a single instruction—to cross the virtual crosswalk and reach the opposite sidewalk. Therefore, our participants were able to choose their own speeds and directions within the virtual environment. We believe that the high-level immersion that the participants experienced was the result of a combination of factors. Specifically, they were exposed to a compelling virtual reality experience in which their visual, aural, haptic, proprioceptive, and vestibular systems were occupied throughout the experiment. This reflection, in conjunction with the data analyses results, suggests that the virtual crowd manipulated the participants' movement behavior because an assessment of their intentions revealed that they regulated their movement behavior according to the movements of the virtual characters that surrounded them; this was especially the case when the participants were immersed in low-speed and high-density crowd situations.

Three limitations were revealed through our discussions with the participants. The first relates to the omission of haptic feedback. Specifically, some participants stated that they had expected to feel the virtual characters touching their bodies when they were exposed to the high density situation. According to their comments, the lack of haptic feedback sometimes caused them to feel that the virtual reality scenario was not sufficiently realistic. The second limitation relates to the motion capture studio in which the experimental study took place. The participants stated that they were aware that there was limited space in front of them and that this caused them to not want to increase their speed due to their fear that they might run into the wall. The third limitation relates to the equipment that was used. Although the participants mentioned that they were quite comfortable walking with all the equipment attached to their bodies, they also stated that they had thought that running while wearing all the equipment might be problematic because there was a chance that the backpack computer might become detached from its harness or that the sensors of the motion capture system might become detached from the Velcro straps. From our experiences dealing with the aforementioned devices, we knew that none of this could have happened; nonetheless, this limitation caused the participants to fear increasing their speeds and running within the virtual environment. In conclusion, these limitations should be considered by any researchers who conduct studies that require participants to move within virtual environments while surrounded by a virtual crowd.

6 | CONCLUSIONS AND FUTURE WORK

We investigated how different parameters of a virtual crowd surrounding our participants did or did not affect their movement behaviors when they were instructed to cross a virtual crosswalk within a virtual environment (a metropolitan city). The results indicated that the virtual crowd affected the participants' movements. Specifically, the results showed that the *density* and *speed* conditions impacted participants' speeds, and the *density* and *direction*conditions impacted their deviation and trajectory lengths. Moreover, interaction effects were found between the conditions, indicating a relationship between the examined conditions and how participants' movements were affected. We believe that developers and researchers who examine human–virtual crowd interactions should consider these movement manipulation effects when developing the parts of a virtual reality experience that involve humans completing walking tasks.

This study is a step toward further exploration of the interactions between humans and moving virtual crowds and, more specifically, the effects of crowd movement on human movement behavior. Our future research will investigate how humans walk within a virtual crowd population that is moving in perpendicular and opposite directions. Moreover, the issue of how humans walk within a virtual crowd population that is moving in various directions should be explored. We are also interested in conducting studies to investigate the effects of assigning politeness behavior to virtual pedestrians. Moreover, human–virtual crowd interaction could be studied with a virtual crowd that is walking within a constrained environment or along curved paths, rather than in a straight line as the virtual crowd in this study did. Because the current approach investigated only individual pedestrians belonging to a virtual crowd, it is vital to further examine the movement behaviors of humans walking along with virtual characters that have been grouped into small teams that are moving in a specified direction. Moreover, we plan to confirm whether humans' movement behaviors correlate significantly with two important theoretical concepts of virtual reality: presence and embodiment. To this end, both human motion data and self-reported ratings obtained from questionnaires will be collected. Finally, it would be interesting to investigate the movements of humans who are immersed in a virtual crowd population composed of characters of different ages and genders, as this would enable further understanding of how they perceive and interact with virtual characters.

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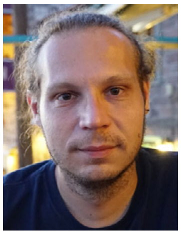

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