Within a Virtual Crowd: Exploring Human Movement Behavior during Immersive Virtual Crowd Interaction

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Figure 1: A participant crossing the road while being immersed in a virtual metropolitan city.

ABSTRACT

This paper presents an exploratory study aiming at investigating the movement behavior of participants when immersed within a virtual crowd. Specifically, a crosswalk scenario was created in which a virtual crowd was scripted to cross the road once the traffic light turned green. Participants were also instructed to walk across the road to the opposite sidewalk. During that time, the assessment of participant movement behavior was captured by the use of objective measurements (time, speed, and deviation). Five density conditions (no density, low density, medium density, high density, and extreme density) were developed to investigate which had the greatest effect on the movement behavior of the participants. The results obtained indicated that the extreme density condition of the virtual crowd did indeed alter the movement behavior of participants to a significant degree. Given that density had the greatest effect on the movement behavior of participants, a follow-up study was also conducted that utilized the density findings and explored whether density can affect the speed and direction of participants. This was achieved through examining five speed conditions and six directional conditions. The follow-up study provided some evidence that during an extreme density condition the speed of the crowd also affects the movement behavior of participants. However, no alteration in human movement behavior was observed when examining the direction of the virtual crowd. Implications for future research are discussed.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **User studies**.

KEYWORDS

virtual crowd, human movement behavior, human-crowd interaction, virtual reality

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1 INTRODUCTION

There are numerous applications related to virtual reality, ranging from games to movies, in which virtual characters are required to interact with. The way that we perceive this interaction has been a topic of interest for various researchers. Previously conducted studies found that when people were asked to interact with virtual characters, the interaction was similar to those performed in

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real situations in terms of subjective, objective, and physiological measurements [Pan et al. 2012; Pertaub et al. 2002] even if the participants were aware that the interaction was taking place with virtual characters and not with real humans [Freeman et al. 2003]. In addition, apart from single character interaction [Koilias et al. 2019; Mousas et al. 2018; Pan et al. 2012], studies that investigate interaction in either small groups of characters or virtual crowds have also been a point of interest to the research community [Krogmeier et al. 2019; Kyriakou et al. 2017; Olivier et al. 2014; Pelechano et al. 2008; Rıos et al. 2018].

Among others, navigation in virtual environments is a fundamental requirement for efficient interaction [Olivier et al. 2017]. Natural walking within virtual environments is useful for a number of different virtual reality applications and it is still considered the most realistic walking interface available [Usoh et al. 1999]. Thus, a number of studies have been conducted to further understand human movement behavior when walking within virtual environments. Among other research directions, interaction between participants and virtual characters in immersive virtual reality setups with the intention of understanding how variations assigned to a virtual character can affect the movement behavior of participants has also triggered the interest of the virtual reality community [Ahn et al. 2012; Dickinson et al. 2019; Pelechano et al. 2008].

For immersive virtual reality experiences there is no sufficient research on how humans interact with virtual crowds and whether or not a virtual crowd can alter the behavior of humans [Kyriakou et al. 2017; Slater 2009]. Taking into consideration the fact that there are cases in which virtual reality users might interact with moving virtual populations (virtual crowds), it is assumed that studies concerning human-virtual crowd interaction could help developers gain the necessary knowledge to develop virtual reality experiences that are more realistic for the users of such applications. Thus, a study which would investigate whether or not the parameters of a virtual crowd (density, speed, and direction) can alter the movement of participants within virtual environments was considered necessary. In particular, the main purpose of this study is to investigate whether a simple walking task performed by participants can be affected by a virtual crowd that surrounds the participants within the virtual environment.

Two virtual reality studies were conducted in which participants were immersed into a metropolitan city scenario and were asked to navigate themselves along a busy crosswalk (see Figure 1). The first study (the main study) investigated whether the density conditions of a virtual crowd could alter the movement behavior of participants. Based on the findings of the main study, a second study (the follow-up study) was also conducted in order to understand whether the density finding which affected the movement behavior of participants to a higher degree could alter the walking speed and the direction of the participants by examining the five crowd speed and the six crowd directional conditions respectively. The study utilized a simple method to capture the movement behavior of participants and all the presented results are based on objective measurements. Based on the abovementioned study, this research aims to answer the following research questions:

- **RQ1:** Does the density of a virtual crowd affect the movement behavior of participants?
- **RQ2:** Given the density condition which affected the movement behavior of participants to a higher degree, does the speed of a virtual crowd affect the speed of participants?
- **RQ3:** Given the density condition which affected the movement behavior of participants to a higher degree, does the direction of a virtual crowd affect the direction of participants?
- **RQ4** Does participant movement behavior correlate with the movement behavior assigned to the virtual crowd?

The rest of this paper is organized in the following sections. Section 2 describes related work on human-crowd interaction as well as human movement behavior in virtual environments. The main study that explored the effects of crowd density is presented in Section 3 and the follow-up study that investigated the effects of crowd speed and crowd direction on human movement behavior is presented in Section 4. The obtained results are discussed in Section 5. Finally, conclusions, limitations, and future work are presented in Section 6.

2 RELATED WORK

Virtual reality can be considered as a powerful tool used to conduct perception-action related experiments [Loomis et al. 1999]. To date, it has been used to understand movement behavior in sports [Bideau et al. 2009], tasks related to spatial cognition [Mallot et al. 1998; Mohler et al. 2006] and more. The advantage of virtual reality technology in studying human behavior is that it provides researchers the ability to control and manipulate the parameters of the stimuli, while the experimental conditions the participants get exposed to remain the same. Thus, several studies have evaluated the effects of virtual reality on human perception and behavior [Loomis and Knapp 2003; Ruddle et al. 2013; Zanbaka et al. 2005].

Various studies have been conducted that investigate interaction between humans and either individual or groups of virtual characters. Interaction with virtual content during locomotive tasks performed by participants triggered the interest of the research community [Bruneau et al. 2015; Mousas et al. 2019; Olivier et al. 2017]. Such studies are mainly focused on either how humans perceive the virtual characters or on how human behavior is altered. Among others, several types of interaction such as following behavior [Lemercier et al. 2012; Rio et al. 2014], side-by-side [Perrinet et al. 2013], face-to-face walking [Ducourant et al. 2005], group formations [Karamouzas and Overmars 2010], and collision avoidance [Mousas et al. 2019; Olivier et al. 2017] have been explored in the past few years. Such studies try to examine whether the experimental conditions can influence the movement of participants within virtual environments. This current study explores human-virtual crowd interaction and specifically focuses on human movement behavior when participants are immersed within a moving virtual crowd.

Previous studies regarding human behavior have found that participants try to maintain a greater distance when interacting with realistic virtual characters [Bailenson et al. 2001]. Moreover, negative reactions are triggered when a participant's personal space is violated by a virtual character [Wilcox et al. 2006]. Regarding interactions with a small group of virtual characters, participants have been found to retain greater distance when approaching virtual characters from the front compared to approaching them from behind [Llobera et al. 2010]. It has been found that participants provide more space to virtual characters who engaged them during mutual gaze interaction and participants tend to move farther from virtual characters that violate their personal space [Bailenson et al. 2003]. Moreover, another study [Bruneau et al. 2015] found that participants tend to follow a longer path around dense groups of virtual characters. These findings motivated us to study how human behavior, and more specifically the movement of participants, is altered when placed within a moving virtual crowd.

Among other human-crowd interaction studies, a virtual reality framework examining human-virtual crowd interaction and ways to improve the level of realism of simulation algorithms was developed by Olivier et al. [Olivier et al. 2014]. Dickinson et al. [Dickinson et al. 2019] studied the effects of crowd density across three experimental conditions on the affective state and behavior of participants. The results show a significant increase in negative affect when interacting with a high-density crowd, measured using a self-reported rating. They also found significant differences in certain aspects of participant behaviors using a video analysis technique. Rios et al. [Rıos et al. 2018] studied the effect of crowd social behavior on human behavior when following others during a virtual reality evacuation scenario. The results from this study indicated there is not yet an accurate model to determine under what circumstances and to what extent this behavior emerges.

Studies concerning human perception on virtual crowds have also been conducted. The effects of characteristics assigned to crowd groups have been examined [Ennis et al. 2010; McDonnell et al. 2009; Peters and Ennis 2009] and it has been found that grouping virtual characters together improves the realism of the virtual crowd in cases when the virtual crowd has the proper size, as well as the proper number of characters used for the simulation process. Another study [Huerre et al. 2010] investigated the effects of both the position and the orientation of virtual characters, when they are part of a crowd, on the plausibility of the virtual crowd and found that rule-based crowd formations are more realistic than random formations. The perception of participants on the realism of the virtual crowd was also examined [Ennis et al. 2011] and it was found that among other significant parameters, the interaction scenario and the behaviors assigned to the virtual characters influence the perception of crowd realism. The egocentric features that should be assigned to a virtual crowd were also studied [Ahn et al. 2012; Pelechano et al. 2008]. It was found that low presence or low comfort levels appear when there is an absence of collision avoidance implementation mechanisms or when shaking artifacts appear among pedestrians.

To understand human movement behavior in virtual environments, several methods were proposed to evaluate the trajectories of participants. Performance criteria [Souman et al. 2011; Zanbaka et al. 2005] such as time of completion, distance traveled, walking speed, and empirical observations [Zanbaka et al. 2005] have been extensively used in the past. It should be noted that speed measurements have shown to be among the most important features of human motion [Jiang et al. 2018; Ruddle et al. 2013]. Other criteria for evaluating the trajectories include metrics, [Fink et al. 2007] such as the curvature radius and the Euclidean distance from a straight line that connects the start and the goal position, principal component analysis [Whitton et al. 2005], or even geometric and temporal evaluation criteria, [Cirio et al. 2013] such as duration, angular velocity profile and shape of the trajectory. Based on these different methods of analyzing the captured trajectories of participants it is possible to understand how people move and interact under various experimental conditions [Cirio et al. 2013]. In spite of the distinction between virtual and real environments on walking trajectories, [Bailenson et al. 2001] the collected data from the virtual reality experiments can provide useful insights on how the participants' movements are altered in accordance with the experimental conditions.

The current study is an extension of previous studies that examine human-virtual crowd interaction [Ahn et al. 2012; Kyriakou et al. 2017; Pelechano et al. 2008] and human movement behavior in virtual environments [Bruneau et al. 2015; Cirio et al. 2013; Mousas et al. 2019]. The objective is to investigate participants' movement behavior when immersed within a virtual crowd when crossing a crosswalk in a virtual metropolitan city. The study investigated if human movement behavior is altered across experimental conditions as well as whether the characteristics of a virtual crowd, including density, speed, and direction, can change human movement behavior within a virtual environment.

3 MAIN STUDY

This section presents the main study that assessed the effects of virtual crowd density on human movement behavior. It will describe the methodology employed, the implementation details, and the obtained results.

3.1 Participants

The participants were recruited through class announcements and emails. The participant group was comprised of 18 undergraduate and graduate students. Of the group, 3 were female and 15 were male. The students' ages ranged from 19 to 27 years, with a mean of $M = 22.83$ ($SD = 2.47$). All the students had previously experienced virtual reality at least once. All participating students were volunteers and there was no type of compensation involved. Also, none of the participants experienced motion sickness during the experiment. Finally, regarding the sample size ($N = 18$) we would like to note that our decision regarding the small sized sample is based on a number of similar studies that also investigate movement behavior [Jiang et al. 2018; Olivier et al. 2017; Simeone et al. 2017]. It is common in such studies for the sample size to be decreased when participant repetitions for a given task are increased.

3.2 Experimental Conditions

Five experimental conditions were developed to investigate the effects of crowd density on human movement behavior. A within-group study design was used in order to make direct comparisons among the different conditions of the experiment. Thus, all participants had to experience all the experimental conditions described below. There has been significant research on investigating moving crowds and crowd dynamics [Helbing et al. 2007; Still 2014]. However, for this study the moving crowd density model (number of pedestrians per square meter), as introduced by Still [Still 2014],

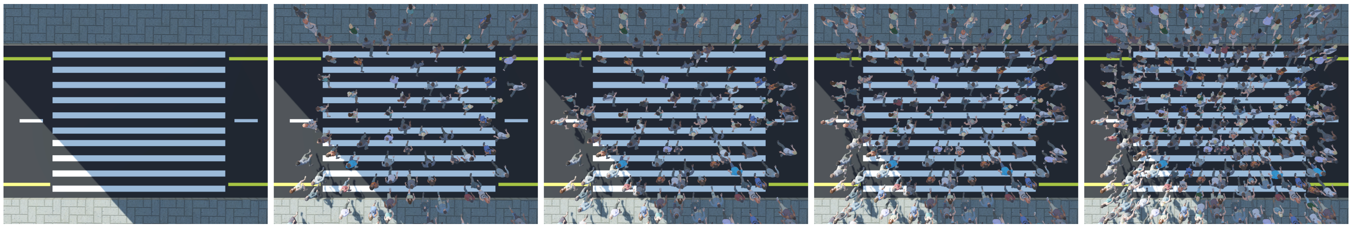


Figure 2: The experimental density conditions used in the study. From left to right: ND, LD, MD, HD, and ED conditions.

was used. To understand the effects of crowd density on human movement behavior, we used an empty scene (without a moving crowd) in order to capture the movement behavior of participants when walking in an unconstrained virtual environment. Then, the condition was examined against four crowd density models. Figure 2 illustrates all density conditions. It should be noted that for the four density conditions a simple walking motion (regular speed) was assigned to each virtual character and each character belonging to the crowd was assigned to move across the opposite sidewalk. The five experimental conditions were:

- **No Density (ND):** The participants in the virtual environment are free from crowds. This was used as the baseline condition.
- **Low Density (LD):** This density condition places one pedestrian within every square meter.
- **Medium Density (MD):** This density condition places one and a half pedestrians within every square meter.
- **High Density (HD):** This density condition places two pedestrians within every square meter.
- **Extreme Density (ED):** This density condition places two and a half pedestrians within every square meter.

3.3 Setup and Virtual Reality Application

Our research team conducted the virtual reality study by using our department's motion capture studio. The dimensions of the studio were eight meters long and eight meters wide, with a ceiling height of four meters. This studio was appropriate for the experimental study as there were no obstacles, other than a computer desk and chairs in the real space.

The HTC Vive Pro head-mounted display device was used for projecting the virtual reality content and the MSI VR One backpack computer (Intel Core i7, NVIDIA GeForce GTX1070, 16GB RAM) was used to run the application. A virtual reality backpack computer was used for two reasons. Firstly, using cables that connect the head-mounted display to the computer was avoided, as the cables might have affected the movement behavior of the participants. Secondly, the use of a wireless transmitter for the virtual reality headset was avoided as such a transmitter produces latency and therefore this latency might have caused nausea and might have altered the locomotive behavior of the participants. Thus, the use of a virtual reality backpack computer ensured that participants would be able to walk properly in the virtual environment and that the virtual reality content would be transmitted at the proper frame rate.

The application used for this study was developed in the Unity3D game engine version 2019.1.4. A virtual metropolitan city was designed in 3ds Studio Max and then imported to the Unity3D game engine to be used for the study. The virtual environment (crosswalk) used for this experiment is illustrated in Figure 3. The participant is placed on the sidewalk at a crosswalk in the virtual metropolitan city. Virtual pedestrians (virtual crowd) were pre-scripted to cross the road and reach the opposing sidewalk. Thirty different virtual characters (15 male and 15 female) were designed in Adobe Fuse and the animations were assigned using the Adobe Mixamo. Each of the characters' crossing scenarios was repeated multiple times. Each character was initialized to surround the participant and was scripted to reach a target position on the opposite sidewalk. After reaching the assigned target position, each character was scripted to move to another location in the virtual environment to help alleviate congestion on the sidewalk. The density conditions were automatically generated by randomly placing the virtual characters in positions that fulfilled the necessary density constraints.

Figure 3: The virtual crosswalk used in this study.

Sunlight was used to light the scene and audio related to the crowd scenario enhanced the sensation of being in a metropolitan city. It should be noted that previous studies indicated that sound related to the context of the virtual reality experience enhances participant presence perception [Hendrix and Barfield 1996; Serafin and Serafin 2004]. We also know from a previously conducted study that the self-avatar alters the movement behavior of participants [Mousas et al. 2019]. Therefore, participants were not represented with a self-avatar for two reasons. First, the objective was to capture the general movement behavior of participants that was not influenced by a self-avatar that might have not matched the appearance of each participant. Second, we wanted to understand whether participants behave as members of the virtual crowd even when there is no self-avatar to bodily place them within the virtual crowd. Concluding, it should be noted that the distance between the two sidewalks was seven meters, which means that participants were asked to walk this distance.

3.4 Objective Measurements

The position tracking capability of the head-mounted display (HTC Vive Pro) was used to capture the movement of participants, and more specifically to capture the spatiotemporal properties of the root trajectory. Several different measurements [Cirio et al. 2013; Fink et al. 2007; Hollman et al. 2006; Souman et al. 2011; Whitton et al. 2005] can be extracted from the capture motion, however only a small number are related to the task and the objectives of this experiment. The captured trajectories were filtered in 100 equidistant points and therefore the measurements are based on the filtered points. The measurements include the following:

- **Time:** The time that participants needed to cross the road (reach the opposite sidewalk). The time was measured in seconds.
- **Speed:** The average speed of the participants' walking motion from the start to the goal position. The speed was measured in meters/second.
- **Deviation:** The average deviation (absolute value) between the global trajectory of the virtual crowd and the trajectory of the participant. The average deviation was measured in meters.

3.5 Procedure

The experiment was conducted at the motion capture studio of our department. Once the participants arrived the researcher provided information to them about the project, and they were asked to sign the provided consent form in accordance with the Institutional Review Board of Purdue University. Then, the participants were asked to complete a demographic questionnaire. In the next step, the researcher helped the participants with the backpack computer and the head-mounted display. Once everything was set, the participants were asked to take a short walk within a virtual replica of the motion capture studio to ensure they were comfortable enough when wearing all the devices.

After becoming comfortable and familiar with the virtual reality equipment, the researcher asked the participants to remove the headset and move toward a marked location in the real environment and face the opposite direction. Once participants landed on the marked position and before the experiment started the researcher informed them that once the application started, they would be placed into a virtual reality metropolitan city and the task they would have to perform was to cross the road. The participants were informed that first a traffic light would turn green and then they would hear a "beep" sound that would signal them when they should start walking. It was decided to delay the time in which the participants should start walking to ensure that a proper number of characters surrounded the participants. This helped place the participant within the virtual crowd. Participants were told they could have breaks between repetitions of the conditions if needed and that they had full permission to leave at any time.

Additionally, all participants were informed that they would cross the virtual crosswalk to reach the opposing sidewalk 15 times (5 conditions $\times$ 3 repetitions). They were also told they would be informed when the experiment had ended. Once the participant finished each repetition, they were asked to remove the head-mounted display and move back to the marked location at the other side of the room. The balance for first-order carry-over (residual) effects between the conditions was ensured using Latin squares [Keedwell and Dénes 2015]. The total duration of the experiment lasted on average 30 minutes.

3.6 Results

This section presents the results obtained from the main study. All the analyses were performed using IBM SPSS v. 23.0 [Nie et al. 1975] software. A one-way repeated measure analysis of variance (ANOVA) was used to analyze the obtained data using the five experimental conditions as independent variables and the motion measurements as dependent variables. The normality assumption of the measurements was evaluated graphically using Q-Q plots of the residuals [Ghasemi and Zahediasl 2012]. The Q-Q plots indicated that the obtained data fulfilled the normality assumption. The individual differences were assessed using a post hoc Bonferroni test if the ANOVA was significant. A $p < .05$ was deemed as statistically significant.

The effect of crowd density on the participants' movement behavior was compared using three objective measurements (time, speed, and deviation) across the five experimental conditions (ND, LD, MD, HD, and ED). The results for the objective measurements are presented in Figure 4 and descriptive statistics for the objective measurements are provided in Table 1. Regarding the **deviation** measurement, no significant differences were found across the five experimental conditions [$\Lambda = .759$, $F(4, 14) = 1.112$, $p = .389$, $n_p^2 = .241$].

Regarding the **time** that participants needed to cross the virtual crosswalk, significant effects at the $p < .001$ level were found [$\Lambda = .214$, $F(4, 14) = 12.880$, $p < .001$, $n_p^2 = .786$] across the five experimental conditions. Pairwise comparisons indicated that the mean time for the ND condition was significantly lower than that for the LD condition at the $p < .05$ level, MD condition at the $p < .005$ level, HD condition at the $p < .005$ level, and ED condition at the $p < .001$ level. Additionally, the mean time at the LD condition was significantly lower than that for the HD condition at the $p < .01$ level and ED condition at the $p < .001$ level. The mean time at the MD condition was significantly lower than that for the HD condition at the $p < .05$ level and ED condition at the $p < .001$ level. The mean time at the HD condition was significantly lower than that for the ED condition at the $p < .05$ level. Finally, no differences were found between the LD and MD conditions.

Regarding the walking **speed** of participants, significant differences were found across the five experimental conditions at the $p < .001$ level [$\Lambda = .042$, $F(4, 14) = 79.273$, $p < .001$, $n_p^2 = .958$]. Pairwise comparisons indicated that the mean speed during the ED and HD conditions were significantly lower than that for the ND, LD, MD, and HD at the $p < .001$ level. The mean speed during the MD condition was significantly lower than for the ND condition at the $p < .005$ level and the mean speed during the LD condition was significantly lower than for the ND condition at the $p < .05$ level. Finally, no differences were found between HD and ED, and between LD and MD conditions.

Table 1: Descriptive statistics of each measurement across the five experimental conditions and patterns of differences.

Condition	*M*	*SD*	*Min*	*Max*	Pattern of Differences
			Time		
ND	4.43	.62	3.43	5.30	ND<(LD=MD)<HD<ED
LD	4.79	.82	3.23	6.40	
MD	4.86	.69	3.65	6.05	
HD	5.25	1.03	3.45	7.28	
ED	5.87	1.24	3.56	7.82	
			Speed		
ND	1.78	.29	1.39	2.30	(HD=ED)<(LD=MD)<ND
LD	1.64	.22	1.30	2.05	
MD	1.58	.20	1.07	1.85	
HD	1.28	.21	.61	1.61	
ED	1.21	16	.84	1.53	
			Deviation		
ND	1.26	.19	.96	.34	ND=LD=MD=HD=ED
LD	1.33	.16	1.08	.48	
MD	1.31	.29	.83	.49	
HD	1.54	.30	.91	.68	
ED	1.73	.30	1.11	1.48	

4 FOLLOW-UP STUDY

The main study indicated that the density of a virtual crowd can indeed be a factor in altering human movement behavior in an immersive crowd interaction scenario. Based on the finding that the extreme crowd density affected the movement behavior of participants to a higher degree in terms of both speed and time measurements, it was decided to conduct a follow-up study to investigate whether variations in crowd speed and direction can alter the movement behavior of participants, while being immersed in an extreme crowd density scenario. Thus, the following subsections describe the methodology, conditions, and results obtained from this follow-up study.

4.1 Participants

In this follow-up study, the participant group was comprised of 20 undergraduate and graduate students. Twelve of them had participated in the main study. Of the sample, 4 were female and 16 were male. The students' ages ranged from 19 to 27 years, with a mean of $M = 23.15$ ($SD = 2.56$). All the students had previously experienced virtual reality at least once. All participating students were volunteers and there was no type of compensation involved. Also, none of the participants experienced motion sickness during the follow-up study.

Figure 4: The time, speed, and deviation measurements for all examined conditions in this study.

4.2 Experimental Conditions and Measurements

Five experimental conditions regarding the speed of the virtual crowd and six experimental conditions regarding the direction of the crowd were developed. As previously mentioned, the extreme density was assigned to the virtual crowd. The speed of the crowd was based on intervals between a walking (speed = 1) and a running (speed = 2) motion. For the implementation of the in-between speed conditions we used the gait-cycles motion blending method of the Mecanim animation system of Unity3D. For the speed conditions the same speed was assigned to all characters (not variations in speed). It is not clear if this decision affected the realism of the crowd and it is discussed later. The speed conditions were as follows:

- **Sp1:** The baseline walking motion (speed = 1).
- **Sp2:** Fast walking motion (speed = 1.25).
- **Sp3:** In-between walking and running motion (speed = 1.5).

- **Sp4:** Slow running motion (speed = 1.75).
- **Sp5:** Full running motion (speed = 2).

For the direction conditions a simple method that changes the angle on the path that the crowd follows while crossing the road was implemented. For this part of the experiment, six conditions were implemented ranging from 0 degrees to 10 degrees. We chose to randomize the direction (positive or negative value of degrees) of each condition for each participant. The crowd (postive) direction conditions are shown in Figure 5. The direction conditions were as follows:

- **Dir1:** The angle of the path is 0 degrees.
- **Dir2:** The angle of the path is ±2 degrees.
- **Dir3:** The angle of the path is ±4 degrees.
- **Dir4:** The angle of the path is ±6 degrees.
- **Dir5:** The angle of the path is ±8 degrees.
- **Dir6:** The angle of the path is ±10 degrees.

It should be noted that for the five speed conditions only the speed of the participants was captured and used for analysis. Similarly, for the six direction conditions only the deviation measurement (absolute value) was used for analysis.

4.3 Procedure

The procedure followed for this follow-up study is similar to the one followed during the main study. The only difference is that participants were exposed to eleven conditions (five speed and six directional conditions) and were asked to repeat the walking motion three times, which means participants crossed the crosswalk 33 times (11 conditions × 3 repetitions). Latin squares were used to counterbalance the conditions. The total duration of the follow-up study lasted no more than 30 minutes.

4.4 Results

A one-way repeated measures ANOVA was used to analyze the speed data. The five experimental conditions of speed were used as independent variables and the speed of participants as dependent variables. The results for the speed measurements are presented in Figure 6 and descriptive statistics are given in Table 2. Regarding the **speed** that the participants used to cross the virtual crosswalk, significant effects at the $p < .05$ level were found [$\Lambda = .513$, $F(4, 16) = 3.796$, $p < .05$, $n_p^2 = .487$] across the five experimental conditions. Pairwise comparisons indicated that the mean speed during the Sp1 condition was significantly lower than that for the Sp3, Sp4, and Sp5 conditions at the $p < .05$ level.

Table 2: Descriptive statistics of speed measurements across the five speed experimental conditions and pattern of differences.

Condition	*M*	*SD*	*Min*	*Max*	Pattern of Differences
			Speed		
Sp1	1.56	.20	1.11	1.88	Sp1<(Sp3=Sp4=Sp5)
Sp2	1.60	.19	1.22	1.87	Sp2=Sp3=Sp4=Sp5
Sp3	1.64	.14	1.37	1.88	Sp1=Sp2
Sp4	1,65	.17	1.19	1.89	
Sp5	1.67	.13	1.38	1.84	

Table 3: Descriptive statistics of deviation measurements across the six direction experimental conditions and pattern of differences.

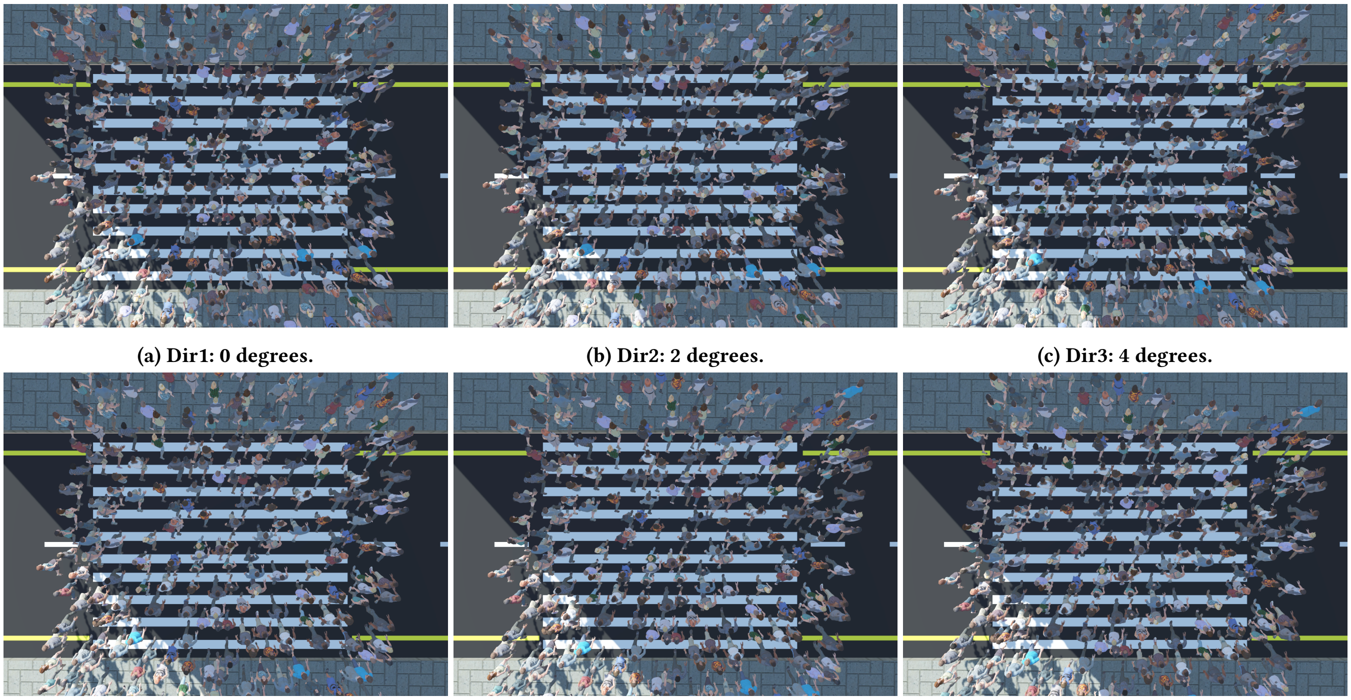
Condition	*M*	*SD*	*Min*	*Max*	Pattern of Differences
			Deviation		
Dir1	.18	.15	.00	.53	Dir1=Dir2=Dir3=Dir4
Dir2	.22	.17	.01	.68	=Dir5=Dir6
Dir3	.21	.17	.04	.71	
Dir4	.26	.19	.01	.59	
Dir5	.21	.14	.03	.52	
Dir6	.28	.27	.01	.82	

A one-way repeated measures ANOVA was used to analyze the deviation data. The six experimental conditions of direction were used as independent variables and the deviation measurement as dependent variables. The results for the **deviation** measurements are presented in Figure 7 and descriptive statistics are provided in Table 3. Regarding the deviation of participants, we were not able to find differences across the six experimental deviation conditions [$\Lambda = .513$, $F(5, 15) = 1.214$, $p = .35$, $n_p^2 = .288$].

The speed of participants and the speed of the virtual crowd, as well as the deviation of participants and the assigned direction of the crowd were screened for possible correlations using the Pearson product-moment correlation coefficient. Regarding speed, the correlation was computed between the participant speed for all five conditions and the speed value assigned to the characters in the virtual crowd. Similarly, regarding deviation, the correlation was computed between the participant deviation for all six conditions and the directional angle value assigned to the virtual crowd. The results regarding **speed** indicated a weak uphill linear correlation [$r = .207$, $n = 100$, $p = .039$]. There was no significant correlation found between the directional angle of the virtual crowd and the deviation of the participants.

5 DISCUSSION

A study was conducted to understand the effects of crowd density on human movement behavior. Five experimental density conditions were developed and the participants immersed within a virtual crowd scenario were asked to navigate themselves along the crosswalk of a virtual metropolitan city. The results obtained from the main study (RQ1) are quite interesting. We found that both the speed and the time variables were most altered when participants were part of an extreme crowd density condition. The results of this main study also indicate the other density conditions (low, mid, and high) were in-between the no density and extreme density conditions. However, the extreme density condition affected the most the movement behavior of participants. Other than the speed and time variable, we were not able to detect differences for the deviation variable. This result was expected as during this part of the study the virtual crowd was moving in the same forward direction across all conditions. Based on the results regarding the effect of crowd density on human movement behavior, it can be suggested that when the density of the crowd increases the participants might become more aware of possible collisions with the



(a) Dir1: 0 degrees.
(b) Dir2: 2 degrees.
(c) Dir3: 4 degrees.
(d) Dir4: 6 degrees.
(e) Dir5: 8 degrees.
(f) Dir6: 10 degrees.

Figure 5: The six directional conditions used for this part of the study. All conditions shown in this figure are in the same (positive) direction for comparison purposes.

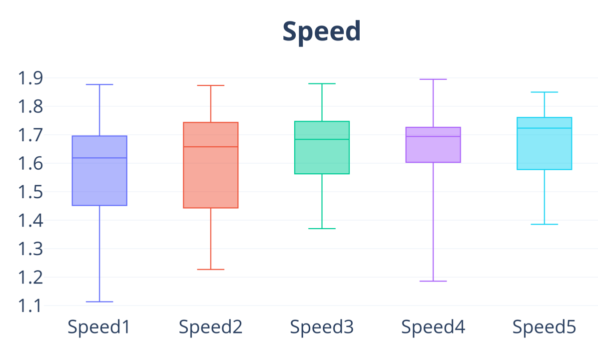


Figure 6: The speed measurements for the five speed conditions of this experiment.

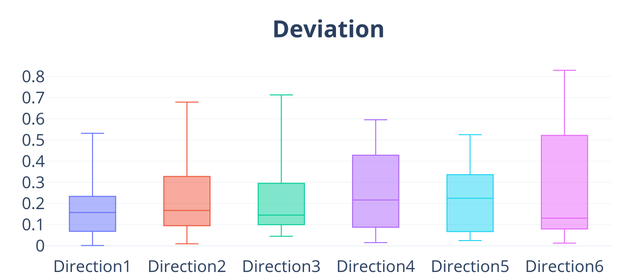


Figure 7: The deviation measurements for the six direction conditions of this experiment.

virtual pedestrians and therefore their walking speed may also decrease. Another interpretation is that due to the high density crowd, participants might not be aware of their spatial position within the virtual environment because of the constrained field of view. Therefore, they might decide to decrease their speed so that they move more carefully in the desired direction in order to safely reach the opposite sidewalk.

To further understand the effects that a virtual crowd can have on the movement behavior of participants, a follow-up study was also conducted. In this follow-up study, by using the obtained information from the main study which showed us that extreme crowd density does affect the most the movement behavior of participants, we aim at understanding whether such extreme density can also alter the speed of participants while examining five speed conditions, and the direction of participants while examining six directional conditions. Regarding the speed variable (RQ2) across the five experimental conditions, it was found that when the speed of the crowd increased the speed of the participants increased as well. However, significant differences were found between the baseline walking speed and the last three speed conditions.

By examining the correlation (RQ4) between the speed assigned to virtual characters and the speed of participants we were able to find a weak correlation. The results from the ANOVA and the speed correlation taken together can allow us to infer that indeed the speed of participants is affected by the speed of a virtual crowd. There is some evidence that a virtual crowd can manipulate the speed of participants when they are placed within a virtual crowd, or that the participants try to regulate their speed based on the speed of nearby pedestrians. Based on the obtained results regarding the speed variations the following conclusions can be made. Even if the speed of participants is slightly affected by the speed of the virtual crowd, the participants might be aware that they are moving within a real environment but they might also feel that the real environment does not match the virtual one. Therefore, the participants might be concerned about accidents (i.e., hitting a wall) and therefore might decide not to move that fast. Note that previous research [Mohler et al. 2007] found that a user's fear of colliding with real-world obstacles when immersed within a virtual environment often reduces the natural locomotion behavior and gait, and consequently alters the movement behavior in virtual environments. Finally, we would like to note that one of the participants mentioned that the backpack computer made him decide to move more slowly because he was concerned about damaging the device. This is another logical explanation that might have affected the speed of participants.

On the other hand, even though we were able to find differences in the speed variable, we were not able to find significant results for the deviation variable across the six direction conditions (RQ3) that were explored during the follow-up study. Unfortunately, this was an unexpected result. Based on the lack of significant results, we would like to provide the following interpretation. When people are walking and have been instructed to perform a task such as crossing a road, they might determine in advance the path they should follow. Thus, it seems to be difficult or improbable for nearby pedestrians to affect the chosen path of participants. In other words, our participants tended to choose a global path in advance instead of a local path that adapts while moving toward the opposite sidewalk. In addition, because the participants were instructed to cross a road, it is possible they thought about the shortest path. Finally, another possible inference is that since the participants were not represented by a self-avatar, there is a chance they were aware they could pass through other characters and move in any direction without causing problems for the nearby virtual pedestrians.

Furthermore, since significant effects were not found across the six deviation conditions, we would like to mention an observation that can be made by looking at the boxplots (see Figure 7) of the results. As the directional angle of the crowd increase, so does the range of whiskers and the inter-quartile of the boxplots. Although we cannot base our discussion on the range of the whiskers and the inter-quartile, we would like to provide the following interpretation. The range increase of the whiskers and the inter-quartile indicates that the direction of the crowd has some effect on the direction of the participants, but not a significant one. The reason may be that participants might have wanted to avoid possible collisions with nearby pedestrians or participants might have felt their intimate space was being violated and therefore this might have altered their direction. A previous study [Wilcox et al. 2006] also indicated that violation of intimate space affected the behavior of participants. In any case, since no significant results were found for the deviation variable, we cannot conclude whether or not the direction of a virtual crowd affected the movement behavior of the participants. However, we note that this is an area that requires further investigation in order to arrive at accurate conclusions.

6 CONCLUSIONS, LIMITATION, AND FUTURE WORK

Based on the analysis of the captured objective measurements, we found that the movement behavior of participants was altered when immersed in a virtual crowd. There were distinct differences in the speed and time measurements in the main study concerning the density of the crowd and in the follow-up study concerning the speed of the crowd. The results show that when increasing the density of the crowd the speed of participants decreases. However, when increasing the speed of the crowd, the speed of the participants increases. These results indicate that the speed of participants can be slightly manipulated either by the density of the crowd or by the speed of it, as the participants tried to regulate their speed based on the characteristics of the crowd. For the five speed conditions, since the speed remained at low levels, the participants constrained the speed of their walking motion themselves. The fact they knew they were in a virtual environment different from a real environment may have made them more cautious.

At this point, there are three main limitations we would like to mention. First, we believe that a questionnaire concerning presence, embodiment, and trust would be useful for such a study. Such questions would have helped us understand to what extent participants felt they were part of the virtual environment as well as being part of the virtual crowd and might also provide insight on how they decided to regulate their movement behavior in the way they did. The second limitation is related to the speed of the virtual characters assigned in the crowd. Regarding the speed conditions, we assigned the same speed to all characters and did not vary the speed, while also maintaining the crowd speed (as a system) at the desired levels. We are unsure if this decision could have affected the realism of the crowd and the way that participants regulated their speed. This might be a limitation of the current study that needs further examination. Asking questions regarding crowd realism might provide useful insights. Finally, a different study design (i.e., studying the interaction between density, speed, and direction) might also be useful to gain more knowledge regarding human-virtual crowd interaction. However, considering this was an exploratory study, the quite interesting results we have obtained offer a promising opportunity for further research.

Future research could investigate the ways participants move within virtual crowds with various characteristics (appearance, age, emotions, etc.). In addition, human-virtual crowd interaction could be studied when participants are instructed to avoid virtual characters that move slowly, or when interacting with crowds that move in the opposite direction or along curved paths. Because the current study only examined moving virtual characters, it is vital to further examine the interactions among various behaviors assigned to a crowd population (walking alone or in groups, stopping at storefronts, talking, waiting, etc.) and understand the way the participants interact with such behaviors and understand the virtual crowd in general.

The current study is a step forward towards understanding the movement behavior of participants during a human-virtual crowd interaction scenario in which density, speed, and direction conditions are examined. We can safely assume that a great number of interesting insights about the participants' movements can be obtained when performing such studies. Finally, we believe that the findings of this research along with future studies can prove to be an invaluable resource when developing various virtual reality applications and games in which users are placed within moving virtual crowds.

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