Effects of Speed of a Collocated Virtual Walker and Proximity Toward a Static Virtual Character on Avoidance Movement Behavior

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ABSTRACT

We explored the avoidance movement behaviors of study participants immersed in a virtual reality environment. We placed a static virtual character at the midpoint between the start and target spot for the avoidance task, and a virtual walker character in front of the starting spot and scripted it to reach the target spot. Participants were placed behind the virtual walker in order to measure its influence on participants' behavior. We developed nine experimental conditions assigned to the virtual walker character by following a 3 (speed: slow vs. normal vs. fast walking speed) × 3 (proximity: close vs. middle vs. far proximity to the static virtual character) study design. For this within-group study, we collected data from 22 study participants to explore how speed and proximity walking patterns assigned to a virtual walker character could impact participants' avoidance movement behaviors and decisions. Our data revealed that 1) the speed factor impacted the participants' avoidance movement behavior; 2) the proximity factor did not significantly impact the participants' avoidance movement behavior; 3) the virtual walker character did not significantly impact participants' avoidance decisions regarding the static virtual character; 4) in all examined conditions, the side-by-side distances between the participants and the static virtual character were inside the social space according to the proxemics model; and 5) in conditions in which a slow virtual walker character was present or in the condition of normal speed and far proximity, we observed an increased number of participants pass the virtual walker character.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality

1 INTRODUCTION

The popularity and availability of virtual reality (VR)-enabled head-mounted displays (HMDs) has increased in recent years. Accordingly, immersive virtual environments and virtual social spaces are becoming increasingly widespread. Due to the increased availability of VR applications, there has been significant interest in understanding how varying VR factors can affect user perceptions, behaviors, and actions in immersive virtual environments. We know from previous studies that VR content can affect how users perceive themselves and other virtual entities and how users interact in virtual environments. For example, prior studies have shown that virtual reality content could impact presence [12, 56], embodiment and self-presence [25, 56], emotional reactivity [19, 35], and more.

Although several studies have analyzed human locomotive behavior in virtual environments [8, 18, 42, 53], only a few have examined how humans perform collision avoidance tasks with virtual characters (either static or walking) [4, 22, 31, 38, 39, 49, 50]. To the best of our knowledge, no study has been conducted so far in which study participants avoided a static virtual character while following another collocated virtual walker character performing the same avoidance task. Thus, even if such avoidance tasks are typical tasks that humans perform in their everyday lives, no definitive findings are available regarding whether or how a collocated virtual walker character can impact humans' avoidance movement behaviors. We think a better understanding of how a collocated virtual walker character may or may not impact human movement behavior could be beneficial for VR developers. For example, our findings could be used to help VR developers create new simulation algorithms that correctly handle such situations. This will also allow developers to create more precise and effective aspects of VR experiences, such as locomotion in immersive environments with collocated virtual walkers (e.g., virtual malls and museums). Thus, not only does VR benefits from the improvements of human-virtual human simulations to populate immersive virtual environments, but it plays a great role in our study. Therefore, we can understand under which conditions the collocated virtual walker may impact people.

To further understand how humans interact in virtual environments, specifically with virtual characters, we conducted a study to explore how a collocated virtual walker character could impact participants' movement behavior. Specifically for our study, we instructed participants to walk from a start to a target spot in a virtual environment and avoid the static virtual character we placed at the midpoint. In addition, we placed a virtual walker character in front of the participants, which we scripted to reach the target spot and avoid the static virtual character located at the midpoint in the virtual environment. Figure 1 shows an example of a virtual walker character moving toward its target spot from both a top view and the participant's point of view.

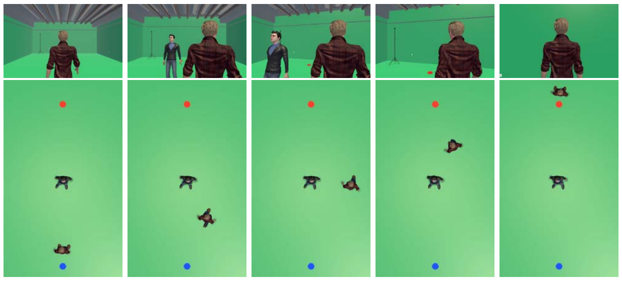

Figure 1: Example stills from an avoidance movement maneuver performed by a virtual walker character seen from above (bottom) and a participant's first-person perspective (top) performing the same activity.

We followed a 3 (speed: slow vs. normal vs. fast walking speed) × 3 (proximity: close vs. middle vs. far proximity to the static virtual character) study design to create nine experimental conditions assigned to the collocated virtual walker. In our study, we instructed the participants to reach the target point by avoiding that virtual character (we did not mention that they had to follow the virtual walker character or how to perform the avoidance task). During that

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time, we captured the participants' trajectories, which we later used to extract several measurements regarding their avoidance movement behaviors and decisions. Based on the collected data, we aimed to answer the following research questions:

- **RQ1:** How do proximity and speed factors assigned to a collocated virtual walker character impact the study participants' avoidance movement behaviors?
- **RQ2:** How do proximity and speed factors assigned to a collocated virtual walker character impact the study participants' avoidance decisions regarding a static virtual character?
- **RQ3:** How do proximity and speed factors impact the study participants' interactions with the collocated virtual walker character during the avoidance task?

2 RELATED WORK

In previous years, researchers conducted collision avoidance studies to understand how study participants perform such tasks in either real or virtual environments. Fink et al. [16] explored collision avoidance of stationary obstacles during a goal-reaching task in both real and virtual environments. Their study showed significant results regarding how humans performed the avoidance task, such as participants having more significant deviations, larger obstacle clearance, and slower walking speeds in the virtual environment than in the real one. Argelaguet et al. [53] showed that when people avoided a static virtual object, they decreased their walking speed and increased their clearance distance from that virtual object compared to when avoiding a real object. They also showed that participants kept a greater distance from an anthropomorphic obstacle than they did from an inanimate obstacle and that the personal space was shown to have an elliptical shape. Specifically, based on the elliptic shape of personal space theory [18], in the anthropomorphic condition, the clearance distance was more significant when the orientation of the virtual human was from a profile position as opposed to a front position.

Bailenson et al. [1] became interested in the interpersonal distance that study participants maintained from a virtual character. They demonstrated that this distance was greater when individuals approached the character from the front instead of the back. They also reported that participants in the study maintained a larger personal space with a virtual figure who engaged in eye contact. Later, Gérin-Lajoie et al. [17] found that participants slightly increased the global shape of their personal space in virtual environments compared to real ones.

Olivier et al. [43] showed that study participants could predict a potential collision with walking virtual humans and therefore choose an optimal collision avoidance strategy; however, the researchers conducted this study in a desktop setup. Mousas et al. [38] explored participants' movement behaviors in a virtual environment when they attempted to avoid a virtual character with and without gazing functionality assigned to it and when the participants were represented with and without a self-avatar. Their results showed that when they represented the study participants with a virtual body and made the virtual character gaze at them, they followed longer paths, took more time to reach the target spot, and deviated more from the static virtual characters. In a follow-up study, Mousas et al. [39] explored how the appearance of virtual characters impacted study participants' avoidance movement behaviors. They found that the participants followed longer paths when avoiding a zombie virtual character than a mannequin, human, or cartoon virtual character. Nelson et al. [40] went a step further and explored the potential impact of various render styles of a static virtual character on study participants' avoidance movement behavior. They found that eerie rendering styles impacted several of their collected measurements, such as trajectory length, duration, speed, minimum distance, and side-by-side distance. They also found that the majority of the participants decided to avoid the virtual characters by keeping them to their left side, confirming Bailenson et al.'s [1] results, which found that participants kept a minimum distance behind the virtual characters. Finally, Miller et al. [33] analyzed the proxemics and gaze of participants in social virtual reality sessions. They found that the interpersonal distance increased with the size of the virtual room, and both mutual gaze and interpersonal distance increased over time.

Regarding collocated experiences, Scavarelli and Teather [54] introduced collision avoidance techniques for physically collocated VR users. They compared avatars, bounding boxes, and camera overlays shown in the position of a second study participant. However, the second study participant was simulated and static, similar to the virtual objects that Fink et al. [16] used. Scavarelli and Teather [54] found that each technique had different advantages and disadvantages. The camera overlay resulted in more collisions, but the participants preferred it. The bounding box had the fewest collisions, but the avatar offered faster movement. Podkosova and Kaufmann [48] conducted a study in which collocated participants simultaneously walked in the same real and virtual environments in an experiment on imminent collision prevention. While traveling on paths that could cause collisions, the participants had to avoid avatars, which were presented in their respective positions, until they were two meters apart. In this study, Podkosova and Kaufmann [48] did not examine movement behavior. They mainly focused on the participants' subjective preferences for one type of avatar. In another study,

Kyriakou et al. [29] explored the impact of collisions between the participant's self-avatar and the virtual crowd. They also explored how such collisions could impact the participant's perceived realism and ease of navigation in the virtual environment. They observed that keeping the participant and virtual crowd paths separate enhanced the realism and lifelikeness of the virtual environments, characters, and system. Bönsch et al. [4] explored collision avoidance between study participants and a virtual character. Their results indicated that the participants favored collaborative collision avoidance. Specifically, they anticipated that the virtual character would move aside to open a path to walk through while still being open to personalizing their walks. Sohre et al. [55] explored the effect of participants' collision avoidance behaviors with virtual characters in an immersive setup. In their first condition, the two virtual characters avoided colliding with each other but not with the participant. In their second condition, the two virtual characters could predict a potential collision between themselves and the participant and perform the necessary maneuver to avoid the potential collision. According to their findings, the participants reported a higher sense of presence and perceived realism and lower discomfort and intimidation when the virtual characters went around them instead of colliding with them. Lastly, Patotskaya et al. [45] explored motion perception from the perspective of distinct movement patterns as observed in people with neurotic versus emotionally stable personality traits. To do so, they designed a VR experiment and studied the avoidance behaviors of participants when encountering both neurotic and emotionally stable types of virtual characters in a constrained VR environment. They found that their participants' behaviors were affected by the character's motion.

Although several researchers have previously explored the avoidance behavior of study participants during a collocative experience, especially with virtual crowds [10,32,51,57] and collocated walkers [46], the impact of a collocated virtual walker character on study participants' avoidance movement behaviors and decisions has not yet been examined. Thus, in this study, we tried to provide additional insights in this direction. Our results could help us further understand human avoidance movement behavior in VR environments in the presence of a collocated virtual walker character.

3 MATERIALS AND METHODS

3.1 Participants

We conducted an *a priori* power analysis to determine the appropriate sample size for our study [9]. For a 95% power, a small effect size of $d = .30$ [13], one group with nine repeated measures, a nonsphericity correction of $\varepsilon = .60$, and an $\alpha = .05$, the analysis recommended a minimum of 22 participants. We recruited the recommended sample size from our universality through e-mails and class announcements. The participants were 19-35 years old ($M = 26.00$, $SD = 4.33$). Of the sample, 11 were male, 10 were female, and one identified as nonbinary/other gender. Five participants reported no previous VR experience, four had no more than two experiences, six had two to five experiences, and seven had more than five experiences. Furthermore, 12 participants reported that they had previously experienced room-scale VR, while 10 reported no previous room-scale VR experience. No participants reported movement disorders or motor implications that could have affected their locomotive movements in a virtual environment. For this study, all participants volunteered without receiving any compensation for their participation.

3.2 Experimental Conditions

For this within-group study, we followed a 3 (speed: slow vs. normal vs. fast walking speed) × 3 (proximity: close vs. middle vs. far proximity to the static virtual character) study design. We thus developed nine experimental conditions (slow speed & close proximity, slow speed & middle proximity, slow speed & far proximity, normal speed & close proximity, normal speed & middle proximity, normal speed & far proximity, fast speed & close proximity, fast speed & middle proximity, and fast speed & far proximity). Each participant experienced all nine conditions mentioned in this section in balanced order according to Latin squares [58].

We assigned a different speed to the virtual walker character for each level of the speed factor. We set the normal speed to equal the normal walking speed of humans. Researchers estimated this speed to be 1.20 m/s, according to the U.S. Manual on Uniform Traffic Control Devices [14]. Then, we set the low speed to be a 20% decrease from the normal walking speed (i.e., .96 m/s) and the fast speed to be a 20% increase from the normal walking speed (i.e., 1.44 m/s).

For the proximity factor, we defined three trajectories for the virtual walker character to follow. Specifically, we based the avoidance trajectories on the proxemics social interaction model [20] and set it as the side-by-side distance between the static virtual character and the virtual walker character. More specifically, we defined the close proximity to equal the upper boundary of the far phase of the intimate distance (i.e., .46 m), the middle proximity to equal the upper boundary of the close phase of the personal distance (i.e., .76 m), and the far proximity to equal the upper boundary of the far phase of the personal distance (i.e., 1.22 m).

The virtual walker character followed set paths designed as Bézier curves (see Figure 2). We scripted the virtual walker character for all conditions to avoid the static virtual character by keeping it on the walker's left side. We based our decision on prior works that reported that most study participants tended to avoid virtual characters by keeping them on their left side [37, 40] regardless of handedness, cultural background, or other demographics that could be factors influencing participants' degree of social interactions and decision making [15, 35, 40]. We also considered this a key aspect that helped us standardize the experimental conditions across all participants.

3.3 Measurements

We captured the trajectories of the participants when performing the avoidance task and then extracted several measurements related to their avoidance behaviors and decisions. We did so to explore how the participants planned and executed their avoidance movements around the static virtual character and whether the virtual walker character impacted their avoidance movement behaviors and decisions. Specifically, we extracted the following measurements:

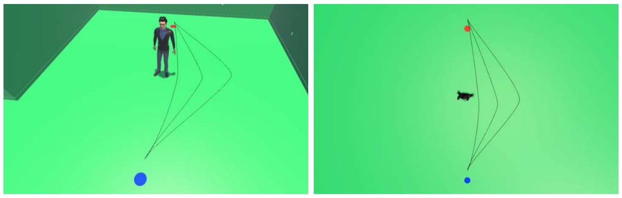


Figure 2: The avoidance movement trajectories that the virtual walker character was scripted to follow to avoid the static virtual character. This figure shows the static virtual character that we placed at the midpoint between the start (blue) and target (red) spots and that the participants and the virtual character walker were instructed and scripted, respectively, to avoid.

- **Duration:** The time a participant spent traveling from the start to the target spot in the virtual environment (measured in seconds).
- **Trajectory length:** The length of the captured trajectory between the start and target spots (measured in meters).
- **Speed:** The average speed of the participant's movement when walking in a virtual environment (measured in meters/second).
- **Minimum distance:** The minimum distance (measured in meters; from center-to-center) between the position of a participant and the static virtual character (i.e., how closely the participant approached the static virtual character during the avoidance maneuver).
- **Side-by-side distance:** The distance between the position of a participant and the static virtual character when they were side-by-side (measured in meters).
- **Side of minimum distance (in front or behind):** We extracted information to understand whether the minimum distance between the position of a participant and the static virtual character was when the participant was in front of or behind the virtual character (measured in meters).
- **Avoidance side (right or left):** We counted how many times the participant avoided the virtual character by keeping them to their right or left side.
- **Distance to the virtual walker character:** The average distance (measured in meters) between the position of a participant and the virtual walker character during the avoidance task.
- **Virtual walker character pass:** We counted how many times the participant decided to pass the virtual walker character.

To extract these measurements, we utilized the raw captured data. We used the first five measurements (**duration**, **trajectory length**, **speed**, **minimum distance**, and **side-by-side distance**) to explore how the participants executed their avoidance movements. We used the next two measurements (**side of minimum distance** and **avoidance side**) to understand how they planned and decided to perform the avoidance task. Finally, we used the last two measurements (**distance to the virtual walker character** and **virtual walker character pass**) to understand how the participants interacted with the virtual walker character.

In this study, the participants performed two trials per experimental condition (one after the other), similar to the studies conducted by Berton et al. [3], Mousas et al. [39], and Nelson et al. [40]. Therefore, we captured each of the previously mentioned measurements twice. We should note that this is a common practice in human movement analysis research. Moreover, we computed and used the average of the two trials in our statistical analysis for all collected measures except the **side of minimum distance**, **avoidance side**, and **virtual walker character pass** measurements, which we treated per trial.

3.4 Study Site, Equipment, and VR Application

We conducted our study in the motion capture studio of our department. The room's dimensions were 8×8×4 m (length×width×height). We considered previously published research indicating that appearance mismatching between a real and virtual environment impacted the study participants' movement behaviors and arousal levels [36]. For this reason, we designed a virtual environment replicating the appearance of our motion capture lab space (see Figure 3 and Figure 5).

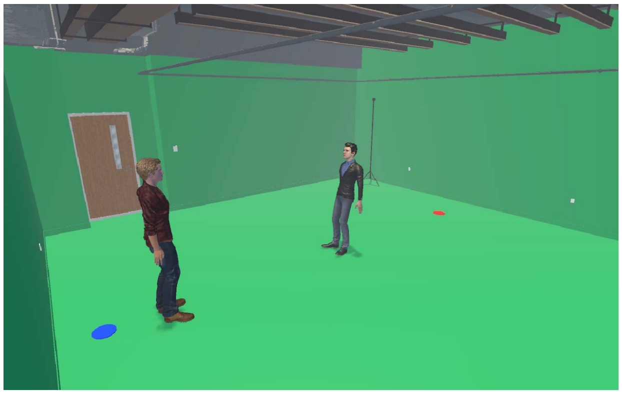


Figure 3: A perspective view of the main scene of our VR application. We instructed the participants to avoid the virtual character standing between the start and target spots. We placed the virtual walker character in front of the start spot (blue mark).

We used the Unity game engine (version 2019.1.4) to develop our VR application. In the main scene of our application (see Figure 2 and Figure 3), we placed blue (start spot) and red (target spot) marks on the floor. The distance between the two spots was 7 m, which is enough for humans to perform a smooth avoidance maneuver [39, 40]. We placed the static virtual character at the midpoint (3.5 m from the start and target spots). We aligned the static virtual character based on the start and target spot and faced the participant automatically once we loaded a new trial. Our application recorded the participant's trajectory once the participant started walking toward the target spot. The research team was responsible for monitoring this process. As we also see in Figure 3, we placed the virtual walker character in front of the blue spot (.50 m). As discussed in the previous section, we scripted the virtual walker character to avoid the static virtual character by following different speeds and proximity levels. We also scripted the virtual walker character to reach a target spot further away from the red spot (participant's target). We should note that both the start and target spots assigned to the virtual walker character were invisible.

We used two white male virtual characters to standardize the conditions across participants (we exposed all participants to the same stimuli). We illustrate the two characters in Figure 4. We designed the virtual walker character using Character Creator 3 and downloaded the static character from Mixamo. We assigned an idle motion to the static virtual character and walking motion cycles to the virtual walker character. The two models shared the same body proportions (height [175 cm] and shoulder width [42 cm]) and did not differ among the experimental conditions. We downloaded all motions assigned to the virtual characters from Adobe's Mixamo. We used Unity's Mechanim animation engine to set and loop the static virtual character's idle motion and blend the virtual walker character's assigned locomotion to achieve the necessary walking speeds. Similar to previous research [35], we assigned a neutral idle motion (low amplitude) to our static virtual character since we wanted to make it look alive. Following the guidance of previous studies [39, 40], we also did not assign `LookAt` functionality to the static virtual character, since gazing could affect the avoidance movement of the participants [38]. Moreover, we opted not to use self-avatars to capture the participants' general avoidance behaviors to prevent them from being impacted by the appearance of the self-avatars assigned to them [38].

Figure 4: The two virtual characters we used in our study (left: virtual walker character; right: static virtual character).

In terms of equipment, we used an MSI VR One backpack computer (Intel Core i7, NVIDIA GeForce GTX1070, 16 GB RAM) and an HTC VIVE Pro HMD to run and project the content, respectively. We also used an HTC VIVE tracker to capture the participant's movement measurements mentioned in Section 3.3.

3.5 Procedure

When the participants arrived at the research location, the research team handed them a consent form that had been reviewed and approved by our university's Institutional Review Board. After reviewing the consent form and agreeing to participate, the participants were asked to complete a brief online demographic questionnaire using the Qualtrics survey platform. The research team helped the participants put on all equipment (see Figure 5 for a participant wearing all gear and performing the avoidance task in our motion capture studio). The research team asked the participants to walk in the VR environment to ensure their comfort and to become aware of the one-to-one size matching between the real environment and the virtual replica. We should note that no virtual character was in the virtual environment at that time.

Once the participants became familiar with the VR equipment, the research team activated the start and target spots on the ground. Then, the research team asked the participants to move toward the start spot (blue mark) and face the target spot (red mark). Then, a black screen appeared, initiating the experimental condition. The research team informed the participants that two virtual characters would appear in the virtual environment (one in the middle and another in front of them) once the research team loaded the new scene. Then, they instructed the participants to perform the avoidance task multiple times. The research team informed the participants that the virtual character that they were asked to avoid would not update its global position; however, the virtual character in front of them would also walk. The participants were unaware of the walking speed or path

Figure 5: A participant is wearing all the equipment used for this study while walking in the motion capture studio.

that the virtual walker character would follow. We did not mention to the participants that they had to follow the virtual walker character.

Once the participants arrived at the target spot, the research team turned the screen black. Then, the research team turned on the virtual environment without the virtual characters being present and asked the participant to move toward the starting spot for the next trial. Once the participants reached the start spot and faced the target spot, the research team turned the screen black again. Then, the research team turned on the main scene for the next trial. Between trials, the participants did not remove the HMD. To synchronize the time that both the virtual walker character and the participants started walking, we implemented a beeping sound that played for 2 seconds after the research team initiated the trial. We should note that the participants were aware of this. The research team did not provide the participants with any strategy for avoiding either the static virtual character or the virtual walker character. The research team let the participants plan and execute their own avoidance maneuvers and interactions with the virtual walker character. The research team was in charge of keeping the participants updated on the status of the study. Although no one opted for either, the research team informed the study participants that they could take short breaks or end the experiment at any time.

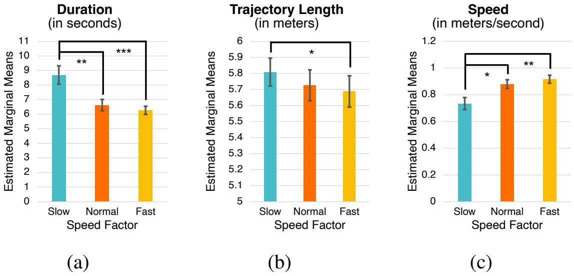
4 RESULTS

4.1 Avoidance Movement Behavior

We used a two-way repeated measures analysis of variance (ANOVA) to analyze the collected data using speed and proximity as our factors. We used Bonferroni-corrected estimates for pairwise comparisons to assess the statistically significant ($p < .05$) results. We screened the normality of our collected data using Q-Q plots of the residuals and Shapiro-Wilk tests at the 5% level. The collected data fulfilled the normality criteria. Figure 6 illustrates all the significant avoidance movement behavior results.

The analysis of the **duration** measurement did not reveal a statistically significant result for the proximity factor (Wilks' $\Lambda = .907$, $F[2,20] = 1.028$, $p = .376$, $\eta_p^2 = .93$). However, we found a statistically significant result for the speed factor (Wilks' $\Lambda = .486$, $F[2,20] = 10.559$, $p = .001$, $\eta_p^2 = .514$). The pairwise comparison based on the estimated marginal means (see Figure 6(a)) indicated that the duration of the walking task lasted longer when we exposed the participants to a slow virtual walker character ($M = 8.69$) than when exposed to normal ($M = 6.63$) at $p = .004$ and fast ($M = 6.27$) at $p = .000$ virtual walker characters. Finally, our analysis did not reveal a statistically significant result for the proximity×speed interaction (Wilks' $\Lambda = .796$, $F[4,18] = 1.155$, $p = .363$, $\eta_p^2 = .204$).

For the **trajectory length** measurement, our analysis did not reveal a statistically significant result for the proximity factor (Wilks' $\Lambda = .863$, $F[2,20] = 1.587$, $p = .229$, $\eta_p^2 = .137$), but we did find a statistically significant result for the speed factor (Wilks' $\Lambda = .709$, $F[2,20] = 4.104$, $p = .032$, $\eta_p^2 = .291$). The pairwise comparison based on the estimated marginal means (see Figure 6(b)) indicated that the participants followed longer paths when exposed to a slow ($M = 5.81$) than a fast ($M = 5.68$) virtual walker character at $p = .038$. The average trajectory length of the participants for the normal-speed virtual walker character ($M = 5.72$) was between the slow and fast conditions; however, no statistically significant result was found. Finally, our analysis did not reveal a statistically significant effect for the proximity×speed interaction (Wilks' $\Lambda = .850$, $F[4,18] = .797$, $p = .543$, $\eta_p^2 = .150$).



(a) (b) (c)

Figure 6: The avoidance movement behavior results: (a) **duration**, (b) **trajectory length**, and (c) **speed**. We indicate statistically significant results with * for $p < .05$, ** for $p < .005$, and *** for $p < .001$. The error bars indicate the standard error.

Next, we analyzed the participants' **speed** data. Our analysis did not reveal a statistically significant result for the proximity factor (Wilks' $\Lambda = .918$, $F[2,20] = .890$, $p = .426$, $\eta_p^2 = .082$). However, we found a statistically significant result for the speed factor (Wilks' $\Lambda = .543$, $F[2,20] = 8.421$, $p = .002$, $\eta_p^2 = .457$). The pairwise comparison based on the estimated marginal means (see Figure 6(c)) showed that the participants' speeds were lower when exposed to a slow virtual walker character ($M = .73$) than when exposed to a normal ($M = .88$) at $p = .008$ and fast ($M = .91$) at $p = .001$ virtual walker character. We did not find a statistically significant result between conditions in which we assigned a normal and fast virtual walker character. Finally, our analysis did not reveal a statistically significant effect for the proximity×speed interaction (Wilks' $\Lambda = .835$, $F[4,18] = .888$, $p = .491$, $\eta_p^2 = .165$).

We did not find statistically significant results for the **minimum distance** measurement for either the proximity factor (Wilks' $\Lambda = .835$, $F[2,20] = 1.983$, $p = .164$, $\eta_p^2 = .165$) or the speed factor (Wilks' $\Lambda = .770$, $F[2,20] = 2.990$, $p = .073$, $\eta_p^2 = .230$) or for the proximity×speed interaction (Wilks' $\Lambda = .834$, $F[4,18] = .894$, $p = .488$, $\eta_p^2 = .166$).

Regarding the **side-by-side distance** to the static virtual character, we did not find statistically significant results for either the proximity factor (Wilks' $\Lambda = .828$, $F[2,20] = 2.075$, $p = .152$, $\eta_p^2 = .172$) or the speed factor (Wilks' $\Lambda = .749$, $F[2,20] = 3.347$, $p = .056$, $\eta_p^2 = .251$) or for the proximity×speed interaction (Wilks' $\Lambda = .792$, $F[4,18] = 1.185$, $p = .351$, $\eta_p^2 = .208$).

4.2 Avoidance Decisions

We collected data to investigate the participants' decisions regarding the execution of the avoidance task. Specifically, we collected data to explore the **side of minimum distance** (in front of or behind the static virtual character). Specifically, in the first trial, we found that most participants kept a minimum distance behind the virtual character: slow speed & close proximity ($n = 15$), slow speed & middle proximity ($n = 15$), slow speed & far proximity ($n = 15$), normal speed & close proximity ($n = 14$), normal speed & middle proximity ($n = 20$), normal speed & far proximity ($n = 17$), fast speed & close proximity ($n = 17$), fast speed & middle proximity ($n = 15$), and fast speed & far proximity ($n = 18$). By comparison, the second trial elicited the following results: slow speed & close proximity ($n = 17$), slow speed & middle proximity ($n = 11$), slow speed & far proximity ($n = 14$), normal speed & close proximity ($n = 14$), normal speed & middle proximity ($n = 16$), normal speed & far proximity ($n = 18$), fast speed & close proximity ($n = 13$), fast speed & middle proximity ($n = 18$), and fast speed & far proximity ($n = 17$).

We also explored whether the participants' **side of minimum distance** was the same (either behind/behind or in front/in front) in both trials. By observing the collected data in both trials, we determined that most of the participants followed a similar pattern for the side of minimum distance in all nine examined conditions. Specifically, we counted the following: slow speed & close proximity ($n = 14$), slow speed & middle proximity ($n = 12$), slow speed & far proximity ($n = 15$), normal speed & close proximity ($n = 12$), normal speed & middle proximity ($n = 16$), normal speed & far proximity ($n = 17$), fast speed & close proximity ($n = 12$), fast speed & middle proximity ($n = 13$), and fast speed & far proximity ($n = 15$). A cumulative McNemar test for all conditions between the two trials also determined no statistically significant difference ($p = .409$).

To further understand the decisions made by the participants regarding their avoidance behavior, we also explored the **avoidance side** (right or left) that participants used to avoid the static virtual character in both trials. The slow speed & middle proximity and the slow speed & far proximity were equally distributed among the participants between the right and left sides ($n = 11$) in both trials, and we determined that the participants followed a similar avoidance-side pattern for the rest of the examined conditions. Specifically, for the first trial, most participants decided to keep the static virtual character on their left side. We counted the following: slow speed & close proximity ($n = 17$), normal speed & close proximity ($n = 16$), normal speed & middle proximity ($n = 19$), normal speed & far proximity ($n = 19$), fast speed & close proximity ($n = 19$), fast speed & middle proximity ($n = 20$), and fast speed & far proximity ($n = 17$). For the second trial, we counted the following: slow speed & close proximity ($n = 13$), normal speed & close proximity ($n = 15$), normal speed & middle proximity ($n = 16$), normal speed & far proximity ($n = 15$), fast speed & close proximity ($n = 13$), fast speed & middle proximity ($n = 18$), and fast speed & far proximity ($n = 17$).

Moreover, we explored whether the participants' **avoidance side** was the same (either right/right or left/left) in both trials. Our data showed that the participants followed a similar avoidance-side pattern. Most participants kept the static virtual character on their left side in all nine examined conditions. Specifically, we counted the following: slow speed & close proximity ($n = 16$), slow speed & middle proximity ($n = 20$), slow speed & far proximity ($n = 14$), normal speed & close proximity ($n = 17$), normal speed & middle proximity ($n = 15$), normal speed & far proximity ($n = 18$), fast speed & close proximity ($n = 16$), fast speed & middle proximity ($n = 18$), and fast speed & far proximity ($n = 18$). A cumulative McNemar test for all conditions also determined no statistically significant difference between the two trials ($p = .533$).

Lastly, we investigated the **side-by-side distance** by considering the proxemics model [20, 34]. Specifically, we used the following proxemic distances to delineate in which social spaces the participants kept the static virtual character in the nine examined conditions: intimate: .15-.46 m; personal: .46-1.22 m; social: 1.22-3.70 m; and public: 3.70-7.60 m. For the first trial, we found that all participants kept the static virtual character in their social space in the proxemics model (1.22-3.70 m). In a more detailed exploration of this finding, we counted the following number of participants in each condition who kept the virtual character in their close phase of the social space (1.20-2.10 m): slow speed & close proximity ($n = 21$), slow speed & middle proximity ($n = 20$), slow speed & far proximity ($n = 18$), normal speed & close proximity ($n = 22$), normal speed & middle proximity ($n = 21$), normal speed & far proximity ($n = 18$), fast speed & close proximity ($n = 22$), fast speed & middle proximity ($n = 22$), and fast speed & far proximity ($n = 18$). For the second trial, we counted the following: slow speed & close proximity ($n = 19$), slow speed & middle proximity ($n = 20$), slow speed & far proximity ($n = 21$), normal speed & close proximity ($n = 19$), normal speed & middle proximity ($n = 18$), normal speed & far proximity ($n = 17$), fast speed & close proximity ($n = 20$), fast speed & middle proximity ($n = 21$), and fast speed & far proximity ($n = 21$).

Moreover, we explored whether the participants' **side-by-side distance** was the same (close/close or far/far phase) in both trials. Our data showed that the participants followed a similar avoidance-side pattern in both trials. Specifically, we counted the following: slow speed & close proximity ($n = 18$), slow speed & middle proximity ($n = 21$), slow speed & far proximity ($n = 19$), normal speed & close proximity ($n = 17$), normal speed & middle proximity ($n = 19$), normal speed & far proximity ($n = 20$), fast speed & close proximity ($n = 19$), fast speed & middle proximity ($n = 19$), and fast speed & far proximity ($n = 21$). A cumulative McNemar test for all conditions also determined no statistically significant difference between the two trials ($p = .895$).

4.3 Avoidance Movement Behaviors and Decisions Regarding the Virtual Walker Character

We also collected data to investigate the participants' avoidance decisions and movement behaviors regarding the virtual walker character. We explored whether participants decided to pass (**virtual walker character pass**) the virtual walker character and not just follow it by staying behind it. Specifically, for the first trial, we counted the following number of participants who decided to pass the virtual walker character: slow speed & close proximity ($n = 13$), slow speed & middle proximity ($n = 13$), slow speed & far proximity ($n = 16$), normal speed & close proximity ($n = 0$), normal speed & middle proximity ($n = 2$), normal speed & far proximity ($n = 8$), fast speed & close proximity ($n = 0$), fast speed & middle proximity ($n = 1$), and fast speed & far proximity ($n = 6$). For the second trial, we counted the following: slow speed & close proximity ($n = 15$), slow speed & middle proximity ($n = 14$), slow speed & far proximity ($n = 16$), normal speed & close proximity ($n = 0$), normal speed & middle proximity ($n = 2$), normal speed & far proximity ($n = 9$), fast speed & close proximity ($n = 1$), fast speed & middle proximity ($n = 0$), and fast speed & far proximity ($n = 4$).

We also explored whether the participants' decisions (**virtual walker character pass**) to pass the virtual walker character were the same (either avoid/avoid or not avoid/not avoid) in both trials. Our data showed that most participants followed a similar pattern in all examined conditions by performing the same activity in both trials. Specifically, we counted the following numbers: slow speed & close proximity ($n = 18$), slow speed & middle proximity ($n = 19$), slow speed & far proximity ($n = 18$), normal speed & close proximity ($n = 22$), normal speed & middle proximity ($n = 20$), normal speed & far proximity ($n = 19$), fast speed & close proximity ($n = 21$), fast speed & middle proximity ($n = 21$), and fast speed & far proximity ($n = 16$). A cumulative McNemar test for all conditions also determined that there was no statistically significant difference between the two trials ($p = .839$).

Finally, we analyzed the measurement for the **distance to the virtual walker character** using speed and proximity as the factors between the participants and the virtual walker character using a two-way repeated measures ANOVA. We used Bonferroni-corrected estimates for pairwise comparisons. We also screened for normality of the data using Q-Q plots of the residuals and Shapiro-Wilk tests at the 5% level, indicating that the obtained data fulfilled the normality assumption. Our analysis did not reveal a statistically significant result for the proximity factor (Wilks' $\Lambda = .967$, $F[2,20] = .342$, $p = .714$, $\eta_p^2 = .033$). However, we found a statistically significant result for the speed factor (Wilks' $\Lambda = .400$, $F[2,20] = 14.998$, $p = .000$, $\eta_p^2 = .600$). The pairwise comparison based on the estimated marginal means (see Figure 7) indicated that the participants' distances to the virtual walker character were shorter when we exposed them to a slow virtual walker character ($M = .85$) than when we exposed them to a normal ($M = .89$) at $p = .002$ and fast ($M = .98$) at $p = .000$ virtual walker character. Finally, our analysis did not reveal a statistically significant result for the proximity×speed interaction (Wilks' $\Lambda = .651$, $F[4,18] = 2.412$, $p = .087$, $\eta_p^2 = .349$).

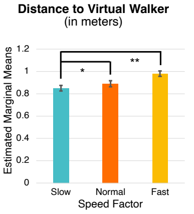


Figure 7: Significant results for the **distance to the virtual walker character**. We indicate statistically significant results with * for $p < .005$ and ** for $p < .001$. The error bars indicate the standard error.

5 DISCUSSION

5.1 RQ1: Avoidance Movement Behaviors Regarding the Static Virtual Character

The results of the avoidance behavior measurements showed that the speed factor assigned to the virtual walker character was enough to impact the participants' walking behaviors in multiple ways. Specifically, we found that the participants' walking speeds were slower when the speed of the virtual walker was slower and were faster when the speed assigned to the virtual walker was higher. As a result, the duration of the avoidance task was longer in the slower condition than in the higher one. This result indicates that participants attempted to coordinate their avoidance movement behaviors in terms of speed and duration with the collocated virtual walker character. Although similar results can be seen in other studies concerning movement coordination during interactions with virtual crowds [24, 27, 28], our study expands on such findings by confirming that a single virtual walker was enough to impact the participants' movement behaviors.

However, by observing the results from the trajectory length measurement, we saw that the participants decided to follow longer paths when exposed to a slow virtual walker character than to when exposed to a normal or fast virtual walker character. We observed the captured trajectories from all slow-speed conditions to interpret this finding. From our observations, we found the following. First, we observed that a few participants' trajectories had a zigzag pattern, unlike smooth avoidance trajectories we have seen in previous studies [37–39] that participants avoided a static virtual character without a collocated virtual walker character. We know from previous studies that participants are aware of their self-presence during collision avoidance tasks [26,38]; therefore, we think this zigzag was the result of the participants' attempts to avoid potential collisions with the slower virtual walker character that was in front of them. Thus, this zigzag path increased the trajectory length. Second, we also observed a few participants who attempted to avoid the virtual walker character without succeeding. Specifically, they decided not to avoid the character and returned to their initially planned path. Although these participants wanted to avoid the virtual walker character, they changed their minds once they realized that the target spot was too close, so they decided to stay behind the virtual walker character. Thus, this additional short maneuver increased the path length that they followed. Another interpretation of these two observations is our participants' approach to follow a local avoidance and adaptation strategy instead of planning a global optimal strategy [30]. Therefore, we argue that several of our participants violated the principle of least effort (a.k.a. principle of minimum energy) [62] when planning and performing their avoidance maneuver, which states that humans tend to optimize their trajectory to use as little energy as possible to reach their goals, agreeing with Basili et al. [2] who showed that collision avoidance is not optimal. Third, we found that several participants passed the virtual walker character (we also discuss this in Section 5.3) by keeping the virtual walker character to their left side and, thus, decided to follow longer paths.

However, as shown in our results, the proximity factor did not impact how the participants decided to perform the avoidance maneuver. We think the results obtained in the minimum distance and side-by-side distance measurements, along with prior knowledge about preplanned avoidance strategies [17, 47], could help us interpret this finding. Specifically, although the participants were unaware of the proximity variation assigned to the virtual walker character, they planned how to execute the avoidance task in advance because they were aware of the virtual walker character as soon as the application started. Therefore, they were not surprised by a sudden event and thus did not need to make adjustments to their planned action, which previous research has shown are more common in cases where sudden events occur [47, 59]. Although the proximity factor made them slightly change how they decided to execute the avoidance task, as discussed in the previous paragraphs, this change in their avoidance movement behaviors was not enough to provide significant results.

5.2 RQ2: Avoidance Decisions Regarding the Static Virtual Character

We also attempted to understand participants' decisions in executing the avoidance task. In terms of the side of minimum distance (in front or behind), based on our collected data, we found that most of the participants followed a similar pattern in both trials. The minimum distance was at the back side of the static virtual character, confirming previously published research [1, 40]. We also found that, in the second trial, most of the participants decided to avoid the static virtual character from the same avoidance side that they did in the first trial.

In terms of the avoidance side (right or left), we found that in two of the conditions (slow speed & middle proximity and slow speed & far proximity), the participants were equally distributed between the right and left side, but in the rest of the conditions, the participants decided to keep the static virtual character on their left side. This finding extends a previously conducted study on obstacle avoidance [52] and confirms a previous study on participants' side preferences during an avoidance task [40]. Our findings also reveal that most participants in the second trial decided to keep the static virtual character on the side where they kept that character in the first trial.

Our findings regarding the proxemics space in which the side-by-side distance fell showed that all participants kept the static virtual character in their social space (1.22-2.10 m). That side-by-side distance was enough for our participants to perform a safe and free-of-collision avoidance maneuver [11, 44]. We also consider that the static virtual character was the same in all conditions; therefore, the participants experienced the same degree of intimacy across conditions, agreeing with the norm of the uncanny valley effect [5, 21]. After all, we used a semi-realistic virtual character, thus eliciting a neutral experience for the participants across all examined conditions [41, 60]; therefore, the participants decided to avoid the static virtual character following a similar side-by-side distance across all conditions.

The previously mentioned findings confirm and strengthen the argument that most of the participants planned how to execute the avoidance task in advance. Specifically, we argue that the participants kept their initial avoidance planning strategies and decisions toward the static virtual character and executed them similarly between the two trials without being influenced by the virtual walker character. These interesting results indicate the participants' decisions when planning and executing the avoidance tasks to which they were exposed. We consider this a novel finding concerning avoidance movements in virtual environments when encountering a collocated virtual walker.

5.3 RQ3: Interaction with the Virtual Walker Character

In addition to understanding how the participants planned and executed the avoidance task, we also wanted to explore how they decided to regulate their walking decisions based on the virtual walker character. Based on the collected data, we found that the participants kept shorter distances from the virtual walker character when exposed to slow compared to normal or fast walking speed conditions.

In terms of direct interaction with the virtual walker character, in conditions where a slow virtual walker character was present or in the condition of normal speed and far proximity, we saw more participants pass the virtual walker character in both trials. We think that in slow conditions or conditions that are moderate speed but with enough clearance, either the participants could create a suboptimal path by circumventing the virtual walker character—as their walking speeds were higher and they were therefore able to reach the target spot without risking any potential collision—or they could find a clear path and increase their speed to reach the assigned target spot quickly enough. In contrast, in conditions where the virtual walker character was moving faster, the participants decided to follow the character, as the optimal path was not clear to them, especially in the close and middle proximities. Finally, we found that most of the participants performed the same activity in the second trial that they performed in the first trial, which indicates that participants were consistent between trials, not only in terms of how to avoid the static virtual character, but also in how to interact with the virtual walker character. In a previous study, we saw a similar result in participants switching from going around to going through when the interpersonal distance between agents of a crowd grows bigger [6]. Our study extends that finding by confirming that our study participants switched between passing or not passing the virtual walked character based on the virtual walker's speed and proximity to the static virtual character. We consider this to be a relatively novel finding.

5.4 Limitations

First, although we were aware of a specialized questionnaire to assess participant perception regarding their interaction with the virtual characters, we decided not to include a questionnaire in this study but instead mainly focus on collecting movement data. We did so primarily because it was a within-group study in which we exposed participants to nine conditions. Therefore, including questionnaires would have made the whole experience cumbersome and tedious.

Second, our study demonstrated the advantages of VR in examining the participants' avoidance movement behaviors in a highly standardized, tentatively controlled, and ecological way. The participants performed the locomotive task in an 8×8 m space, which might have influenced participant behavior. Future studies could benefit from evaluating participants' avoidance movement behaviors in larger physical areas and more complex situations. This could benefit the generalizability of the results.

Third, the eye-tracking data collection would have been informative in such a project, since we could have extracted information on the areas and virtual characters (static virtual character and virtual walker character) that participants viewed during collision avoidance tasks. We consider this an additional limitation because using an HMD that houses eye tracking could provide valuable data. Such data would have provided a deeper understanding of how the two virtual characters affect participants' attention allocation.

Fourth, while many collision avoidance studies in VR do not report gender differences in terms of proximity, in psychology and studies of peripersonal space, these gender differences do occur, as some studies also found the effect of gender on the proximity measures in VR [23, 61]. However, due to the small sample size in each gender, we could not find significant results. Thus, we argue that such limitation should also be further explored to conclude whether a colocated virtual walker would impact study participants based on their gender.

Fifth, in our study, we used human characters instead of a dummy or an androgynous avatar. We know the appearance of an avatar can impact the proxemic behavior of VR users [39, 40]. Moreover, we decided not to represent our participants with a self-avatar.

We know that giving the participant a humanoid character with no features may have potentially affected spatial perception. Since participants were not represented with a self-avatar in the virtual environment, they might have experienced some difficulty in judging the distance between themselves and the other two virtual characters. Such a decision might have also led to different proxemics behaviors as there was no embodiment [7]. However, we did so because we wanted to capture a direct avoidance movement that was not influenced by self-avatars that did not match the appearance of the participants.

To summarize, despite the limitations discussed previously, we would like to stress that such limitations do not invalidate our findings regarding the effects of a virtual walker character's proximity and speed levels on study participants' avoidance movement behaviors. In addition, we think that future researchers should address such limitations to advance the understanding of avoidance movement behavior in the presence of a collocated virtual walker.

6 CONCLUSIONS AND FUTURE WORK

We examined the effect of the proximity and speed of a collocated virtual walker character on the avoidance movement behaviors and decisions made by the study participants around a static virtual character. We found several interesting results regarding how participants regulated and executed the avoidance movement tasks. Our findings on participants' avoidance movement behaviors and decisions intrigue us to explore this direction further. They imply that a collocated virtual walker character can influence participants' avoidance movement behaviors without influencing their decisions.

In addition to the limitations that we should consider in future studies, we would like to expand our work in several directions related to understanding human movement behavior during collision avoidance tasks. For example, we would like to explore collision avoidance scenarios in which more than one virtual character is standing at the midway point by varying their appearance and gender. Furthermore, we would like to explore the avoidance movement behaviors of participants when immersed in virtual crowds. These future research directions could help us further explore how humans plan and execute their avoidance movement behaviors around a static virtual character in virtual environments. Such findings could inform developers interested in creating virtual social environments, training applications, and games. Lastly, we would like to explore how a collocated virtual walker avoids a static virtual character from different sides and when a virtual walker character starts walking from the opposite side. Conducting such a study would help us generalize our findings and further understand how collocated virtual walkers can impact study participants' decisions.

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