Evaluating Collision Avoidance Effects on Discomfort in Virtual Environments

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Abstract—Dynamic, moving characters are increasingly a part of interactive virtual experiences enabled by immersive display technologies such as head-mounted displays (HMDs). In this new context, it is important to consider the impact their behavior has on user experiences. Here, we explore the role collision avoidance between virtual agents and the VR user plays on overall comfort and perceptual experience in an immersive virtual environment. Several users participated in an experiment were they were asked to walk through a dense stream of virtual agents who may or may not be using collision avoidance techniques to avoid them. When collision avoidance was used participants took more direct paths, with less jittering or backtracking, and found the resulting simulated motion to be less intimidating, more realistic, and more comfortable.

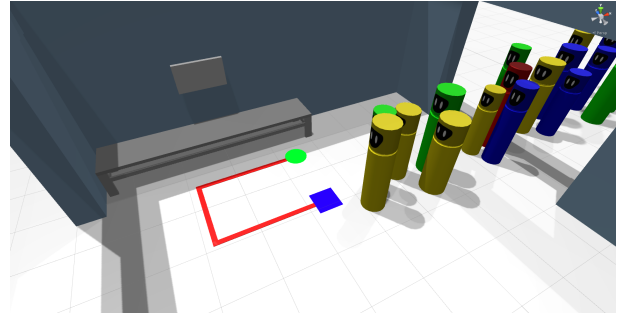*Keywords—Virtual Reality, Crowd Simulation.*

Fig. 1. **Experimental Setup.** Participants are placed in the above virtual environment and asked to walk along the red U-shaped path as a stream of virtual agents walk by. Two conditions are used: one where the agents avoid the users and one were they do not.

I. INTRODUCTION

Advancements in virtual reality (VR) technology have led to increased capability and availability of virtual experiences. While the concept of virtual reality is far from new, the field has seen recent and rapid growth in industry and research. Experiencing an immersive environment in VR increases the importance of certain perceptual elements as compared with other virtual experiences such as that provided by PCs. Here, we study the effect of collision avoidance for virtual characters by observing how the presence or absence of this behavior changes a user's experience when interacting with a virtual crowd.

Collision avoidance is one of the primary ways virtual character behavior supports the presence of the user experiencing a virtual environment. There are a variety of approaches for achieving collision avoidance, enabling virtual characters to maintain a minimum distance between both users and other virtual characters in the environment. More recent methods for collision avoidance incorporate more complex strategies that exhibit anticipatory behavior and more human-like trajectories, as well as robust handling of dense scenarios [1]. In PC-based experiences, collision avoidance is important to make virtual characters act realistically, but in VR collision avoidance takes on a new importance. Characters that don't avoid collisions may cause the user to lose their sense of presence, feel various forms of discomfort, and intimidate or otherwise negatively impact the experience of the user.

In this paper, we investigate the connection between collision avoidance and the quality of experience for the user such as overall comfort and sense of presence in the virtual environment. We do so by conducting user studies in which participants interact with a crowd of virtual agents, both with and without collision avoidance behavior (Figure 1). The effect of the presence or absence of collision avoidance can be seen both through the qualitative experience and the physical actions of the subjects in the virtual environment.

II. BACKGROUND

A. Personal Space

The study of personal space dates back to at least the 1950s with Edward T. Hall's notion of proxemics [2], which identifies the region around each person that they identify as uncomfortable for others to enter. More recently, researchers have turned to VR as a tool to study how humans perceive their personal space. For example, Bailenson et al. used immersive VR (HMDs) to study how much interpersonal distance was maintained between participants and virtual humans. They found a positive correlation between magnitude of emotional reaction and magnitude of avoidance behavior in participants interacting with avatars [3]. In later work, Bailenson and colleagues found that the graphical realism of the simulation had little impact on the minimum interpersonal distance users maintained in VR, but they did find a greater hesitancy to closely approach agents that exhibited more realistic head motion behavior [4].

Measurements. Measuring personal space presents its own challenges. Researchers have analyzed both behavioral measures (how people act) and self-reported measures (how people say they feel) to gauge peoples' social presence and their response to violations of their personal space in immersive virtual environments. This is important because some variables that affect inter-personal avoidance behaviors may not be captured by self-reported measures [5]. Moreover, Ptten et al. found that peoples subjective assessments of their interaction with a virtual agent were significantly influenced by their

own personality traits [6]. Beyond influencing peoples' motion trajectories, violations of personal space can affect their physiological responses; for example Llobera et al. found higher skin conductance readings associated with closer approach distances and greater numbers of approaching characters during interactions both with virtual humans and with human-sized cylinders [7].

B. Interaction with Virtual Crowds

Narang et al. developed a simulation method that robustly generates plausible behaviors for large numbers of virtual humans, including full-body motion and eye gaze as well as motion trajectories. They found a significant impact of the higher fidelity animations on users' ratings of social presence [8]. Pelechano et al. used navigation tasks in virtual environments to evaluate the sensation of being part of a crowd [9].

Recently, researchers have explored interactive crowd simulations in immersive environments. Kyriakou et al. found that facilitating collision avoidance increased perceived realism of virtual characters [10]. Sanz et al. showed that humans use different locomotion behaviors when navigating around human vs non-human virtual obstacles [11]. Bruneau et al. explored user interactions when navigating with groups of virtual humans [12]. While this previous work has considered CAVE-like and semi-immersive environments, our work focuses on users in an HMD-based virtual environment.

Realistic Crowd Simulation. Much of the recent work in crowd simulation has focused on improving the realism in the motion of virtual agents [13]. Other recent work has explored the role anticipation plays in person-person interactions [1], the role non-linearity has is simulating interactions [14], vision-based collision avoidance [15], and physically-based pushing behaviors [16]. A recent survey providing a wide coverage of the field was recently published by Pelechano et al. [17]

III. EXPERIMENT DESIGN

The goal of our experiment was to induce users to interact with virtual crowds with and without collision avoidance. During the experiments, participants wore an HMD which showed a virtual environment of the same basic shape as the physical lab they were in, with the addition of moving simulated agents. Participant movements were tracked and the virtual environment was updated accordingly.

The experiment consisted of two tasks in which the subject walked along a specified path in the virtual environment (Figure 1). After positioning the subject on a starting location in the real world, the HMD was fitted and the virtual environment turned on. The subject would then appear in a virtual room similar to the real one in which they stood. The path was indicated in the virtual environment as a U-shaped red line leading from their current position (indicated by a green circle both on the floor and overhead) to the final position (similarly indicated by a blue square). The first leg of the path traveled in an open area, and the second took the subject head-on through a crowd of virtual agents. In this way traversing the path involved both walking in and outside of a virtual crowd. Both tasks consisted of walking the same path, across which a trial condition was varied. In one condition, the virtual agents

(a) With Collision Avoidance
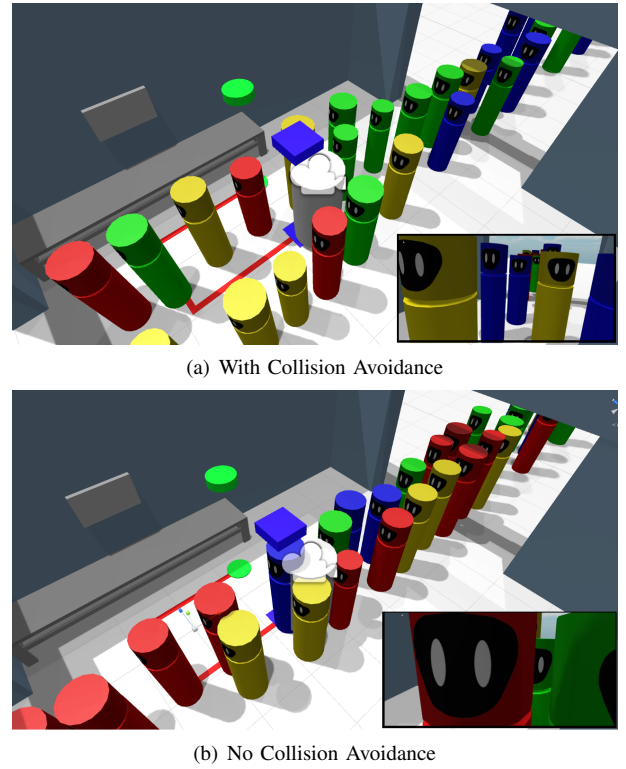

(b) No Collision Avoidance

Fig. 2. **Experimental Conditions.** A comparison of the two experimental conditions. Simulated agents either avoided the participant (a) or did not react to their presence (b). Inset shows first person views. The user is rendered as a white cylinder inside the crowd flow.

performed collision avoidance between themselves and the subject using the Power-Law model proposed in [1] (Figure 2(a)). In the other condition, the virtual agents would perform collision avoidance amongst themselves, but not the subject, passing through them as if they were not present (Figure 2(b)). The order of the trial conditions was randomized for each subject.

During both tasks, each subject's 3D position and orientation were captured at a sample rate of 10 Hertz. For analysis, the trajectories were cropped to an observation region containing the second leg of the path, where interaction with the virtual crowd occurred. Before, between, and after the trials, participants completed the simulation sickness questionnaire (SSQ) proposed in [18]. On completing the study, subjects were asked to complete an additional survey assessing their overall perception of various aspects of their experience. The survey included items related to the experienced realism of virtual character movement, overall comfort during the simulation, and other qualitative measures related to their perception of the virtual characters such as intimidation and reactiveness. Each item was rated on a 1 to 7 Likert scale (See Appendix A for question details).

Physical Set-up. All experiments were conducted in a 3.7 x 2.6m indoor lab area. Position tracking was performed using a 6 camera OptiTrack^{TM} tracking system. The consumer release Oculus VR^{TM} HMD was used for the immersive virtual display. This setup is pictured in Figure 3. We used the Unity Game Engine to render the environment. In order to reduce latency induced by fast head rotations, the internal gyroscope

Fig. 3. **Lab Setup.** A participant being tracked as she moves through the physical lab environment reacts to virtual agents in a simulated crowd.

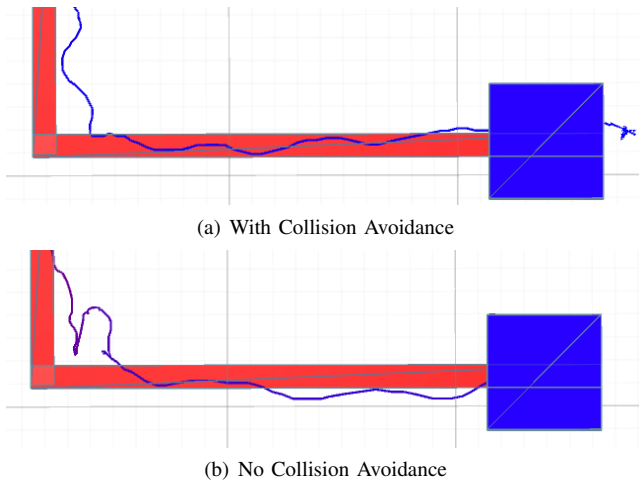(a) With Collision Avoidance

(b) No Collision Avoidance

Fig. 4. **Example Trajectories.** A comparison of the trajectories from two trials of the same user. In the case with no collision avoidance, the user hesitates, backtracks, and ultimately follows a less smooth path.
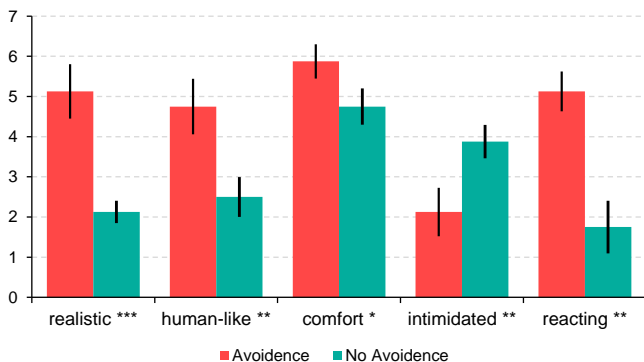

Fig. 5. **Self-reported Experiences.** Participants evaluated both experimental conditions across several perceptual metrics. Stars indicate level of statistical significance: * for p < 0.1, ** for p < 0.05, *** for p < 0.01.

on the Oculus was used for head orientation tracking.

IV. RESULTS & DISCUSSION

A total of 9 subjects participated in the experiment (3 female, 6 male). All but one participant had extensive experience with PC or console based video games. Both quantitative and qualitative measures showed that the absence or presence of

Component	Initial	Trial 1	Trial 2
Nausea	0.13 ±0.4	0.13 ±0.35	0.38 ±0.7
Oculo-Motor	1.3 ±1.3	1.1 ±1.1	1.0 ±1.0

TABLE I.   SIMULATOR SICKNESS QUESTIONNAIRE (SSQ)

collision avoidance behavior had a significant impact on the subjects' experiences.

The responses given in the survey show strong evidence that participants felt the simulation was affected by the characters avoidance. The survey results are depicted in Figure 5. While there was a significant difference in overall comfort level between the trial conditions ($p < 0.1$), stronger effects emerge when factors related to the motion of the virtual characters are considered. Subjects reported significantly higher perceived reactiveness, lower experienced intimidation, and increased human-likeness of the virtual characters ($p < 0.05$) when they exhibited collision avoidance behaviors. Additionally, a very significant increase in perceived realism of character movement was associated with the collision avoidance as well ($p < 0.01$).

Performing the tasks for the experiment had no observable effect on reported physical discomfort levels. A simulator sickness questionnaire was taken before performing any tasks, and after both the first and second tasks in the study. The questionnaire asked participants questions to measure the current extent of nausea and ocular-motor discomfort symptoms. The results are shown in Table I. All participants experienced almost no levels of simulator sickness at any time (almost all participants had scores less than 2 on the 40pt SSQ scale). For the questionnaires taken before the virtual experience and after the first task, no change in either discomfort measure was seen. While a small increase in symptoms was observed in the final SSQ, the change is not statistically significant, suggesting participants did not feel a significant change in their level of discomfort at any point in the study. Possible reasons for lack of symptom levels regularly associated with VR experiences include the short nature of our experiment (the average time spent in VR per trial was 62 seconds), and the participants' backgrounds in other forms of interactive environments and virtual experiences.

The trajectory data captured from the participants motion allows us to perform an objective analysis of behavior displayed in each condition. As participants interacted with the virtual crowd over the different trial conditions, changes in their trajectories could be seen. As a measure of how the discomfort impacted their experience, the path lengths for each trial was computed as the sum of the spatial distances between each sample. These distances were computed in 2D using the 3D coordinate projections onto the ground plane (Figure 4). As is shown in Figure 6(a), the trial condition with no collision avoidance saw a larger path length ($p = 0.06$).

While path length only considers the spatial component of the trajectory, there is also important temporal information to consider, for example, how often does the participant stop or even backtrack. To account for this, we measure the total acceleration taken by each participant over the course of their interaction with the crowd (as measured by the sum of the magnitude of the acceleration at each time step). The results
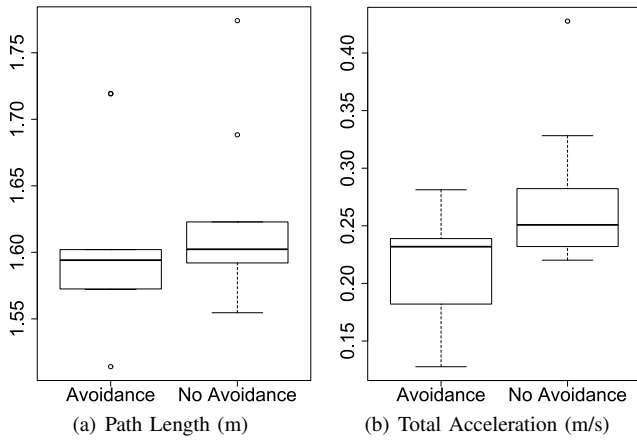
Fig. 6. **Behavioral Analysis.** Behavioral metrics were computed for the portion of the path that intersected the stream of agents. When collision avoidance was used (a) participants took shorter, more direct paths (p = 0.06) and(b) less acceleration was used (p = 0.003). Both metrics indicate less hesitation in walking.

are shown in Figure 6(b). As expected, when in the no-collision avoidance condition participants had more acceleration, indicative of less smooth motion with more stopping, backtracking, and veering off-path. As with path lengths, there was a clear statistical difference between the collision avoidance and non-collision avoidance conditions ($p < 0.01$). The larger statistical strength of the effect suggests that a significant component of the adverse reactions are primarily in the temporal component (e.g., participants stopping because they feel uncomfortable with the lack of collision avoidance).

Figure 4 shows a single participant whose path illustrates the statistical trends described above. The path traveled in the trial with collision avoidance (Figure 4) follows a smooth cadence and has little deviation from the path markers. Without collision avoidance (Figure 4b), the path shows a more erratic and irregular shape, straying from the path indicator. This could indicate the subject either trying to avoid the virtual characters (who no longer avoid them), or perhaps having difficulty focusing on the task due to the discomforting (lack of) interaction.

V. Conclusion

We have conducted an experiment to study the impact of collision avoidance behavior for virtual characters on user experiences in an immersive virtual environment. We found that the presence or absence of collision avoidance has a significant impact on user perception of discomfort, perceived realism and intimidation from virtual characters, as well as the physical actions taken by participants during the study. With high statistical significance, users experienced higher levels of perceived realism, presence, and lower levels of discomfort and intimidation with collision avoidance than without.

Limitations. The limited space of the physical environment constrained the movement based tasks, and resulted in short durations of the VR experiences. The statistical significance for some effects may have been limited by the number of participants in the study, and we hope to perform follow-up studies with a larger group of users with a wider range of previous VR and gaming experience. During the trials, many

participants appeared to look down while walking in order to better follow the path markings. This has the potential to limit the extent to which the users visual experience the crowd interactions (or lack thereof), which may limit the effect of the different conditions.

Future Work. For future work we would like to experiment with different modes of user interaction besides navigation, such as giving people virtual hands to interact with the crowd or allowing verbal communication. Additionally, it may be valuable to directly compare the strength of the discomfort felt from lack of collision avoidance in VR to that felt with first-person non-immersive displays (e.g, PC or console games). Lastly, a natural extension of our work is to consider various types of collision avoidance or collision response between the virtual agents and the user.

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APPENDIX

Survey All questions were rated on a Likert scale of 1 to 7. Participants answered each question for each trial. The questions are as follows:

- How realistic did you find the motion of the characters?

- How human-like did you find the motion of the characters?

- How often did you feel the need to close your eyes?

- How comfortable did you feel?

- How intimidated by the characters did you feel?

- The extent to which you felt as if you were moving when standing still?

- The extent to which you felt the characters were reacting to your presence?