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Assessing the Relevance of Eye Gaze Patterns During Collision Avoidance in Virtual Reality

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Abstract

To increase presence in virtual reality environments requires a meticulous imitation of human behavior in virtual agents. In the specific case of collision avoidance, agents' interaction will feel more natural if they are able to both display and respond to non-verbal cues. This study informs their behavior by analyzing participants' reaction to non-verbal cues. Its aim is to confirm previous work that shows head orientation to be a primary factor in collision avoidance negotiation, and to extend this to investigate the additional contribution of eye gaze direction as a cue. Fifteen participants were directed to walk towards an oncoming agent in a virtual hallway, who would exhibit various combinations of head orientation and eye gaze direction based cues. Closely prior to the potential collision the display turned black and the participant had to move in avoidance of the agent as if she were still present. Meanwhile, their own eye gaze was tracked to identify where their focus was directed and how it related to their response. Results show that the natural tendency was to avoid the agent by moving right. However, participants showed a greater compulsion to move leftward if the agent cued her own movement to the participant's right, whether through head orientation cues (consistent with previous work) or through eye gaze direction cues (extending previous work). The implications of these findings are discussed.

CCS Concepts
• Human-centered computing → Virtual reality

1. Introduction

Immersive virtual reality can play an important role in architectural design reviews, by allowing stakeholders to assess the suitability of the 3D layout of a planned building based on their own first-person experience of the designed space. As most large buildings, such as hospitals, libraries, schools, etc. are typically bustling with occupants, adding virtual human entourage elements to the 3D CAD model is important for conveying an accurate sense of how the space will feel when in use.

Our current research aligns with the larger effort to enable more realistic interactive experiences in virtual environments populated with autonomous intelligent agents [PAB08]. In this work, we focus on the non-verbal cues used to negotiate collision avoidance. This is critical for increasing presence in situations where the user must avoid colliding with a virtual agent, and more generally for crowd simulation or other scenarios where agents interact with each other.

2. Previous Work

Bönsch et al. [BWW*15] found that participants in CAVE-based immersive virtual environments expect agents to collaborate in avoiding collisions, and in an HMD-based VE scenario Sohre et al. [SMI*17] found that participants' ability to fluidly walk through a crowd of oncoming agents was significantly impeded when the agents did not cooperate in avoiding collisions, even though the consequences of any collisions were purely visual.

Most crowd simulation methods model agents as points with an associated position and velocity; collision avoidance is achieved by predicting the paths that other agents are likely to follow, based on this velocity information [KSN*17]. However, some research suggests that humans may also use additional body-based cues to communicate information that can be useful for collision avoidance planning. In real world studies, Dicks et al. [DCO*16] found significant differences in peoples' gait behaviors when they had to avoid collisions with oncoming pedestrians who were looking at their mobile phones versus exhibiting normal social attention. Hu et al. [HAI*16] augmented agents' locomotor animations with an ad hoc head-turning behavior in an attempt to signal social awareness while negotiating orthogonal crossings, and informally noted positive responses to that change.

Although Cinelli and Warren [CW12] have shown that head rotations are neither necessary nor sufficient to induce a change in peoples' locomotor trajectories, several researchers have reported experiments in which participants' decisions on which way to move to avoid an impending collision with a frontally-oncoming virtual agent is affected by the agent's head direction [UK13] or eye gaze direction [NHH09].

Ueda and Kitazaki [UK13] asked participants to execute avoidance maneuvers using a mouse while standing 200cm in front of a large screen showing an impending collision with an approaching agent. Across 20 trials, the agent's head either remained straight or rotated to the right or left 0.5s before their walking direction veered to the left or right. In aggregate, they found that participants tended to begin avoidance in the opposite direction of the agent's head turn before seeing the walking direction change.

Nummenmaa et al. [NHH09] tracked peoples' gaze while they made a 2AFC decision about which way to duck to avoid an oncoming agent, animated on a 20" monitor. The agent's eyes were directed to the side while its head faced forward. Over 20 trials, participants tended to more often look and move in the direction opposite to the agent's gaze.

3. Experiment

Our experiment extends prior work by considering the effect of eye gaze and head direction in combination, and in the context of an HMD-based, rather than monitor-based, scenario.

Fifteen participants (5 male, 10 female, ages 19–48, $\mu = 27.3 \pm 9.1$) were recruited from our University community. They were pre-screened for uncorrected visual acuity better than 20/70 and for stereo vision ability, then provided written informed consent. Participants wore an HTC Vive head mounted display with embedded SMI eye tracking, which was calibrated for each participant at the start of the experiment. The experiment took place within a 15'x15' open space in our VR lab and the virtual environment was modeled and rendered using Unity 5.6.

For each trial, the participant would begin by standing on a target at the end of an empty virtual hallway, which had a green square at one end and a red square at the other end (Figure 1). The display would turn black, and when it turned on again, the participant would see an agent at the opposite end, walking towards them down the center of the hallway. The participant was instructed to begin walking straight towards the agent once the display was no longer black. A non-rendered object moved about 4ft in front of the agent, and when the participant collided with this object, the display turned black again. Participants were instructed to avoid the unseen agent and continue on towards the target. After the

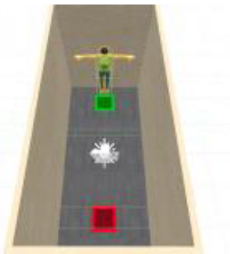

Figure 1: *The virtual hallway, showing the targets at each end of the hallway, and the avatar for scale.*

avoidance maneuver was made, the display would re-reveal the hallway, and the participant was directed to continue to the target on the floor at the end of the hallway. Upon reaching the target, they had to turn around to face the opposite end of the hallway, and then the next trial would immediately begin. Each block of trials featured 7 different scenarios of distinct non-verbal cues (Figure 2), which were programmed to start as soon as the display was initiated. These scenarios were:

(a) Control: agent's head and eyes both facing forward
(b) Head and eyes facing the participant's right
(c) Head and eyes facing the participant's left
(d) Head forward and eyes right
(e) Head forward and eyes left
(f) Head right and eyes left
(g) Head left and eyes right

Head and eye rotation angles were kept constant throughout each trial. In the conditions with eye rotation, the eyes were rotated 20° within the head. Similarly, the head rotation angle was approximately 20° with respect to the torso. In addition, the agent's head and body, as well as the surrounding regions, were programmed to recognize when the participant's eye gaze hit them. These data were processed to create a log capturing what the participant was looking at each ~1/100ths of a second. The participant's position was also recorded to track the chosen path of avoidance.

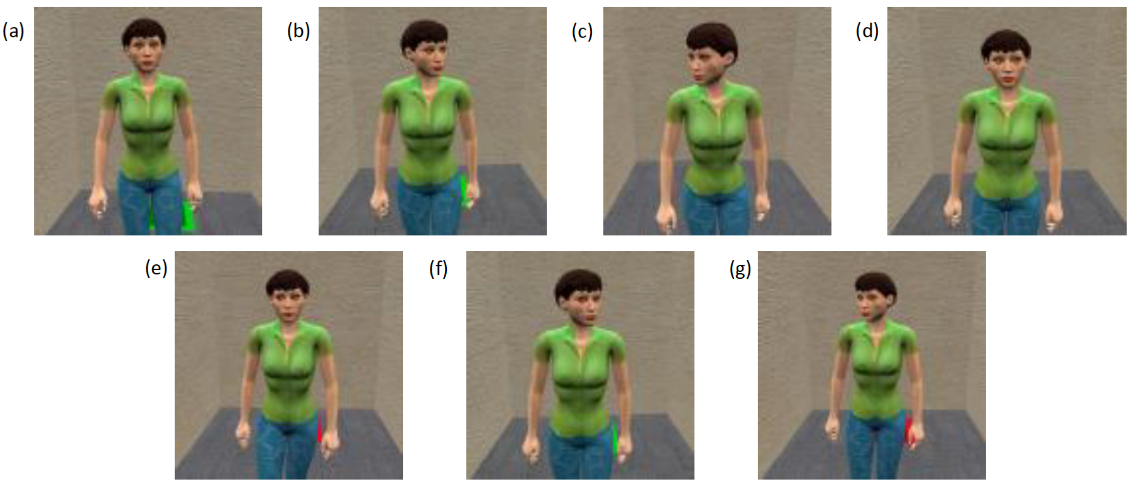

Figure 2: T*he seven scenarios that were each executed twice. (a) agent's head and eyes facing forward (control), (b) head and eyes towards the participant's right, (c) head and eyes left, (d) head forward and eyes right, (e) head forward and eyes left, (f) head right and eyes left, (g) head left and eyes right.*

4. Results

The data are shown in Figure 3, which includes one graph for each of the seven simulations. The light grey lines show the raw trajectory data for each participant (corresponding to the scale on the left vertical axis), and the colored points represent the average positions across all participants (corresponding to the scale on the right vertical axis), discretized in 100 distance-based intervals specified by the x-axis. Along the y-axis, negative values represent positions to the right of center, and positive values represent positions to the left of center, from the participant's point of view. The color of each point indicates participants' most common eye gaze location within the interval: agent head (blue), agent body (purple), to the left of the agent (green), and to the right of the agent (orange). Dark grey dots indicate positions after the collision was avoided; given the goals of this study, the gaze location at these points in time is irrelevant.

5. Discussion

The presence of a rightward deviance in the control graph (Figure 3a) suggests a bias to pass on the right, presumably attributing to societal norms. Participants passed to the right 60% of the time in the control case.

We can see that this natural tendency to pass on the right was heightened when the approaching agent signaled its intent to move leftward (Figures 3c, 3e). When the head and eyes both faced left, only 23% of participants passed on the left, and those who did tended to swing wider than in the control condition. Even when the eyes alone faced left, 70% of participants chose to pass to the right and the minority who passed to the left again swerved earlier and wider than in the control condition.

Conversely we did not, however, observe an increased tendency to pass on the left when the agent signaled its intent to move rightward. When the head and eyes both faced right, 66% of participants still passed to the right, and when the eyes alone faced right, only 40% of participants ducked left, the same as in the control condition. These results stand in contrast to the findings of [NHH09], and the reason for the discrepancy is not clear.

Notably, in the two scenarios in which the eyes *alone* were presenting the cues (Figures 3d,e), avoidance patterns were almost identical to when the head and eyes *both* were presenting the cues (Figures 3b,c). This confirms that eye gaze patterns have relevance in collision avoidance. The fact that adding head orientation cues does not appear to change the results much actually suggests a dominant role for eye gaze in cuing intent.

The scenario with the head turned right and eyes gazing left (Figure 2f) produced the only left-favoring graph (Figure 3f), and 50% of participants in this condition passed to the left. A possible interpretation of this result is as a reflection of the societal norm of making eye-contact while communicating with someone. Because we used similar angles of head and eye rotation, when they were in opposing directions they tended to cancel out, so that the eyes appeared to be focused centrally. It's possible that this central focus was interpreted as eye-contact, thus emphasizing the signaling intent of the head orientation and convincing the participant

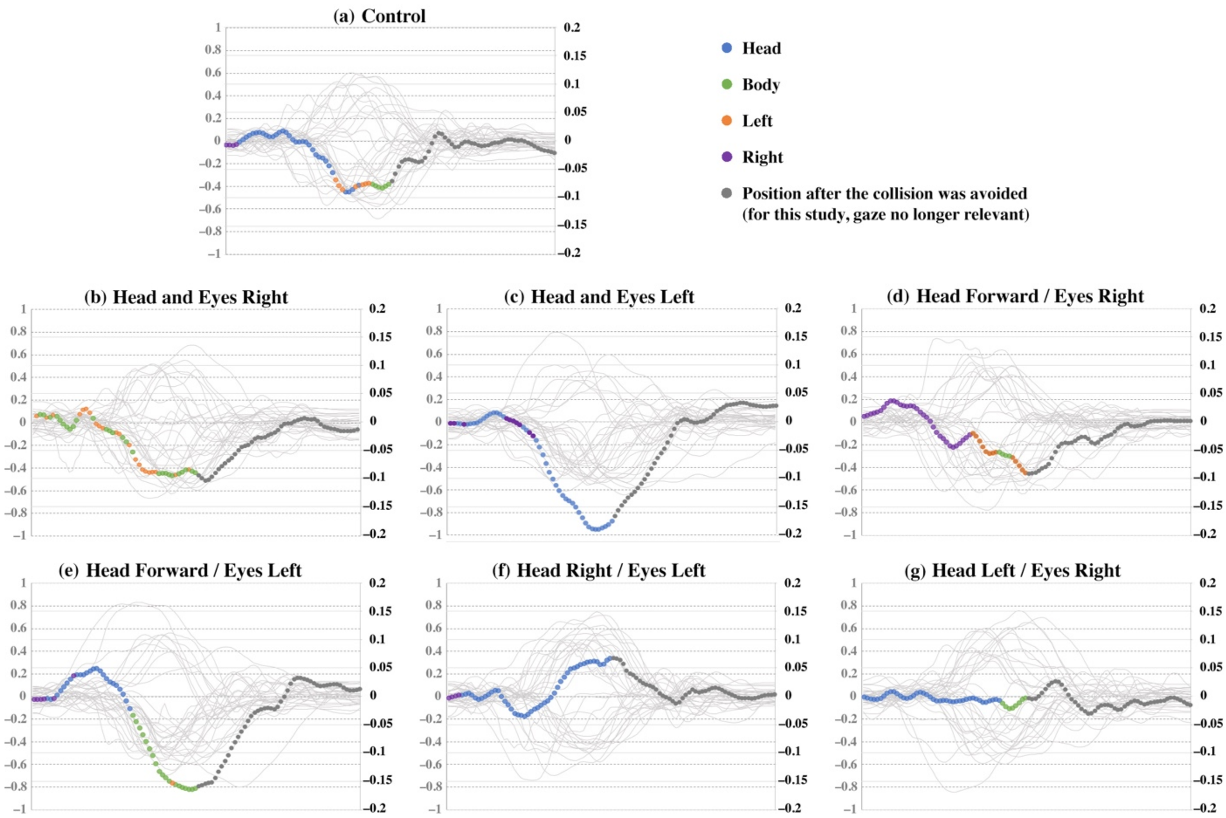

Figure 3: *Results displayed in 7 graphs, one for each variation of cues.*

to move against their familiar rightward avoidance.

The colors of the dots in Figure 3 show that participants often spent considerable time looking at the agent's head (blue). In many cases the head was fixated until the moment the display turned black (Figures 3c, 3f, 3g). More time was spent looking to the left of the agent (orange) in the conditions where the agent's eyes were facing to the right of the participant (Figures 3b, 3d), perhaps indicative of some collision avoidance planning.

In exit surveys, participants were asked if they were aware of the agent's head pose, and if so, how much it influenced the direction in which they chose to move on a scale from 1 (not at all) to 7 (very much). 11 of 15 participants responded that they were aware, with an average ranking of 5.09. Similarly prompted for eye gaze direction, 11 participants responded that they were aware with an average ranking of 5.82. This suggests that when people did notice the cues they were taken into account, while the perceived irrelevance of cues is a consequence of unawareness.

One participant reported noticing the directional changes in head orientation but not in eye gaze, and described that both in the experiment and in real life situations, she feels awkward making eye contact with a random passerby. This response exposes an additional variable that should be taken into account when analyzing collision avoidance negotiation: the participant's temperament. The way it plays into their interaction with others can potentially affect the awareness/relevance of non-verbal cues.

A possible approach to extending these findings would be to increase or vary the initial distance between the user and the agent. This experiment was limited to a short hallway (10' x 10'). Therefore, participants walking at a normal pace never had more than 5 seconds before making an avoidance movement. Increasing the walking distance could result in a more informed assessment of when and for how long different cues are being focused on. This becomes relevant in terms of visibility. A few participants reported in the exit surveys that the eyes were hard to see, especially from farther away. Based on the average rankings on the surveys mentioned above, eye-gaze-based cues had slightly more influence on the participant's decision than the head orientation cues (5.82 vs. 5.09). However, if participants had initially assessed the situation from a significantly farther distance, then the eyes might have had less influence because of the lack of visibility.

Overall, this experiment shows that in collision avoidance situations, not only do people use the head orientation of an approaching agent to infer its directional intent and appropriately plan their avoidance, but that the agent's eye gaze direction also has comparable influence. This substantiates and informs the development of autonomous intelligent agents who exhibit both appropriate head and eye movement cues for collision avoidance negotiation, which may accordingly increase presence and improve the experience of VR.

Acknowledgments

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