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# Interaction between real and virtual humans during walking: perceptual evaluation of a simple device

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## Abstract

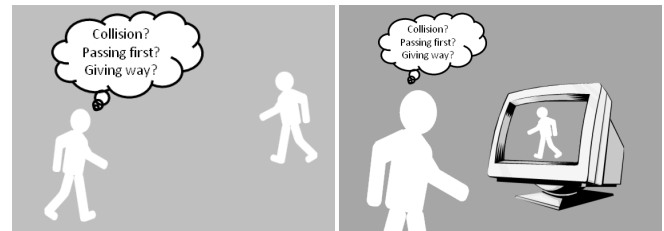
Validating that a real user can correctly perceive the motion of a virtual human is first required to enable realistic interactions between real and virtual humans during navigation tasks through virtual reality equipment. In this paper we focus on collision avoidance tasks. Previous works stated that real humans are able to accurately estimate others' motion and to avoid collisions with anticipation. Our main contribution is to propose a perceptual evaluation of a simple virtual reality system. The goal is to assess whether real humans are also able to accurately estimate a virtual human motion before collision avoidance. Results show that, even through a simple system, users are able to correctly evaluate the situation of an interaction on the qualitative point of view. Especially, in comparison with real interactions, users accurately decide whether they should give way to the virtual human or not. However, on the quantitative point of view, it is not easy for users to determine whether they will collide with virtual humans or not. On one hand, deciding to give way or not is a two-choice problem. On the other hand, detecting future collision requires to determine whether some visual variables belong to some interval or not. We discuss this problem in terms of bearing angle.

**CR Categories:** I3m [Computer Graphics]: Miscellaneous—Perception

**Keywords:** Virtual reality, perceptual evaluation, navigation, collision avoidance

## 1 Introduction

One promising application of immersive virtual environments is the interaction between a real human and a virtual environment in complex tasks. A complex task, that is nevertheless very usual, is navigation in an environment containing moving and reactive obstacles such as humans. Realistic interactions between real and virtual humans in navigation tasks is however a difficult challenge. In this paper, we focus on the problem of collision avoidance: is it possible for a real human to walk in a virtual world shared with virtual



**Figure 1:** The main objective of this paper is to evaluate the information conveyed by an animation of a walking virtual human (right image), with comparison to similar real situations (left image). Our main question is: does the conveyed information allow a real observer to take realistic navigation decision from the visualization of a synthetic walker?

humans and to avoid collisions with them in a realistic manner? To reach such an objective, it is first required to ensure that the real human correctly perceives the information needed for collision avoidance. This information is the visual perception of the virtual human relative motion. A virtual reality system combines several components to provide the real user with the required visual information:

- a *display system* is used to visualize the virtual world.
- a *rendering engine* computes the visual aspect of the virtual world.
- an *animation engine* computes the motion of mobile objects and especially of virtual humans.
- *steering methods* provide virtual humans with autonomy of navigation with respect to their goals, static obstacles and moving obstacles. More important, they must consider the virtual existence of the real user in the virtual world.

The three last components create the visual content of the scene, which are rendered on the display system. They all have to be carefully validated before ensuring a desired level-of-realism of interactions. The presented study evaluates both the visual content and the display system during interactions between a real and a virtual human. Our contribution is to provide a reference evaluation by selecting simple techniques or affordable systems for each of the component of the virtual reality system. Visual display is made through a classical desktop screen, users perceive the virtual world under a first-person perspective. Rendering is performed by an OpenGL-based engine. Virtual humans are animated using a motion-capture edition technique: recorded locomotion cycles are modified to synthesize motion with desired speed and orientation. This technique has been proved to achieve believable motions at low computational costs [Kulpa 2005].

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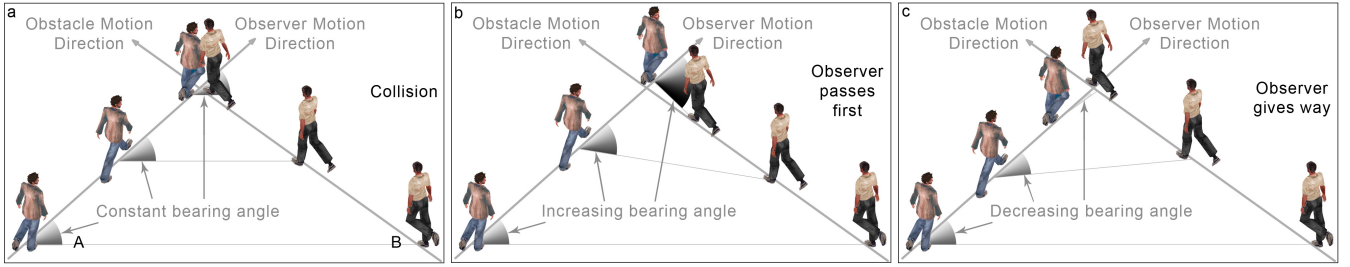
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**Figure 2:** Future collision can be detected by observing the variation of the bearing angle (i.e., the angle between the walking direction and the direction under which another walker is perceived). When the bearing angle is constant, a collision is predicted (a). If the absolute value of bearing angle increases, the observer (A) is likely to pass first (b). When it converges toward zero, he is likely to give way (c) (inspired by Cutting et al. [Cutting et al. 1995]).

In the proposed study, we choose to evaluate the visual content and display. Therefore we decouple perception and action and as a result, no navigation interface is involved. The decoupling of perception and action is however discussed in the paper. Finally, virtual humans are steered by a method that was demonstrated to synthesize realistic global collision avoidance trajectories [Pétré et al. 2009].

Our main objective is to answer the following question: does the displayed visual content allow a real human to react and avoid a virtual human in a realistic manner? This objective is schematically illustrated in Figure 1. In real situations of pair-interactions (i.e., when two walkers avoid each other), humans are capable of avoiding collision.

As a result, visual content and display can be evaluated according to two criteria: first, the conveyed information should allow users to early detect future collisions, and second, users should be able to anticipate their role in interactions.

## 2 Related Work

A fundamental task during human navigation is to avoid collisions with static or moving obstacles to ensure security. This implies interactions between walkers to avoid each other. A challenging question is therefore to understand what is the relevant information they need and how interaction is solved.

**Will there be a collision?** According to Cutting and colleagues [Cutting et al. 1995], two questions have to be successively answered by walkers when confronting a moving obstacle: will a collision occur? In the positive case, when this collision will occur? The first question is answered by parallaxic differential displacements or constancy in one’s gaze movement angle, also called *bearing angle* (i.e., the angle between the walking direction and the direction under which another walker is perceived). Figure 2 illustrates this notion in the case of two walkers. We consider 3 different situations (figures a, b and c) and describe them from the perspective of the walker A. Walker A initially perceives walker B with a given bearing angle. In the situation of Figure 2a, walker A always perceives B under the same bearing angle: a collision is predicted. In the situation of Figure 2b, the absolute value of bearing angle increases (i.e., the gaze’s movement diverges), A will not collide with B and is likely to pass first. Finally, in the situation of Figure 2c, the absolute value of bearing angle decreases (i.e., the gaze’s movement converges): walker A is likely to give way to walker B. The second question (*when collision will occur?*) is answered by determining the time to contact from the optical flow. The optical flow, produced by the motion of an object or an observer, is indeed able to

directly provide information concerning the time remaining before a collision [Lee 1982].

**How to avoid a collision?** Once detected, walkers have to adapt their trajectories to avoid a collision and pass at respectful distance. Despite its obvious relevancy to understand human interaction, collision avoidance strategies were only observed and described recently. Experiments enabled to identify and quantify pair-interactions (i.e., collision avoidance between two walkers) [Crétual et al. 2009; Pétré et al. 2009]. The experimental setup was a  $90^\circ$  crossing between two walkers. A particular distance was considered to classify crossing patterns: the *minimal predicted distance* (*mpd*) was computed at each time step. The *mpd* is the minimal distance (between the centers of the walkers’ body) at which participants would meet in the future if they do not modify their trajectories (speed and heading). Each walker’s trajectory can be linearly predicted as follows:

$$P_{pred}(t, u) = P(t) + (u - t)\vec{V}(t) \quad (1)$$

where  $P_{pred}$  is the predicted position at time  $t$ ,  $u$  the future time ( $u > t$ ),  $P$  the current position, and  $\vec{V}$  the velocity vector.

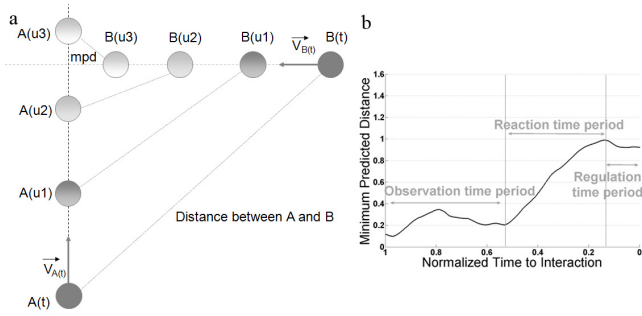
The *mpd* between two subjects A and B is therefore computed from their respective predicted position  $P_{pred,A}$  and  $P_{pred,B}$  as follows:

$$mpd(t) = \min_{u>t} \|P_{pred,B}(t, u) - P_{pred,A}(t, u)\| \quad (2)$$

This linear extrapolation is illustrated on Figure 3a.

*mpd* reflects the collision risk: a low *mpd* value indeed indicates that walkers will collide. *mpd* would vary if and only if at least one walker is adapting his motion. In Pétré et al. [Pétré et al. 2009], avoidance strategies were considered during the interaction: it starts when participants are able to see each other and ends when the actual distance between them is minimal. Motion adaptation was quantified using acceleration. Indeed, participants have a linear motion in absence of any another participant.

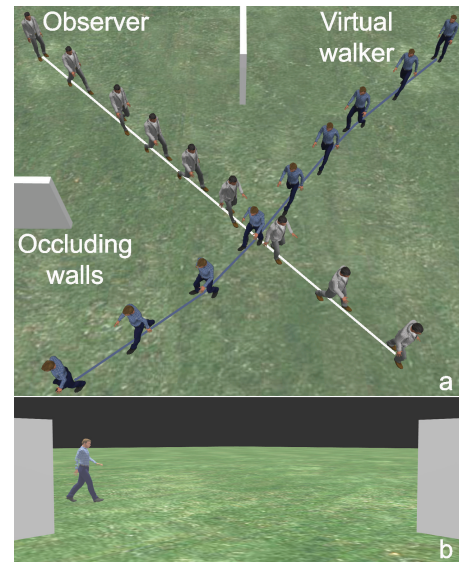
Results showed that participants were able to predict *mpd* since adaptations are observed only for low *mpd* values. The minimal actual distance between participants during each trial was distributed around  $0.8m$  with a minimum value of  $0.5m$ . When *mpd* was higher than  $1m$ , no acceleration was detected. The interaction is made up of three successive steps (Fig. 3b): the *observation step* during which *mpd* remains quite constant and can take low values, the *reaction step* during which *mpd* increases and the *regulation step* during which *mpd* is maintained at a quite constant level, sufficient to avoid collision. This regulation step demonstrates that



**Figure 3:** a) For each time step  $t$ , the velocity vector  $\vec{V}_{Subject(t)}$  of each walker A and B allows to linearly extrapolate their positions for future time  $u$ . *mpd* at time step  $t$  is computed as the minimal distance at which walkers would meet if they do not modify their velocity vector. b) For each crossing, *mpd* can be computed along time to understand walkers adaptations. Three successive steps (observation, reaction and regulation) were identified during interaction according to *mpd* evolution.

collision avoidance is solved with anticipation. An interesting point was that participants' adaptations depend on the crossing order. The participant passing first is the one passing in front of the one giving way. It was observed that the participant passing first makes less effort than participant giving way. He prefers velocity adaptation while the participant giving way prefers a change of heading [Crétual et al. 2009]. These experimental results allowed to construct an egocentric model for solving pair-interactions between virtual humans (see [Pettré et al. 2009] for more details): this model will be hereafter called *Tangent model*. It was mathematically assessed by comparing simulated trajectories to real ones thanks to Maximum Likelihood Estimation technique. However, to allow human interacting with a virtual walker guided by this model, this mathematical validation is not sufficient. Indeed one must ensure that human accurately perceives virtual walker actions.

**Human perception evaluation** Evaluation of human perception can be used to consolidate the validation of our simple virtual reality setup, including the Tangent model. A key approach is to identify fundamental motion pattern. Many applications are performed using anticipating or predictive tasks. During these tasks, the observed motion can be modified or can undergo temporal or spatial occlusions. This highlights key instants or perceptual clues that are relevant for the observer. Eye-tracking systems can also be used to evaluate where observer is looking. Two kinds of methods can then be used to investigate human visual perception [Bideau et al. 2010]. The first method consists in perceptual judgment. It can use video sequences directly recorded [Williams et al. 1994; Jackson et al. 2006] or computer generated with different levels of details [Johansson 1973; Vignais et al. 2009]. Authors take interest in the observer's answers compared to the expected ones if they would have well perceived the observed motion. The second method focuses on perception-action coupling. Authors measure the physical responses of the participant (who is not only an observer but also an actor) to a visual stimulus [Bastin et al. 2008; Bideau et al. 2010]. These two methods can be used to assess the perception of a locomotor model by an observer. Indeed, if an observer is able to accurately anticipate the presented motion, it would mean that model parameters are relevant. Human could therefore interact with a virtual walker guided by the model since human understands the observed actions. Because we want first to investigate if a minimalist equipment is sufficient to well perceive the model, we have chosen to study the judgment task of an observer facing a computer screen.



**Figure 4:** a) Global view of the experimental display for collision and crossing order judgment during a  $90^\circ$  crossing between an observer and a virtual walker. b) First-person point of view of the observer during the experiment.

Previous works on interactions between walkers and the avoidance of moving obstacles allow us to draw several conclusions. Walkers are able to anticipate the trajectory of perceived walkers and to react accordingly. The motion adaptation strategy used to avoid collision between two walkers is role-dependent. We remind that our far-term objective is to enable realistic interactions between real and virtual walkers. It is then required to ensure a real human is able to perceive and anticipate correctly virtual humans' motion. Especially, it is required that the real human is able to answer the two following questions. First, will a collision occur with the virtual human? The answer will determine the existence or the absence of a reaction. Second, am I (the real human) likely to pass first or second? The answer will determine the type of reaction and the avoidance strategy. The following section proposes a method to perceptually evaluate a system composed of: the Tangent model to steer a virtual human, a motion-capture based technique to animate the walking virtual human, and a standard desktop display screen to provide participants with visual information. Our goal is to determine if humans are able to accurately answer these two questions using such a system.

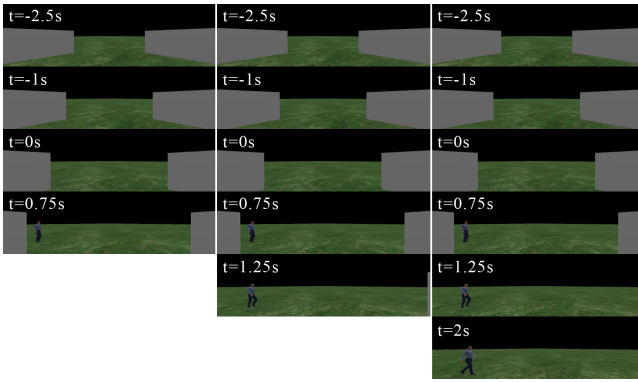
### 3 Method

#### 3.1 Participants

13 men volunteered for this experiment. They gave written and informed consent before their inclusion and the study conformed to the Declaration of Helsinki. They were 30 years old. All had normal or corrected-to-normal vision. They were naive with respect to the purpose of the experiment.

#### 3.2 Stimuli

A two-choice prediction task was developed. Figure 4a illustrates an example of the trajectories followed by the observer and the virtual walker and figure 4b the situation participants could observe at the first-person viewpoint.



**Figure 5:** Snapshot of the three cutoff times 0.75s, 1.25s and 2s (respectively left, middle and right columns) for a 0m  $mpd$ . Time 0s matches the instant when the observer first sees the virtual walker.

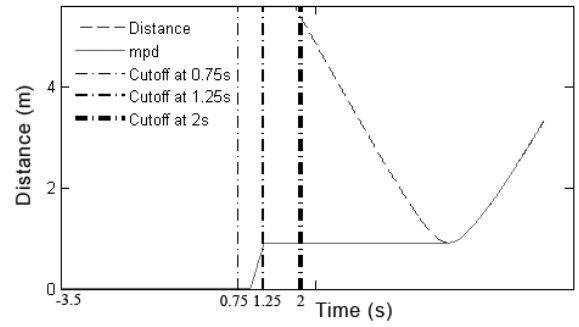
Participants did not steer the avatar but were passive until they had to judge the situation. We investigated their perception of the initial phase of interactions. According to the previous section (*How to avoid a collision?*), decisions about collision avoidance were indeed made during this *observation step*.

**Viewpoint** The viewpoint was at the *first-person* perspective (Fig. 4b). It was set at average human-eye height (1.6m) and was linearly moving at mean human comfort velocity ( $1.3m \cdot s^{-1}$ ) [Öberg et al. 1993; Cavagna et al. 2000]. The view direction was horizontal and headed toward the direction of motion. The horizontal field of view was  $135^\circ$ .

**Virtual human** Instead of using for example a sliding box as a moving obstacle, we chose to animate a virtual human. Indeed, its movement can modify the way its trajectory is perceived by the subject. Since the final goal is to study interaction of between real and virtual humans, having the animation of the virtual character is important. The virtual human was always initially moving along the same path which was orthogonal to the one of the camera. At the beginning of the observer motion, occluding walls prevented the participants to see the virtual human. The virtual human walked at mean human comfort velocity. The initial  $mpd$  value (i.e., the minimum distance between the camera and the virtual human would meet if no adaptation is made) was controlled by changing the initial position of the virtual human. These  $mpd$  values were:  $-1m$ ,  $-0.66m$ ,  $-0.33m$ ,  $0m$ ,  $0.33m$ ,  $0.66m$  and  $1m$ . Note that  $mpd$  has a signed value. The sign allows to take into account the crossing order during interaction. We arbitrarily defined that  $mpd$  is negative when the observer is likely to give way. Conversely,  $mpd$  is positive when he is likely to pass first. When  $mpd = 0m$ , observer and virtual walker converged toward the same point at the same time. Finally note that a collision will occur if no adaptation is made for the following  $mpd$  values:  $-0.33m$ ,  $0m$  and  $0.33m$ . As a result, the situation can be initialized using the existence of collision and the crossing order.

**Reference time** When both the camera and the virtual human started moving, the virtual human was invisible to the participant (because of occluding walls (Fig. 4)). Our reference time was the one when virtual human started to be visible ( $t = 0s$ ).

**Avoidance behavior** The virtual human may adapt or not his own motion to avoid future collision. In half of trials, virtual pedestrian had no motion adaptation: his path followed a straight line.



**Figure 6:** Cutoff times according to  $mpd$  evolution for an initial 0m  $mpd$  when the Tangent model is activated.

For this Straight walking model, there is no motion adaptation and therefore a collision can occur. These trials were then the control set of the experimental setup. In the other trials, virtual walker used a collision avoidance behavior: its role is to compute a motion adaptation allowing the virtual human to pass at respectful distance. Adaptation occurs when  $\|mpd\| < 0.9m$ . This reaction may occur at  $t = 1s$ , value experimentally observed in previous works (see Section 2), which appears to be a sufficient time period to evaluate the situation. To compute motion adaptations, we used the Tangent model based on experimental results on collision avoidance between two real pedestrians [Pettré et al. 2009]. The duration of the adaptation is about 0.2s. Therefore, no collision can occur.

**Cutoff times** We used three cutoff times. First cutoff time was set at  $t = 0.75s$ . This cutoff was then prior to any adaptation (when avoidance behavior is not activated). The second cutoff time was set at  $t = 1.25s$ . This time followed immediately the virtual human's motion adaptations. The third cutoff time was set at  $t = 2s$ , during the regulation step. The resulting sequences the participants could observe are illustrated in Figure 5 for a 0m  $mpd$ . For this initial  $mpd$ , Figure 6 shows the correspondence between cutoff and actual  $mpd$  when the Tangent model is activated.

**Technical details** We used the MKM (Manageable Kinematic Motions) [Kulpa et al. 2005; Multon et al. 2008] animation platform to compute locomotion animation of virtual humans. This animation engine ensures that the virtual walker followed correctly the desired paths and that the resulting motion was free from artifacts such as feet sliding on the ground. We used the Ogre3d engine to render the scene. The scene was made of a textured floor and gray walls (Fig. 4).

### 3.3 Apparatus and Procedure

Test stimuli were presented on a 24inch wide screen. Participants were seated in front of the screen (Fig. 7). Their view was unconstrained and binocular.

There were 84 possible combinations of experimental conditions: 7  $mpd$  values, 3 cutoff times, virtual human reacting or not, coming from the left or the right side. We repeated each condition 3 times. As a result, each participant judged 252 situations. We randomized the order of each situation. There was not temporal constraint to answer questions: next trial was presented once the observer answered all items. No feedback concerning the actual answer was given. The session lasted around 1.5h. Before, a training session was performed, including 12 trials without temporal occlusion. Three  $mpd$  values were randomly chosen ( $-0.33m$ ,  $0m$ ,  $1m$ ) and crossing can be performed on the right or on the left. The vir-



**Figure 7:** Experimental apparatus: participant was seated in front of a 24inch wide screen, observing animated sequences where he crosses a virtual walker.

tual pedestrian trajectory was guided either by the Straight walking model or by the Tangent model. This training session allowed participants to become familiar with the experimental procedure.

Immediately after each experimental trial – corresponding to one of the 84 possible conditions – the following questions were asked to the participant using a graphical user interface, with self-evaluation of their confidence according to a 7-point scale:

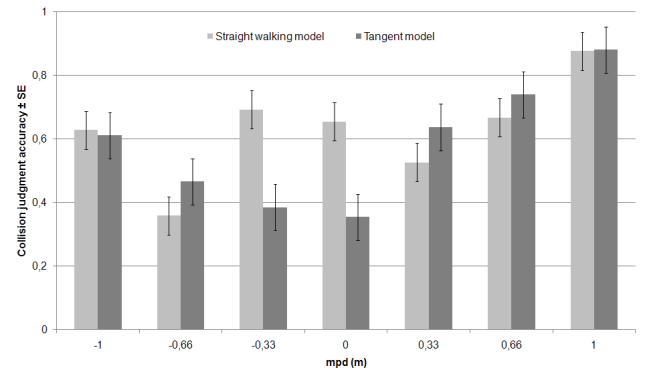
- Will you collide the virtual human?
- Level of confidence: 1 = not at all confident, 4 = moderately confident, 7 = extremely confident.
- Would you pass first or give way?
- Level of confidence: 1 = not at all confident, 4 = moderately confident, 7 = extremely confident.

### 3.4 Analysis

We evaluated the correctness of the participants' answers for each condition. Correct answers are the same for right and left crossings.

Collision distance threshold was set at  $|mpd| = 0.33m$  and  $0m$  since it is the distance between observer and virtual human mid-bodies. Moreover, for  $|mpd| = 0.66m$  no collision occurs according to experimental results [Crétual et al. 2009; Pettré et al. 2009]. Therefore, when the Tangent model is not activated, there is a collision if  $mpd = -0.33m, 0m$  or  $0.33m$  whatever the cutoff time. This is also the case when the Tangent model is activated for these  $mpd$  values if the cutoff is  $0.75s$  since the Tangent model has not yet reacted. Concerning the crossing order, observer gives way when  $mpd < 0m$  and passes first when  $mpd > 0m$  for all situations. For  $mpd = 0m$ , observer cannot determine crossing order when there is no adaptation of the virtual walker. For this reason, we did not take these answers into account. When the Tangent model is activated, observer always gives way for  $mpd = 0m$ .

Dependent variables for both questions were : the ratio of correct judgments and the mean associated confidence rate. Each dependent variable was analyzed into separate three-ways analysis of variance (ANOVA) with repeated measures on the following factors: model,  $mpd$  and cutoff time. Greenhouse-Geisser adjustments to the degrees of freedom were applied, when appropriate, to avoid any violation of the sphericity assumption. When appropriate, Newman-Keuls post-hoc tests were used to further analyze significant effects. T-test were also performed to compare only two conditions.



**Figure 8:** Ratio of correct answers concerning collision detection is influenced by  $mpd$ . There was no difference between both models at the same  $mpd$  except for  $-0.33m$  and  $0m$   $mpd$  values where accuracy for Tangent model is lower.

## 4 Results

Before detailing results, it is important to point out that paired T-tests did not show any difference between Straight walking model and Tangent model conditions for the  $0.75s$  cutoff time for all dependent variables ( $p > 0.05$ ). This indicates a high reproducibility of participants' answers since these conditions are identical for the  $0.75s$  cutoff time (i.e., Tangent model is not yet enabled, Cf. Section 3, Avoidance behavior).

### 4.1 Collision judgment

**Analysis** Correct collision answers were defined using a  $|0.33m|$  collision threshold. In that case, judgment accuracy (i.e., a ratio) was  $0.60 \pm 0.01$  (SE). This ratio was mainly influenced by  $mpd$  ( $F(1.68, 20.16)=9.97, p < 0.005, \eta^2=0.20$ ) as illustrated on Figure 8. Better answers were obtained for a  $1m$   $mpd$  with a judgment accuracy of  $0.88 \pm 0.03$  (SE).

Surprisingly, cutoff time did not influence collision judgment accuracy ( $p > 0.05$ ).

Results showed a very small influence of the model ( $F(1, 12)=6.14, p < 0.05, \eta^2=0.006$ ) with better accuracy for straight walking model ( $M_{Straight}=0.63^1, SE=0.02; M_{Tangent}=0.58^2, SE=0.02$ ). There is also a  $mpd \times$  model interaction ( $F(6, 72)=9.81, p < 0.001, \eta^2=0.07$ ).

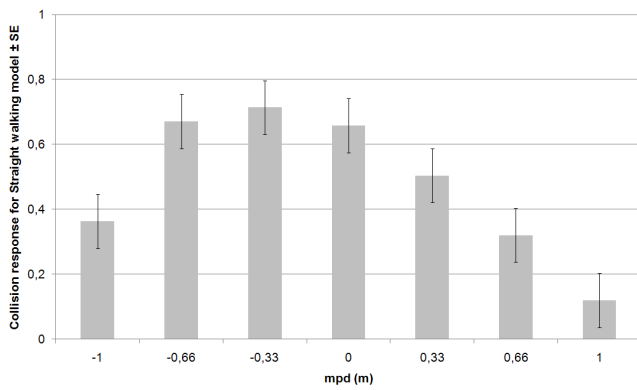
When comparing judgment accuracy for both models at the same  $mpd$  (Fig. 8), results did not show difference except for  $-0.33m$  and  $0m$   $mpd$  values where accuracy for Tangent model is lower ( $mpd=-0.33m: M_{Straight}=0.69, SE=0.05; M_{Tangent}=0.38, SE=0.05; mpd=0m: M_{Straight}=0.65, SE=0.05; M_{Tangent}=0.35, SE=0.03$ ).

Let us denote that this judgment accuracy did not differ from the one, computed with a  $|0.66m|$  collision threshold, that is  $0.58 \pm 0.01$  (SE)( $t=1.67, df=545, p=0.09$ ).

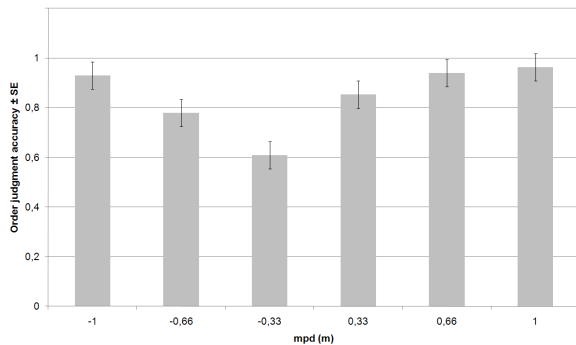
**Interpretation** Results showed that collision judgment accuracy was not influenced by cutoff time. It indicates that participants quickly estimate the current situation. However, in such an experimental situation the evaluation task was difficult. One can incriminate experimental instructions since no particular definition of collision was given to participants. Our criterion for collision

<sup>1</sup>Mean value for Straight walking model

<sup>2</sup>Mean value for Tangent model



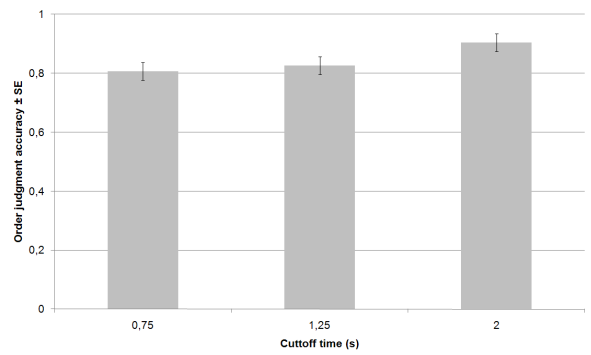
**Figure 9:** Perceived collision for Straight walking model according to *mpd*. 1 indicates that participants always detect a collision while 0 indicates that participants never detect a collision. Higher risk of collision is perceived for *mpd* values ranging from  $-0.66m$  to  $0.33m$ .



**Figure 10:** Order response accuracy according to *mpd*. Lower accuracy was obtained for  $-0.66m$  and  $-0.33m$  *mpd* values.

classification depending on *mpd* value threshold ( $|0.33m|$ ) maybe does not match personal space of observers (i.e., a protective zone that allows enough time to perceive potential risks and to plan and perform necessary adaptations [Templer 1992]). To answer this assumption, we considered the perceived collision (without the notion of correct answer) in straight walking condition (Fig. 9). As expected, this variable depends on *mpd* ( $F(1.70, 20.45)=15.36$ ,  $p<0.001$ ,  $\eta^2=0.38$ ). Perceived collision can allow us to refine security distance in this experimental situation: participants feel threaten for *mpd* values ranging from  $0.33m$  behind to  $-0.66m$  in front. This result suggests that observer takes a notion of personal space into account. This space is asymmetric and leaves more room empty of any obstacle in front of the observer. This result must be taken into account for future analysis.

No difference was observed when the Tangent model is activated or not for identical *mpd* values, except for  $-0.33m$  and  $0m$ . In such cases, collision accuracy for Tangent model surprisingly decreases. It should be noted that in fact we compared on Figure 8 correct answers that are different between both models: for *mpd* =  $-0.33m$  and  $0m$ , collision and no collision are correct answers respectively for Straight walking model and Tangent model. For example when *mpd* =  $-0.33m$ , observer's answer 'yes, there is a collision' in around 70% of concerned trials. This is almost the same answer percentage for Tangent model concerned trials. This shows again that observers quickly get a judgment which is moreover persistent.



**Figure 11:** Order response accuracy according to temporal occlusion. The higher the cutoff time, the better the correct answer.

## 4.2 Crossing order judgment

**Analysis** Participants answered correctly the question about crossing order. Accuracy was  $0.84 \pm 0.01$  (SE): this result is better than for collision judgment ( $t=13.53$ ,  $df=1012$ ,  $p<0.05$ ). Order accuracy was influenced by *mpd* ( $F(1.22, 14.67)=11.96$ ,  $p<0.005$ ,  $\eta^2=0.29$ ) (Fig. 10). Lower accuracy was obtained for  $-0.66m$  and  $-0.33m$  *mpd* values when observer actually gave way to the virtual pedestrian with a higher perceived risk of collision.

Order response accuracy is also influenced by temporal occlusion ( $F(1.38, 16.6)=21.95$ ,  $p<0.001$ ,  $\eta^2=0.03$ ) (Fig. 11). The higher the cutoff time, the better the answer accuracy. Even for  $0.75s$  occlusion answer accuracy is still good ( $M_{0.75s}=0.81$ ,  $SE=0.02$ ).

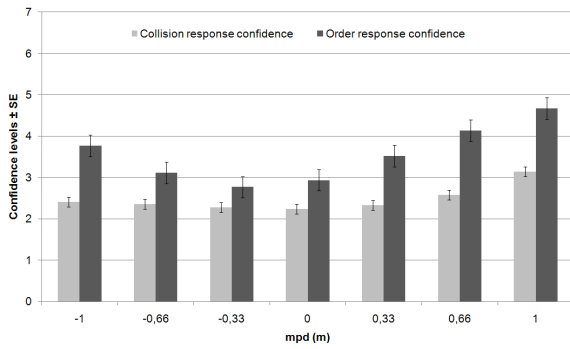
Results did not show any influence of the Tangent model activation ( $p=0.06$ ).

**Interpretation** Participants were able to accurately detect crossing order in this experimental setup. This is very interesting since it was shown that crossing order was a fundamental parameter linked to the collision avoidance strategy (Cf. Section 2, *How to avoid a collision?*). Even though temporal occlusion slightly influences judgment accuracy, this latter remains high (more than 80%). Therefore, the necessary information seems to be quickly available for participants. The model did not influence order judgment accuracy. Lower accuracy was found for  $-0.66m$  and  $-0.33m$  *mpd* values for both models. These values seem to be a critical threshold for visual perception of interaction between observers and the virtual walker. However, although the Tangent model can interfere with collision judgment accuracy for  $-0.66m$  and  $-0.33m$  *mpd*, order judgment accuracy is not modified when the Tangent model reacts compared to the Straight walking one.

## 4.3 Confidence

**Analysis** Confidence level concerning collision judgment was  $2.47 \pm 0.04$  (SE). This level was influenced by *mpd* ( $F(2.20, 26.44)=7.35$ ,  $p<0.001$ ,  $\eta^2=0.14$ ). Only confidence for  $1m$  *mpd* was higher than other values (Fig. 12). Contrary to collision judgment accuracy, participants' collision confidence depends on temporal occlusion ( $F(1.09, 13.12)=22.88$ ,  $p<0.001$ ,  $\eta^2=0.18$ ). Confidence level increased with cutoff time ( $M_{0.75s}=2.1$ ,  $SE=0.2$ ;  $M_{1.25s}=2.5$ ,  $SE=0.2$ ;  $M_{2s}=2.9$ ,  $SE=0.2$ ). There was no influence of the model on this confidence level ( $p=0.5$ ).

Confidence level concerning crossing order judgment was:  $3.56 \pm 0.05$  (SE). Participants were quite more confident for crossing order than for collision judgment ( $t=15.68$ ,  $df=1090$ ,  $p<0.01$ ). This



**Figure 12:** Confidence level for collision and crossing order judgments according to  $mpd$ .

level was influenced by  $mpd$  ( $F(1.78, 21.34)=15.85$ ,  $p<0.001$ ,  $\eta^2=0.35$ ). Confidence was higher when  $mpd$  was  $-1m$ ,  $0.66m$  and  $1m$  (Fig. 12). As for collision confidence, crossing order confidence is influenced by temporal occlusion ( $F(1.56, 18.70)=19.03$ ,  $p<0.001$ ,  $\eta^2=0.09$ ;  $M_{0.75s}=3.2$ ,  $SE=0.2$ ;  $M_{1.25s}=3.6$ ,  $SE=0.2$ ;  $M_{2s}=3.9$ ,  $SE=0.2$ ). The model also influenced this variable ( $F(1, 12)=19.51$ ,  $p<0.001$ ,  $\eta^2=0.01$ ), with higher level for Tangent model ( $M_{Straight}=3.4$ ,  $SE=0.2$ ;  $M_{Tangent}=3.7$ ,  $SE=0.2$ ).

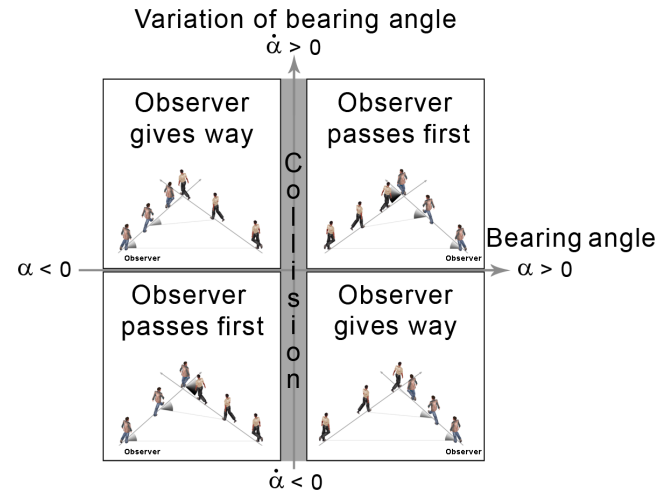
**Interpretation** Participants have low self-confidence either for collision or crossing order. Crossing order confidence is quite higher than the collision one but remains still weak. Nevertheless, it is associated with fine judgment accuracy. Therefore, participants may not be aware of the relevant information that allows them to provide appropriate answers. This result may challenge the use of questionnaire for perception judgment since observers are not necessarily aware of their answers accuracy. It is worth pointing out that confidence can be linked to perceived personal space. Indeed, they are more confident, particularly for crossing order judgment, when  $mpd$  is equal to  $-1m$ ,  $0.66m$  or  $1m$ , i.e., when the virtual pedestrian is out of this perceived personal space.

## 5 Discussion

The main objective of this paper is to evaluate a very simple visual content and display in the context of collision avoidance between an observer and a virtual walker. This objective can be seen as a preliminary stage to provide realistic interaction between real and virtual humans. Visual content and display were evaluated on two points: the ability of observers to detect a collision and to anticipate their role in collision (i.e., passing first or giving way).

Results showed that judgment of crossing order was easier than for collision detection when an observer is in front of a simple display. Crossing order implies different collision avoidance strategies between two real walkers [Crétual et al. 2009; Pettré et al. 2009]: role in interactions are then correctly anticipated. Therefore we can assume that this display modality allows users to perceive the right kind of reaction but not the appropriate quantity of adaptation. This difference can be explained by studying bearing angle. In fact, relative motion between the observer and a moving obstacle can be defined by the bearing angle  $\alpha$  and its derivative  $\dot{\alpha}$ . A collision would be detected when  $\dot{\alpha}$  is close to zero, under a threshold (Fig. 13). Observers have then to accurately determine whether  $\dot{\alpha}$  is equal to this value. On the contrary, the crossing order depends on the sign of both  $\alpha$  and  $\dot{\alpha}$ . When their signs are equal, observer passes first and conversely when their signs are opposite observer gives way to the virtual walker. Crossing order judgment results then in determining

the quadrant matching the actual situation (Fig. 13). Moreover,  $\dot{\alpha}$  value depends on the display scale whereas its sign is independent from this scale. In our experiment the scale is lower than 1. One can imagine that the evaluation of  $\dot{\alpha}$  could be more difficult in such a situation whereas its sign could be well estimated.



**Figure 13:** Bearing angle ( $\alpha$ ) can explain that judgment of crossing order was easier than collision detection. Collision is identified only if observer can accurately determine that  $\dot{\alpha}$  is close to zero. It matches a very restrictive zone. On the contrary, crossing order judgment depends on the sign of both  $\alpha$  and  $\dot{\alpha}$ . It results then in determining the quadrant matching the actual situation.

Experimental procedure could be refined to increase the accuracy of our results. For example, it could be interesting to control the viewpoint of the subject by using a chin rest. This could ensure that the rendered horizontal field of view maps the one of the subject. However the goal of this experiment is to evaluate the use of a simple device so we did not want to use a chin rest and this head-locking is not in accordance with theories in favor of an active role of the head during locomotion [Grasso et al. 1996; Prévost et al. 2003]. Instead of mapping the horizontal field of view of the display with the one of the subject, we prefer to extend it to allow a kind of peripheral vision. But at last, it is this combination of the monitor and the large field of view of the display that we evaluate.

Participants felt threaten for  $mpd$  values ranging from  $0.33m$  behind to  $-0.66m$  in front. We can wonder whether these values depend on experimental settings such as velocity of the observer. Nevertheless, it was shown that velocity does not influence personal space dimensions during obstacle circumvention while walking [Gérin-Lajoie et al. 2007]. Results could then be refined by taking into account perceived security distance for collision judgment accuracy thresholds. This care may also prevent from problems linked with distance misperception. Even if our device did not use stereovision, perceived security distances are nevertheless close to the ones observed in real situations [Gérin-Lajoie et al. 2005; Cinelli and Patla 2007].

We have chosen to use a first-person viewpoint. In that case, observer does not explicitly see his body shape. The observer can therefore lose some clues about his own motion; for example he has no idea about his stepping activity. It would then be interesting to use several viewpoints such as an other subjective view – an improved first person viewpoint for which observer can see his limbs or a third person one for which the observer stands back behind his avatar – or a topographic view. This can obviously help us to determine the best viewpoint for interaction and immersion but also the



most suitable viewpoint for locomotion model assessment.

As explained above, our setup allows user to perceive the right kind of reaction but not the appropriate quantity. To estimate this quantity, it will be important to integrate perception-action coupling in future experiments. In a first stage, action could be obtained by the use of a 'metaphor' such as a joystick: the user would not be only an observer but also an actor controlling his trajectory with this device. Action can also be directly measured using a head-mounted display (HMD). Locomotor adaptations would be investigated with a motion capture system. Using a HMD may also increase observer's immersion and make perception easier. Indeed, it allows viewpoint adaptation: display moves according to head motion. This would be in accordance with 'real life' behavior. In such a case, locomotion is associated with a 'go where we look' strategy with an active role of head orientation that provides a reference frame for the control and the body reorientation [Grasso et al. 1996; Prévost et al. 2003]. Head motion would then be implied in perception and action process. Note that the use of immersive environment using HMD to study steering behavior and the avoidance of stationary obstacle for human locomotion has previously been studied [Fink et al. 2007]. Similar path shapes in real and virtual worlds suggest very promising applications of virtual environments to study locomotor behavior. At last to both improve perception and measure action, the use of immersive environment coupled with an omni-directional treadmill, as the 'CyberCarpet' developed in the European CyberWalk Project, should be a very interesting experimental design.

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