Collision Avoidance in the Presence of a Virtual Agent in Small-Scale Virtual Environments

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Abstract

Computer-controlled, human-like virtual agents (VAs), are often embedded into immersive virtual environments (IVEs) in order to enliven a scene or to assist users. Certain constraints need to be fulfilled, e.g., a collision avoidance strategy allowing users to maintain their personal space. Violating this flexible protective zone causes discomfort in real-world situations and in IVEs. However, no studies on collision avoidance for small-scale IVEs have been conducted yet.

Our goal is to close this gap by presenting the results of a controlled user study in a CAVE. 27 participants were immersed in a small-scale office with the task of reaching the office door. Their way was blocked either by a male or female VA, representing their co-worker. The VA showed different behavioral patterns regarding gaze and locomotion. Our results indicate that participants preferred collaborative collision avoidance: they expect the VA to step aside in order to get more space to pass while being willing to adapt their own walking paths.

Index Terms: H.5.1 [Multimedia Information Systems]: Artificial, Augmented, and Virtual Realities—Evaluation/Methodology

1 Introduction

Nowadays, virtual agents (VAs), computer-controlled human-like representations, are embedded in virtual environments (VEs) for two reasons: (1) They can enliven an architectural scene by representing more realistic situations, and (2) VAs can function as assistants, e.g., to guide users through an immersive VE (IVE) or by performing certain tasks within the IVE either individually or in collaboration with a user. McGlashan showed the benefit of VAs as a dialogue counterpart and a speech interface used to control the VE [13]. System commands like deleting or coloring objects can be given to a VA, while the progress of the initiated operation can be shown by synthesized speech answers. Furthermore, Bowman et al. [5] state the benefits of VAs as a 3D user interface. VAs can manipulate virtual objects directly without the need for specific interaction techniques addressing the user's needs.

To successfully facilitate the use of VAs, various requirements have to be met for their implementation. Relevant factors are challenges due to the uncanny valley [15] or the concept of the personal space (PS) [11]. The PS describes a flexible protective zone maintained around one's own body in real-life situations [9]. It has been shown that this concept is also applicable to virtual reality scenarios, e.g., users keep a PS around their own representation in Second Life [8] and keep smaller distances to virtual objects than to virtual humans (VHs) [2]. Here, a VH is defined as a model that looks and behaves like a real person, while a VA characterizes a computer-controlled VH, a virtual embodied agent.

The size and shape of the PS depends on different personal factors like age and gender [1] or environmental factors like obstacle movements [10] or gaze behavior [3]. The PS is typically shaped elliptically with about twice as much space in one's front area compared to one's back and sides [1]. Additionally, the PS can be divided into four segments differing in the distance from the user, reflecting the type of relationship to other persons. Thus, the PS is also considered as a non-communication channel [1].

The PS of users were examined in several studies. In Bailenson et al. [3], users were immersed using a head-mounted display (HMD) in an empty virtual room containing a male VA. The VA showed five different gazing behaviors from closed eyes to realistic gaze with blinks, head turns and pupil dilation. As control condition, a cylinder with the same width and height as the VA was shown. All participants had to remember certain features of the VA and labels on his front and back side. Results indicate (a) that participants maintained more PS to the VA showing more realistic gaze behavior than to the VA who did not or to the control cylinder, (b) the PS was slightly larger in front of the VA compared to the back, and (c) a significant correlation between the PS and the gaze behavior for women was found. The study was extended in [4]. Here, a male and a female VH were shown, either as VA or as human-controlled avatar. Repeating the memory task showed that participants keep a greater distance from VHs when approaching their fronts compared to their backs. Additionally, more PS was maintained to VAs engaging in mutual gaze. In a second study condition, the VH approached the standing participant. Here, participants moved farther away from the approaching VA than from the avatar.

In a study conducted in a CAVE, participants had to pass a human or a box with the same dimensions [2]. Both were either real or virtual representations. Furthermore, their orientation was changed (front, back, profile). The results show that participants walked more slowly in case of the virtual representations and kept more distance to the VA. Additionally, the PS's elliptical shape could be shown, while there was no difference in the front and back space.

A result of these studies is that violating the PS will lead to negative user reactions [4, 17]. Thus, people always try to avoid collisions and to maintain their PS. This was also shown in studies not focusing directly on the PS. Two people whose trajectories cross in real-life scenarios do a collaborative collision avoidance: both adapt their paths while participants giving way also decrease speed [14]. Fajen et al. recorded immersed participants while walking in the presence of a virtual, cylindrical obstacle from an origin to a target [7]. It was shown that participants kept an approximately linear path towards their target combined with gradual turns to avoid the obstacle. Here, their turning rate was influenced by their distance to the target and by the obstacle's angle.

The test scenes are mostly large-scale IVEs containing only one VH. Thus, maintaining the PS without colliding with other scene geometry is easy. Research taking more objects into account are, e.g., crowd behavior studies. Here, decisions on when to go around or through a group of VAs are investigated, indicating group density, moving direction and crowd type as basic parameters [6].

To our knowledge, there is no work investigating the collision avoidance in context of small-scale, information-rich environments. Here, several questions arise, e.g., how users react if their ways are blocked by a VA and the maintenance of their own PS would result in a scene collision. Another question is whether users expect the VA to collaborate in a collision avoidance or to even do it entirely.

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(a) (b) (c)

Figure 1: The virtual office which had to be crossed from the green to the red dot (a) and the embedded female (b) and male (a) VAs.

Our goal is to answer those questions and to provide a further building block for a good collision avoidance implementation in IVEs. As a first step, we conducted a user study, described in Section 2, investigating users' reactions while passing a VA showing different behaviors in a small, fully furnished virtual office. The results are presented in Section 3 and discussed in Section 4. A conclusion is given in Section 5.

2 Study

The goal of this study is to investigate the collision avoidance strategies of a human user in a small, information-rich IVE in a CAVE. To gather the relevant insights, the study's task was to pass a VA by physical walking through a narrow passage. We measured the paths taken by participants, and the social presence of the VAs, discussed in detail below. We expected the following hypotheses to be confirmed:

H1: The VA's gender will not influence the results.

H2: (a) In case of mutual gaze, participants will be more comfortable with the VA stepping aside.
(b) In case of the VA focusing his/her desk, participants will be more comfortable with the VA stepping aside.

H3: In case of the VA focusing the board, participants will have no preference between the VA standing still or stepping aside.

H4: If VAs are included meaningfully into the scene (here: by working), participants do not expect them to step aside.

H5: If possible, participants avoid crossing the VA's view.

2.1 Apparatus

We used a five-sided CAVE with the size $5.25m \times 5.25m \times 3.30m$ ($w \times d \times h$) providing a 360° horizontal field of regard. The participants wore active stereo glasses, tracked at 60 Hz and an ART Flystick 2 was provided for interaction. Additionally, the CAVE is equipped with a loudspeaker and microphone array as well as two security cameras. This allowed the supervisor to converse with and to observe the fully immersed participant if needed.

2.2 Virtual Environment and Task

To be consistent with most relevant work, the participants should be able to navigate through our small, information-rich IVE by natural walking. Thus, we modeled a two-person office, adapted to the CAVE's footprint (see Figure 1(a)). The office has a detailed and well-considered interior design. This comprises two fully equipped desks that let only a small passage open, which leads from one desk to the office door (see Figure 1(a)). The vertical aligned desk is considered to be the participant's desk, while the horizontal aligned one is the desk of a VA. The VA is introduced as computer-controlled co-worker, who is either represented by a female or a male SmartBody character shown in Figure 1(b) and (c) [12].

In the study, the participants were asked to walk without any detours from a green dot located on the floor behind their desk to a red dot in front of the office door (see Figure 1(a)). During the different runs a VA blocked their way by standing between the two desks, as shown in Figure 1(b) and (c). The VA showed different behavioral patterns (same behavior across VA's gender) described in the next paragraph. The locomotion, gazing and idle states used for animation were provided by SmartBody [12].

(a)	participant
no VA	C1
VA	*see (b)*

(b)	f_{mGaze}	f_{board}	f_{desk}
m_{stand}	C2	C5	C7
m_{step}	C3	C6	C8
m_{walk}	C4		

Table 1: Assignment of conditions to variables: (a) VA conditions. (b) VA conditions for g_{male} and g_{female}.

2.3 Experimental Design

We chose a within-subject design with three dependent variables: (a) The VA's gender is altered between female (g_{female}) and male (g_{male}), (b) the VA either looks at the participant for mutual gaze (f_{mGaze}) or focuses on objects simulating a working behavior (whiteboard (f_{board}) or monitor (f_{desk})); by this, participants either approach the VA's front, its side or its back and (c) the VA's locomotion alters between standing still (m_{stand}), stepping aside (m_{step}), and walking to the cupboard (m_{walk}) when the participant approaches.

Combining f and m leads to seven conditions (C2-C8) listed in Table 1(b), each tested for g_{male} and g_{female}. Furthermore, a control condition without any VA (C1) is added as preliminary baseline measurement (see Table 1(a)). This results in 15 test cases.

2.4 Procedure

Participants were informed about the general procedure of the study and gave their informed consent. After filling out a demographic questionnaire, they entered the CAVE for a training. One of the VAs waited for them in the CAVE's center. The participants were asked to freely move around the VA without a time limit in order to get familiar with him or her. After finishing the inspection, the participants switched to the second VA for a familiarization under the same conditions. Afterwards, both VAs were shown side-by-side for a final inspection.

Afterwards, the task began. The execution was divided into 15 blocks, each containing four physical walks through the office under one of the 15 test cases. Each block was followed by a set of 7-point Likert scale items in the IVE which had to be answered by using the Flystick. The control condition C1 was always tested first. Afterwards, the conditions C2, C3 and C5 to C8 for g_{male} and g_{female} (12 test cases) were tested in a randomized order. Each block was followed by the Social Presence Survey (SPS) questionnaire [3] and items addressing the VA's behavior. As we had some unpredictable technical problems with C4, it was always tested last, alternately for g_{male} and g_{female}, to not falsify the previous test case results. Both blocks were followed by the same items as before.

After leaving the CAVE, participants filled out a final questionnaire containing the SUS presence questionnaire [16] as well as some questions regarding preferences for the VA's gender and behavior. Finally, all participants attended a semi-structured interview to gather qualitative information on their experience during the task.

In total, the study took about one hour per participant, from which about 35 minutes were spent fully immersed.

2.5 Participants

27 volunteers (23 male, ages M=27.48, SD=4.28) participated in the study. As incentive, two prices (one meal, one beverage) were awarded to two random participants. All participants had used a CAVE before (seven of them only for a short time, e.g., in campus demos) and sixteen worked professionally in a field related to virtual reality. Nine stated that they had already experienced VAs in IVEs. All of the participants had normal or corrected-to-normal vision and normal motor skills. All participants were naïve to the purpose of the study.

	1^{st} *sample*			2^{nd} *sample*		*p*
cond.	*M*	*SD*	*cond.*	*M*	*SD*	
C2	9.944	2.942	C3	10.463	3.255	.144
C5	4.982	2.987	C6	7.592	7.593	**<.001**
C7	3.611	3.147	C8	6.167	6.167	**<.001**

Table 2: Row-wise results of paired-samples t-tests on mean SPS score, with significances marked in bold.

3 Results

For the standardized questionnaires SUS [16] and SPS [3], the proposed scales (7-point scale and 7-point Likert scale from -3=strongly disagree to 3=strongly agree) were used. Our own items had to be answered on a 7-point Likert scale. If not stated differently, they had the rating scale from 1=strongly disagree to 7=strongly agree. For all tests a significance level of 0.05 was used.

The mean SUS score for the reported sense of feeling present in the IVE was M=4.51 (SD=.749), which indicates a reasonably high level of presence [16]. After conducting C1, participants judged whether the virtual office was suitable regarding size and equipment as a two-person office, which they agreed on (M=6.00, SD=.981). Additionally, they judged whether they could reach the office door easily by means of physical walking while avoiding collisions with the scene geometry, which they also agreed on (M=6.78, SD=.49). After the task was finished under all conditions, they judged which VAs they preferred, resulting in the female one (rating scale 1=female, 7=male, M=2.26, SD=1.24).

In order to have a consistent terminology throughout the study, we adapted the SPS questionnaire [3] by replacing "person" by "co-worker" in the items if applicable. Furthermore, their score was computed per condition and per VA's gender. For the evaluation, we performed a three-way ANOVA regarding the three dependent variables locomotion m, focus f and gender g. When appropriate, Tukey's HSD post-hoc tests were used to analyze significant effects. No interaction effects between the variables could be shown, thus the SPS scores for male and female VA are pooled for the subsequent statistics. However, there were significant differences regarding the locomotion m and the focus f, but not for the gender g ($F_{1,312}$=.308, p<.579). For m ($F_{1,312}$=26.566, p<.001) there was a significant difference between m_{stand} (M=6.18) and m_{step} (M=8.07), indicating participants preferred m_{step}. For f (f_{mGaze}: M=10.20, f_{board}: M=6.29, f_{desk}: M=4.89), the following pair-wise significant differences with $F_{2,312}$=63.907 occurred: f_{mGaze} and f_{board} (p<.001), f_{mGaze} and f_{desk} (p<.001) and f_{desk} and f_{board} (p=.005).

Question two of the SPS (SPS2) asks whether participants feel that the co-worker is watching them and is aware of their presence [3]. However, in conditions C6 and C8 the awareness is only given by a side-step while the VAs focus on scene objects instead of the participant. To examine potential differences between the scores with and without SPS2, the answers to SPS2 of those two conditions were pooled and examined by a one-sample t-test, showing no significant difference in the mean M=.11 (p=.499).

Considering Table 1, the SPS score is next examined column-wise for m_{stand} and m_{step}, by paired-samples t-tests resulting in two significant effects shown in Table 2. Furthermore we grouped the "working" behaviors regarding variable m. An independent samples t-test for C5 and C7 versus C6 and C8 resulted in no significant differences (p=.053).

Participants were also asked to judge the VAs' behavior in five items. For the evaluation, we used non-parametric statistics, to reflect the ordinal character of the item responses. The corresponding distribution of answers and medians is shown in Figure 2.

Items Q1–*I felt uncomfortable passing my co-worker on my way to the office door.*– and Q2 –*I wish there would have been more space between my co-worker and me while passing.*–had to be answered after each condition except C1. For both, we performed independent

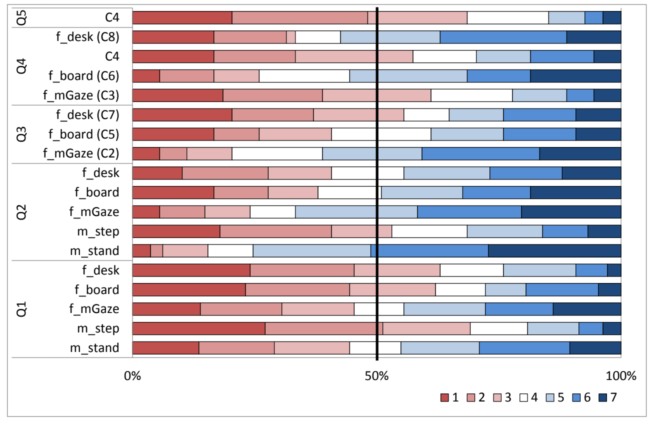


Figure 2: Answers for Q1 to Q5 evaluated regarding the variables m and f (Likert Scale range 1=strongly disagree, 7=strongly agree).

samples Mann-Whitney U tests. For Q1 regarding m, we found a significant difference (p<.001) between the medians 4 for m_{stand} and 2 for m_{step}. Furthermore, there was a significant difference in f (p=.002) between the medians 4 for f_{mGaze} and 3 for f_{board} as well as for f_{desk}. For Q2, a significant difference (p<.001) between the medians 6 for m_{stand} and 3 for m_{step} was shown. Additionally, f had a significant difference (p=.007) between the medians 5 for f_{mGaze} and 4 for f_{board} as well as for f_{desk}.

Item Q3–*I've expected my co-worker to step aside to let me pass.*–had only to be judged for the m_{stand} conditions (C2, C5, C7). Here, a related-samples Friedman's two-way ANOVA by ranks showed no significant differences (p=.114) between the medians 5 for f_{mGaze}, 4 for f_{board} and 3 for f_{desk}. However, conducting the same test on the m_{walk} conditions (C3, C6, C8) for Q4–*I've expected my co-worker to stay in place.*–showed a significant difference (p=.007) between the same medians. Including the scores given for this item in C4 even showed a higher significance (p<.001).

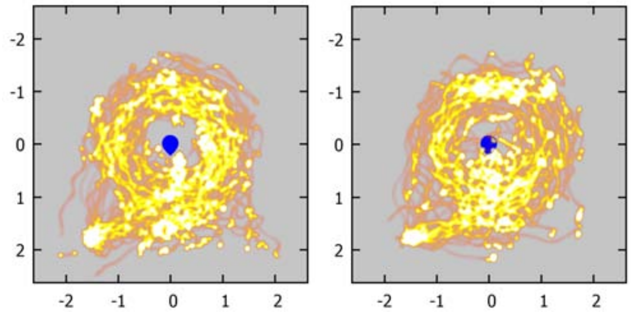
Last, item Q5–*I liked that my co-worker walked to the cupboard in order to let me pass*.–was only asked after C4. The median is 3.

4 Discussion

The virtual office was considered to be suitable and realistic. Thus, we assume that the participants behaved similar to real-life situations. Furthermore, as participants had sufficient space to reach the door in the empty office, following statements regarding discomfort due to too little space can be traced back to the presence of the VAs.

The results concerning the influence of the VA's gender on the outcome of this study supports **H1**, as no interaction or main effects on the SPS score could be found. However, participants judged to prefer the female VA. This is also reflected in the routes participants took in the training, shown in Figure 3. Most participants were virtual reality experts, supposedly with a strong interest in the modeling and animation of the character. However, they kept more distance to the female (see Figure 3(a)), while the male VA was approached very closely (see Figure 3(b)). Besides, a spherical PS for the female VA appears in outlines. Based on results in the literature, we assume that the female was considered to be more human than the male.

In the conditional runs, however, the statistical analysis shows no preference for the female VA. Instead, participants kept as much space as possible to both VAs while avoiding to collide with scene objects. Facing questions regarding the reason for the subjective preference, participants often stated that the male's facial expression was unsightly. Compared to the female, he was not blinking due to a technical problem occurring during the study, resulting in an uncomfortable stare. This was considered to be "aggressive" or "scary". However, only about half of the participants commented on having noticed the missing eyelid movement when the supervisor told them about it.



(a) Female VA (b) Male VA

Figure 3: Participants' routes around the VAs (marked by), visualized as heat maps (normalized to [0,1], linear color mapping gradient from black for the smallest value (0), over red (1/3) and yellow (2/3) to white (1)). The axes' ticks represent meters.

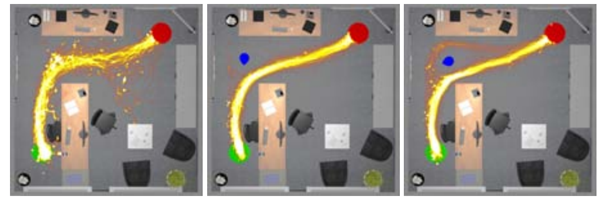
H2 to **H4** concentrate on the different agents' gaze behaviors f in combination with the locomotions m. We could find no interaction effects, so both variables can be considered to influence the results individually. In general, participants preferred the VA to step aside giving more space to pass and by this to collaborate in the collision avoidance. Furthermore, participants stated in the interviews that they would have liked even more space. Passing a stranger so closely was considered to be unpleasant, supporting the assumption that the distance kept to someone reflects the relationship type [1]. Further questions regarding the collision avoidance were answered in two ways: about half of the participants expected a collaborative collision avoidance, while the rest always expected the VA to not hinder the user. However, only few participants liked the VA to go to the cupboard to give more room for passing (C4). Due to technical problems regarding the walking animation, we cannot make valid assumptions why C4 was rated negatively. We assume the reasons to be the huge overlap of the VA's and the user's route as well as the confined space at the door.

No significant difference between the two locomotion types in the mutual gaze behavior could be shown, contradicting **H2a**. In case of the VA focusing the desk, stepping aside was clearly preferred, confirming **H2b**. Here, participants understood the side step as a sign that the VA is aware of their presence. However, they would have liked the VA to look at them before moving. Due to this, we argue that **H2a** was not confirmed, as the VA was obviously aware of the user. This reduces the risks of, e.g., a sudden movement onto the adapted users' trajectory, leading to more confidence while passing.

Participants preferred the side step while the VA was looking at the whiteboard, contradicting **H3**. We assume that only being visible in the peripheral view of a stranger was no assurance of being perceived by the VA. This is supported by a participant's comment that he would have been ok with the standing VA if he knew him or her better. The same is true for **H4**. This hypothesis cannot be confirmed either, as participants preferred the side step.

H5 can only be confirmed for the working behaviors. In the mutual gaze conditions, going around the VA to avoid crossing its view was considered a detour and only done rarely (see Figure 4 (b)). However, more participants surrounded the VA in the working behaviors as shown exemplarily in Figure 4 (c). They tried to evoke another behavior compared to the last run of the same block by crossing the view intentionally. However, as participants stated in the interview, they felt uncomfortable and did not repeat it after getting the same reaction.

Based on the results presented above users seem to prefer VAs who react on the user's presence while bearing prime or at least partial responsibility for collision avoidance. Thus, we recommend to introduce a VA "awareness zone": VAs should gaze towards users entering this awareness zone before stepping aside to maintain the integrity of the user's PS.



(a) Condition C1 (b) Condition C3 (c) Condition C5

Figure 4: All 54 runs from green to red, pooled for male and female VA, visualized as heat maps. shows the final position of the VA.

5 Conclusion

In this article, we presented an evaluation of users' reactions on different behaviors shown by a VA blocking the users' way in a small-scale, information-rich IVE. Based on the results we recommend an awareness zone for VAs fulfilling the needs for a VA who noticeably reacts on the user's presence while taking responsibility for or at least collaborating in collision avoidance due to the user's PS requirements.

In future work, we want to investigate the influence of the human user's gender on the results. Furthermore, we want to evaluate the idea of an awareness zone in scenarios in which physically walking as well as flying is used for navigation.

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