



HAL
open science

Collision avoidance behaviours of young adult walkers: Influence of a virtual pedestrian's age-related appearance and gait profile

Sheryl Bourgaize, Michael Cinelli, Pierre Raimbaud, Ludovic Hoyet,
Anne-Hélène Olivier

► To cite this version:

Sheryl Bourgaize, Michael Cinelli, Pierre Raimbaud, Ludovic Hoyet, Anne-Hélène Olivier. Collision avoidance behaviours of young adult walkers: Influence of a virtual pedestrian's age-related appearance and gait profile. SAP 2024 - ACM Symposium on Applied Perception, Aug 2024, Dublin, Ireland. pp.1-10, 10.1145/3675231.3675233 . hal-04681163

HAL Id: hal-04681163

<https://inria.hal.science/hal-04681163v1>

Submitted on 29 Aug 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

Collision Avoidance Behaviours of Young Adult Walkers: Influence of a Virtual Pedestrian’s Age-Related Appearance and Walking Profile

Sheryl Bourgaize
sbourgaize@uwaterloo.ca
University of Waterloo
Waterloo, Ontario, Canada

Michael Cinelli
mcinelli@wlu.ca
Wilfrid Laurier University
Waterloo, Ontario, Canada

Pierre Raimbaud
pierre.raimbaud@ec-lyon.fr
École Centrale de Lyon, CNRS, LIRIS
UMR5025, ENISE
Univ Rennes, Inria, M2S, VirtUs
Saint-Etienne and Rennes, France

Ludovic Hoyet
ludovic.hoyet@inria.fr
Univ Rennes, Inria, M2S, VirtUs
Rennes, France

Anne-Hélène Olivier
anne-helene.olivier@inria.fr
Univ Rennes, Inria, M2S, VirtUs
Rennes, France

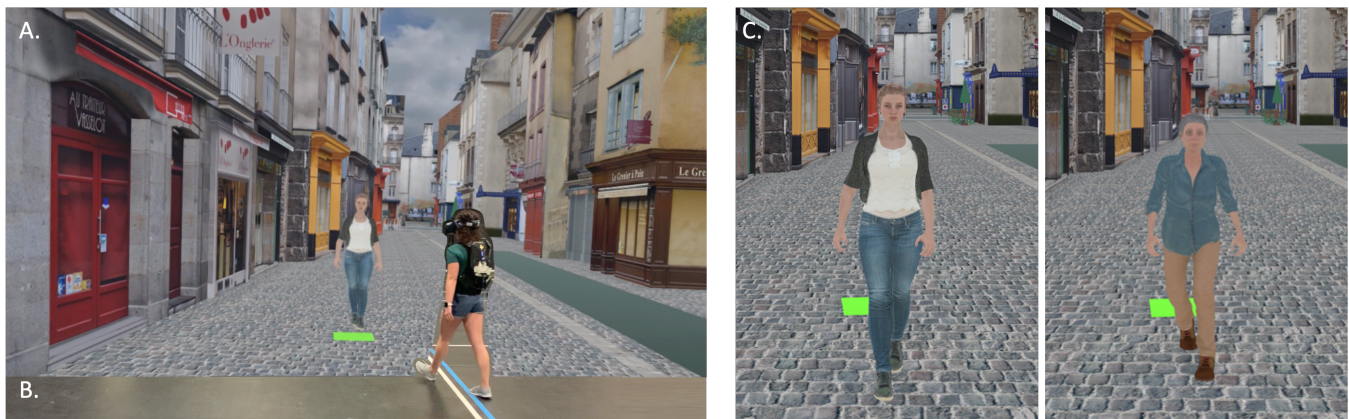


Figure 1: Virtual environment from the viewpoint of the participant’s starting position (A), real-world set-up (B), and the Young Adult (YA) and Older Adult (OA) virtual pedestrians (C).

ABSTRACT

Populating virtual worlds with realistic pedestrian behaviours is challenging but essential to ensure natural interactions with users. In pedestrian encounters, successful collision avoidance requires adapting speed and/or locomotor trajectory based on situational and personal characteristics. Personal characteristics such as the age of a pedestrian can easily be observed, but whether it affects avoidance behaviours is unknown. This is however an important question to ensure realism and variety of the simulations. The purpose of the current study was to examine the influence of a virtual pedestrian’s (VP) age-related appearance and gait profile on avoidance behaviours during a circumvention task. We expected that older adult (OA) gait characteristics and/or appearance would result in more cautious behaviours. Young adults (YA; $n=17$, 23.6 ± 2.7 yrs)

SAP '24, August 30–31, 2024, Dublin, Ireland

© 2024 Copyright held by the owner/author(s). Publication rights licensed to ACM. This is the author’s version of the work. It is posted here for your personal use. Not for redistribution. The definitive Version of Record was published in *ACM Symposium on Applied Perception 2024 (SAP '24)*, August 30–31, 2024, Dublin, Ireland, <https://doi.org/10.1145/3675231.3675233>.

navigated a virtual street using a HMD. Individuals walked 8m towards a goal, while avoiding an approaching VP who would approach and steer towards the participant’s left, right, or continue straight, while exhibiting different age-related appearances and gait profiles: 1. YA appearance, YA gait; 2. OA appearance, OA gait; 3. OA appearance, YA gait; and 4. YA appearance, OA gait. Results indicate that clearance was larger when the appearance of VP resembled an OA, and when the VP walked like an OA compared to a YA. Larger clearance distances observed with OA characteristics may be due to societal norms associated with the principle of parental respect as well as a cautious strategy for any potential instability (wavering) in balance commonly observed in OA. This research sheds light on how age-related cues influence pedestrian interactions, with implications for the design of populated virtual environments.

CCS CONCEPTS

• **Human-centered computing** → *Empirical studies in interaction design*; • **Computing methodologies** → *Simulation environments*; **Virtual reality**; **Perception**; **Motion processing**.

KEYWORDS

Proxemics, Collision Avoidance, Virtual environments, Human locomotion, Visual perception, Older Adults

ACM Reference Format:

Sheryl Bourgaize, Michael Cinelli, Pierre Raimbaud, Ludovic Hoyet, and Anne-Hélène Olivier. 2024. Collision Avoidance Behaviours of Young Adult Walkers: Influence of a Virtual Pedestrian's Age-Related Appearance and Walking Profile. In *ACM Symposium on Applied Perception 2024 (SAP '24)*, August 30–31, 2024, Dublin, Ireland. ACM, New York, NY, USA, 10 pages. <https://doi.org/10.1145/3675231.3675233>

1 INTRODUCTION

Navigating cluttered environments is often necessary in everyday life. Circumvention (travelling around someone/something) is a common locomotor strategy that humans adopt to avoid a collision with obstacles placed directly in the travel path that cannot be stepped over. Circumvention is often seen in situations such as while walking to and from work, school, or the grocery store, which requires stepping around obstacles or other people in the travel path.

Virtual Reality (VR) is a useful tool for recreating and studying these types of avoidance situations, where environments can easily be populated with virtual pedestrians and obstacles. Moreover, when designing crowds of virtual pedestrians, knowledge on circumvention behaviors can help in creating appropriate social distances between characters and with users, incorporating elements of proxemics into virtual environments [Hall 1959]. Proxemics, as defined by Hall, is the study of how people use and perceive space in their interactions with others. Incorporating proxemics into virtual environments not only enhances realism but also deepens our understanding of human interaction dynamics in both real and simulated settings. For users to feel immersed in VR, it is essential that the virtual pedestrians and their behaviors are realistic. Previous research has shown that the agency of virtual characters (i.e., the extent to which a virtual character is perceived as a representation of a real person [Blascovich 2002]) does influence user experience in social virtual environments [Fox et al. 2014; Oh et al. 2018]. In addition, when interacting with a simulated virtual character in VR, proximity (i.e., personal space) has been identified as an indicator of the user's perception and feeling of social presence [Ennis and O'Sullivan 2012]. Therefore, creating appropriate personal space between users and virtual pedestrians is important for enhancing VR experiences.

With the evolving use of VR for interactive collaboration (workspaces and conferences), gaming systems, and clinical tools, the knowledge of personal space could help design appropriate virtual spaces. Creating realistic virtual interactions involves incorporating data obtained from real-world interactions, such as when avoiding collision with other pedestrians. The factors that affect personal space during circumvention, and their integration into VR applications is still ongoing. One such factor is age. While current VR paradigms and crowd simulations have incorporated the behaviors of young adult walkers, there is a lack of literature regarding the simulation of population specific walkers that are a part of the human variability within a crowd, such as older adults. The age of

a person can easily be observed in the appearance of an approaching person (i.e., hair colour, posture, skin texture, etc.), as well as based on their gait-pattern (i.e., wider base of support, increase in medio-lateral trunk sway). Since it is very challenging to dissociate age-related appearance and motion from one another to determine which characteristic(s) is/are important for social interactions in a real-world experiment, the choice to conduct the experiment in VR was appropriate for such an evaluation. In this kind of environment, the appearance and motion of a virtual pedestrian could indeed be controlled, dissociated, and thus perceived separately by our study participants.

The purpose of our experiment is to determine the influence of a virtual pedestrian's age-related appearance and walking profile on spatiotemporal patterns of avoidance during a circumvention task. This work aims to answer the following questions: i) Do we circumvent older adults differently than younger ones? ii) Is the difference due to age-related appearance or gait-pattern, or a combination of both? To answer these two questions, we manipulated in our study the age-related appearance and walking pattern of a virtual pedestrian in VR, and observed the effect on collision avoidance behaviours by the VR users.

This work provides important contributions to the perception of character motion while using a realistic, daily navigation task in VR. We demonstrate how young adults avoid collisions differently with Older Adult (OA) walkers versus Younger Adult (YA) walkers, which has important implications for understanding crowd dynamics. Older adult walkers are a significant part of the human variability within a crowd, therefore findings will help to enhance VR experiences and create ecological virtual environments.

2 RELATED WORKS

2.1 Proxemics

The field of proxemics has focused on understanding interpersonal distances and personal space between humans. Hall [Hall 1959] and Sommer [Sommer 1959] originally demonstrated that people maintain personal or buffer space around themselves and each other. Although the size of the buffer space remains remarkably stable across individuals, certain conditions foster its expansion or contraction, specifically when interacting with other people. Findings from the field of proxemics have strongly suggested that we do not treat all humans equally as there are differences in the comfortable distance maintained between oneself and other people based on height [Patla et al. 1996], age [Iachini et al. 2016], and gender [Hecht et al. 2019; Iachini et al. 2014, 2016]. In VR, proxemics has established itself as a valuable resource for creating social behaviours. For example, when designing crowds of virtual characters, knowledge on proximity can help in creating appropriate social distances between characters and with users [Ennis and O'Sullivan 2012]. However, proxemics research related to older adults is limited, outdated, and inconsistent [Camperio Ciani and Malaman 2002; Gioiella 1978; Latta 1978; Mishara et al. 1974; Remland et al. 1995; Winogron 1981]. Incorporation of older adult virtual characters is important for creating ecological virtual environments, but at present it is unclear whether age-related appearance affects interpersonal space, especially in a navigational context.

2.2 Collision Avoidance

Personal space is a construct described in the navigation literature as the amount of space one leaves around their body to circumvent an obstacle [Gérin-Lajoie et al. 2005]. The role of this personal space is to provide a safety zone large enough to ensure sufficient time to perceive upcoming hazards and perform adjustments to gait in order to successfully avoid colliding with the obstacles [Cinelli and Patla 2007; Gerin-Lajoie et al. 2008; Gérin-Lajoie et al. 2005; Olivier et al. 2012; Pfaff and Cinelli 2018]. For example, individuals will initiate a path deviation away from the midline and will walk far enough laterally away from it to ensure a sufficient clearance distance. Research has evolved to quantify this buffer zone, examining changes in the magnitude and timing of avoidance behaviours according to situational complexity [Cinelli and Patla 2007; Fajen and Warren 2007; Gerin-Lajoie et al. 2008; Gérin-Lajoie et al. 2005]. Only recently has research moved away from examining avoidance strategies in response to inanimate objects (i.e., poles and mannequins [Cinelli and Patla 2007; Gerin-Lajoie et al. 2008; Gérin-Lajoie et al. 2005; Vallis and McFadyen 2003]) and instead started to examine strategies between pairs of humans [Buhler and Lamontagne 2019; Creem-Regehr et al. 2013; Davis et al. 2010; Huber et al. 2014; Olivier et al. 2018; Pfaff and Cinelli 2018; Podkosova and Kaufmann 2018], some of which have successfully been validated in VR [Olivier et al. 2018]. This showed again the ecological validity of using VR to evaluate and understand human walking behaviours in social context, as demonstrated in other VR human-centred evaluations [Dickinson et al. 2020; Pan and Hamilton 2018; Raimbaud et al. 2023]. However, very few studies have explicitly examined how the appearance of an approaching person influence how walkers avoid one pedestrian versus another [Bourgaize et al. 2020; Fiset et al. 2020; Knorr et al. 2016; Lynch et al. 2018; Van Basten et al. 2009]. The collision avoidance study of Rapos et al. [Rapos et al. 2021] is of particular interest as the authors demonstrated that when older and younger adult walkers interact on a 90-degree collision course, the walkers will alter their avoidance behaviours depending on the age of the opposing person. Interestingly, when an older walker interacted with a young adult walker, the younger adult primarily contributed by adapting his/her motion to avoid the collision [Rapos et al. 2021]. However, it is unknown to what degree social factors are involved in this type of interaction.

2.3 Motion and Age Perception

The incorporation of human-derived data is a common means to enhance the reality of crowd simulations, virtual environments, and video games [Trivedi and Mousas 2023]. For instance, Guy and colleagues [Guy et al. 2011] developed a computer-generated crowd simulation that incorporated personalities into some of the virtual characters. To validate the ability of their modelling approach to generate virtual characters with a given personality, user participants viewed several different computer-generated crowds and were asked a series of questions regarding the perceived personality of several highlighted virtual characters. Results indicated that users were able to accurately pick out specific virtual character's personalities of "aggressive", "shy", "assertive", "tense", "impulsive", and "active" [Guy et al. 2011]. Other graphics research has examined the influence of body shape (i.e., waist-to-hip ratio) and motion

(i.e., hip sway and shoulder movement) on realistic male and female virtual characters and found that adding stereotypical indicators of sex to the body shapes influenced sex perception [McDonnell et al. 2009]. Furthermore, findings of Zibrek and colleagues [Zibrek et al. 2020] demonstrate how a virtual character's movements can be perceived as more or less attractive. Correspondingly, Pototskaya et al. [Pototskaya et al. 2023] explored young adults's avoidance behaviours in response to virtual characters exhibiting personality traits which are considered to be more pleasant (emotional stability) and less pleasant to observe (neuroticism) according to the appeal ratings in the study of Zibrek et al. [Zibrek et al. 2020]. Findings demonstrated that more attractive movements lead to a smaller proximity distance. The collective results of previous works suggest that we can identify different characteristics about a person based on their visual appearance and movement profile. While current VR paradigms and crowd simulations have incorporated the behaviours of young adult walkers, there is a lack of literature regarding the simulation of population specific walkers that are a part of the human variability within a crowd, such as older adults.

The age of a person can easily be observed in the appearance of an approaching person (i.e., hair colour, posture, skin texture, etc.), as well as based on their gait-pattern (i.e., wider base of support, increase in medio-lateral trunk sway). The perception of this visual information is immediately available during a collision situation and remains constant throughout the interaction. Gait is a rich source of information for a variety of characteristics, which has been exploited in research involving the perception of human biological motion using the point-light technique (arrangement of moving lights located at anatomical landmarks) [Johansson 1973]. An observer is able to perceive a moving outline of a human point-light display as a walking human, as well as make accurate judgements about the walker's characteristics including age [Montepare and Zebrowitz-McArthur 1988], sex [Kozlowski and Cutting 1977], identity [Loula et al. 2005], and vulnerability [Johnston et al. 2004]. Notably, individuals are able to perceive the age of a walker based merely on point-light walking profiles, such that younger walkers are perceived as more powerful and happy compared to their older adult counterparts [Montepare and Zebrowitz-McArthur 1988]. Evidently, individuals can readily perceive the characteristics of another individual using only gait-based information. However, it has not been determined if the age-related gait pattern of an approaching person influences spatial and temporal measures of collision avoidance.

Incorporation of older adult virtual characters is important for creating ecological virtual environments, but at present it is unclear whether age-related appearance affects interpersonal space, especially in a navigational context. As such, the aim of our experiment was to determine the influence of a virtual pedestrian's age-related appearance and walking profile on spatiotemporal patterns of avoidance during a circumvention task. Age was a criterion for participation in our study since it would have been expected that participants would have different avoidance behaviours depending on their age, so we focused in this paper on YA participants for their ease of evolving in virtual environments and wearing VR headsets. Based on previous work by Rapos et al. [Rapos et al. 2021], it was expected that YA participants would adapt circumvention behaviours more when interacting with a virtual pedestrian

with OA age-related characteristics compared a pedestrian with YA characteristics.

3 METHODS

3.1 Participants

Seventeen young adults participated in this study (12 males, 5 females; 23.59 ± 2.67 years). All participants had normal or corrected-to normal vision and were free of any self-reported musculoskeletal and neurological disorders. All participants provided informed consent prior to participation. Testing procedures were approved by local ethic committees.

Demographic and anthropometric measures including mass and height were recorded for each participant (See Table 1). Participants' shoulder width was measured between acromioclavicular joints. All participants completed the Global Physical Activity Questionnaire to determine they all met the World Health Organization's minimum physical activity recommendation of at least 600 MET-minutes (Metabolic Equivalent of Task-minutes) per week.

3.2 Experimental Setup

The study was conducted in a large room with an 8m pathway cleared. The experiment took place in a virtual environment representing that of a nearby city street that was familiar to all participants (Figure 2). The virtual environment and pedestrians were designed in the Unity3D 2021 game engine. The virtual pedestrian appearances were obtained using the Character Creator 3 Realism software. The walking profiles of the virtual pedestrians genuinely represented the age group they were meant to appear as. The walking profile from one female YA (24 years) and one female OA (65 years) were acquired from a colleagues PhD thesis kinematic dataset [Martin 2021] and integrated into the skeleton of the virtual pedestrians (See Figure 1). The virtual pedestrians were created using the same body dimensions. The walking velocities of the YA and OA were 1.4m/s and 1.2m/s, respectively. The YA stood at a height of 1.72m, had a mean stride length of 1.50m, and step width of 0.09m, whereas the OA stood at a height of 1.62m, had a mean stride length of 1.45m, and step width of 0.12m. The shoulder widths of both the YA and OA was 0.31m when measured between acromioclavicular joints. Participants were visually immersed in the virtual environment through a Head-Mounted Display (HMD) – the HTC Vive Pro Eye. The HMD resolution was 1440 x 1600 pixels per eye (2880 x 1600 pixels combined), refresh rate 90 Hz, field of view 110°. Participants wore a backpack, which housed a laptop including the virtual environment software, allowing participants to freely walk about the virtual street up to 10m with sufficient space to bypass another individual.

3.3 Conditions

We aim at determining the influence of a virtual pedestrian's age-related appearance and walking profile on spatiotemporal patterns of avoidance during a collision avoidance task. To this end, we manipulated the visual appearance and gait profiles of the virtual pedestrian by using the following conditions:

1. **Congruent YA:** The virtual pedestrian looks like a YA and walks like a YA.
2. **Incongruent YA:** The virtual pedestrian looks like a YA but walks like an OA.
3. **Congruent OA:** The virtual pedestrian looks like an OA and walks like an OA.
4. **Incongruent OA:** The virtual pedestrian looks like an OA but walks like a YA.

Note that in all conditions the walking path of the virtual pedestrian varied between one of three paths, relative to the participant: left, right, continue straight. Only the straight trials were of interest and included in statistical analyses. The left and right trials were included to elicit the most natural avoidance behaviours.

3.4 Avoidance Task

While being in VR, participants were asked to walk at a self-selected and comfortable pace between a starting point and a goal 8m away. Both the starting point and goal were indicated by large green squares at ground-level. Participants were instructed to walk to the goal, while avoiding a collision with the virtual pedestrian who was approaching from head-on. To restrict the amount of available time to pre-plan a locomotor trajectory, participants started every trial facing perpendicular to the experimental space. At the start of each trial, participants would take 2-3 steps towards the starting block (i.e., green square) before making a 90° left-hand turn around an occluding wall (i.e., blocking visual information to pre-plan a trajectory), aligning themselves with the goal and approaching virtual pedestrian, and then entering the experimental space. Figure 2 shows the virtual environment, the participant's task, and the virtual pedestrian's trajectories from a top-view perspective. Finally, it should be highlighted that participants did not receive any specific walking instructions or restrictions about their gait speed or path selection. They were free to avoid to either side of the virtual pedestrian.

Each participant performed 48 experimental walking trials. On half the experimental trials the virtual pedestrian looked like an OA, and on the other half they will look like a YA. The walking profile of the virtual pedestrian was matched congruently or incongruently with the virtual pedestrian's age-related appearance (conditions 1-4). The walking path of the virtual pedestrian varied between one of three paths, relative to the participant: left, right, continue straight. Conditions order was pseudo-randomized to avoid more than two consecutive trials of the same condition (48 experimental trials = 2 appearances x 2 walking profiles x 3 directions x 4 repetitions), and everyone experienced the same trial order. We measured participants' cybersickness using the Fast Motion Sickness (FMS) questionnaire, a verbal rating scale ranging from zero (no sickness at all) to 20 (frank sickness) [Keshavarz and Hecht 2011]. The FMS was completed at the start and end of the experiment, as well as every 16 walking trials (6 total FMS scores were recorded for each participant).

3.5 Data Analysis

Data outputted from the HMD provided participants' head position in the medial-lateral (M-L) and the anterior-posterior (A-P) directions as they approached and circumvented around the virtual pedestrian. Prior to data processing, raw positional data was low-pass filtered at 3Hz with a 4th order Butterworth filter using

Table 1: Participant characteristics.

ID#	Gender	Age (years)	Height (m)	Mass (kg)	Shoulder Width (m)	BMI (kg/m ²)	Peak FMS Score (x/20)
1	Female	24	1.63	54	0.38	20.32	5
2	Male	23	1.76	64	0.46	20.66	3
3	Male	29	1.81	72	0.49	21.98	1
4	Female	20	1.52	55	0.38	23.81	2
5	Female	26	1.66	63	0.39	22.86	4
6	Male	25	1.75	65	0.46	21.22	2
7	Male	21	1.74	69	0.42	22.79	0
8	Male	22	1.80	82	0.49	25.31	3
9	Male	23	1.82	71	0.48	21.43	5
10	Male	23	1.78	68	0.45	21.46	0
11	Male	26	1.91	92	0.52	25.22	4
12	Male	21	1.85	74	0.51	21.62	0
13	Female	26	1.73	57	0.42	19.05	5
14	Male	21	1.89	78	0.48	21.84	0
15	Male	28	1.80	72	0.47	22.22	0
16	Female	22	1.62	55	0.44	20.96	0
17	Male	21	1.81	67	0.46	20.45	1
Mean		23.59	1.76	68.12	0.45	21.95	2.06
SD		2.67	0.10	10.17	0.04	1.66	1.98

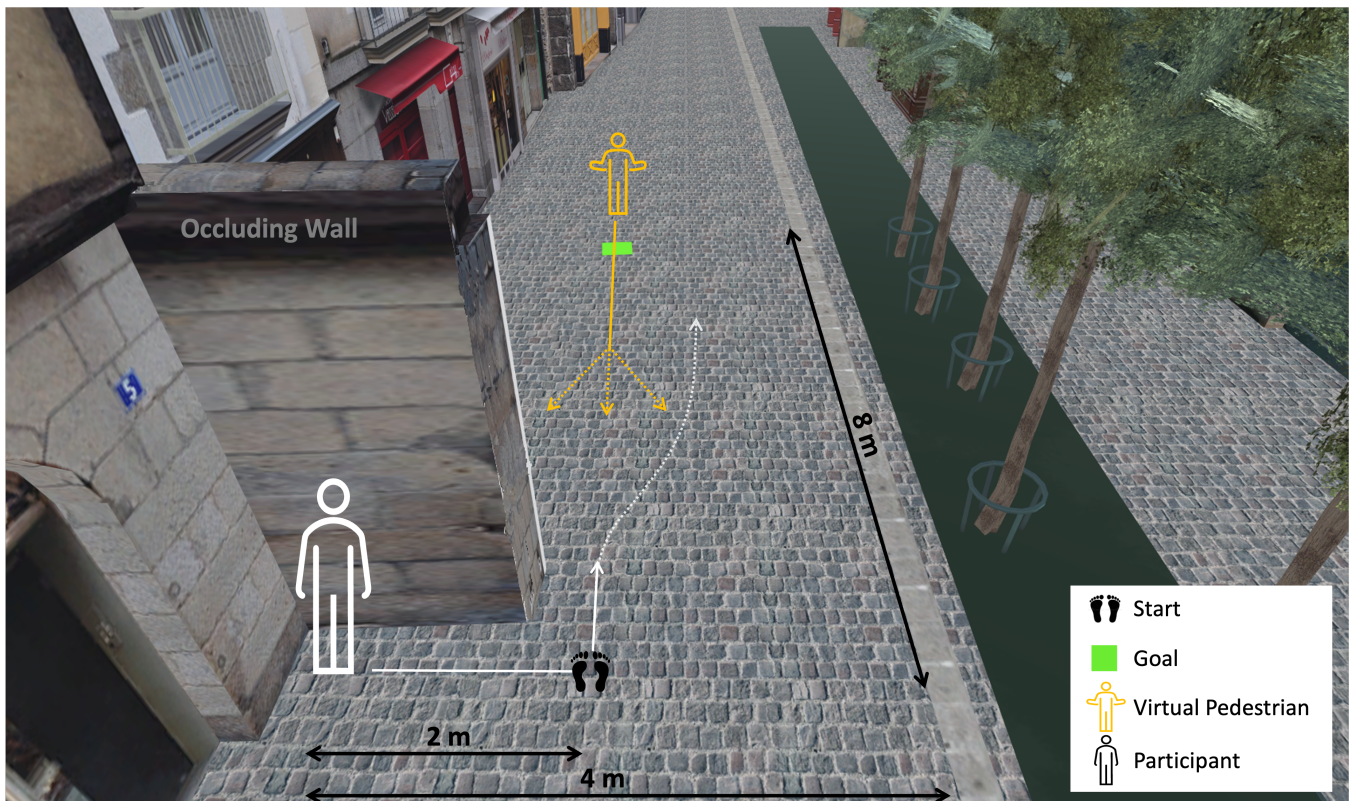


Figure 2: Bird's-eye view of virtual environment and avoidance task.

MATLAB (Version 2015b, MathWorks, Natic MA, USA). Velocity was computed using the time derivative of each participant's location. Using the position and velocity of both participant and virtual pedestrian, participants' avoidance behaviours were calculated as follows. In line with previous collision avoidance studies [Bourgaize et al. 2020; Cinelli and Patla 2007; Fajen and Warren 2007; Fiset et al. 2020; Gérin-Lajoie et al. 2005; Pfaff and Cinelli 2018], we examined the avoidance behaviours of Initial Path Deviation, Time-to-Contact, M-L Clearance, and Rate of Deviation. These variables are important for understanding the dynamics of pedestrian navigation and how walkers adapt their travel speed and/or path trajectory to successfully avoid other pedestrians.

3.5.1 Initial Path Deviation (m). The Initial Path Deviation was defined as the position of the HMD relative to the virtual pedestrian in the A-P direction at the onset of a change in path trajectory. The initial deviation point was found by tracking backwards in time from when the participant's head position produced a lateral movement greater than 2 standard deviations of the average, until the time point when the HMD M-L position had deviated from the straight path by $2cm$. This instant signifies when the early planning phase occurs [Gérin-Lajoie et al. 2005].

3.5.2 Time To Contact (TTC; s). The TTC represents the time that remained before a theoretical collision would occur between the virtual pedestrian and participant had they both continued to walk straight towards each other at their average speed. The speed of the virtual pedestrian and the participant was calculated using an average of the instantaneous velocities during the early planning phase (i.e., prior to the point initial path deviation). TTC was then calculated as the distance between the participant and the virtual pedestrian at Initial Path Deviation over the sum of the participant's and virtual pedestrian's speeds.

3.5.3 M-L Clearance (m). The space required to successfully circumvent the virtual pedestrian in the M-L direction is referred to as the M-L clearance. The M-L clearance represents the absolute amount of space between the participant's head position (mid position of the HMD) and the virtual pedestrian's CoM position at the time of crossing (TOC). TOC occurred when the difference between the participants' A-P head position and the virtual pedestrian's A-P position was equal or closest to zero.

3.5.4 Rate of Deviation (m/s). The speed at which the participants moved in the M-L direction to avoid the confederate is defined as the Rate of Deviation. This value was calculated by measuring the M-L distance travelled by each participant between the time of Initial Path Deviation and TOC, over the time it took to move between the two points.

3.6 Statistical Analysis

Statistical analyses were completed within SPSS software (Version 24.0, IBM Corp., North Castle, NY). For all statistical analyses, the level of significance was set to $\alpha = 0.05$. Data were assessed for normality, sphericity, and homogeneity of variances. Where appropriate, the Greenhouse-Geisser correction was applied for any violations of sphericity. Four separate repeated measures ANOVAs

were performed to test for main and interaction effects on participants' avoidance behaviours of initial path deviation, TTC, M-L clearance, and rate of deviation. There were two within-subject factors: 1) appearance; and 2) gait profile. Bonferroni corrected pairwise comparisons were used to further analyse significant effects. Cohen's f was used as a measure of effect size for the ANOVAs such that, only medium ($0.25 \geq f < 0.40$), and large ($f \geq 0.40$) effect sizes were considered meaningful differences.

4 RESULTS

No collisions occurred throughout the study, and no participant reported an FMS score higher than 5/20.

The mean M-L clearance at TOC across all subjects was $.78m \pm 0.21m$. However, clearance distance depended on both the appearance and gait profile of the virtual pedestrian. There was a significant main effect of virtual pedestrian appearance on clearance distance [$F(1,16)=6.86, p=.019, f=.570$] (see Figure 3). Clearance was larger when the virtual pedestrian looked like an OA ($M = .79m \pm .23m$), compared to YA ($M = .76m \pm .19m$). There was also a significant main effect of virtual pedestrian gait profile on clearance distance [$F(1,16)=7.71, p=.013, f=.610$] (see Figure 4), such that the clearance at the TOC was larger when the virtual pedestrian walked like an OA ($M = .80m \pm .23m$), compared to YA ($M = .76m \pm .20m$). There was no interaction effect.

There were no significant effects of age-related appearance, gait profile, or interactions on the dependent variables of initial path deviation, TTC, or rate of deviation. When considering the initial path deviation, the mean distance between the pedestrian and participant at the onset of a change in path trajectory was $5.37m \pm 1.96m$. The estimated TTC across all subjects was $2.52s \pm 1.09s$, with no differences between conditions. Last, the rate of deviation between initial path deviation to the TOC was calculated as $0.95m/s \pm 0.15m/s$.

A *post-hoc* power analysis of a fixed-effects F-test was performed in G*Power to confirm a sufficient sample size was reached. The estimated output power was 99.3% using a Cohen's f effect size of 0.570, alpha of 0.05, and sample size of 17 [Faul et al. 2007].

5 DISCUSSION

For the current study, we set out to determine the influence of a virtual pedestrian's age-related appearance and gait profile on spatiotemporal patterns of avoidance during a circumvention task in VR. Results support our hypothesis that individuals' avoidance behaviours would be influenced by the age-related characteristics of the approaching virtual pedestrian. Individuals' avoidance behaviour of M-L clearance at TOC was larger when avoiding the virtual pedestrian who presented with OA characteristics.

Our results demonstrate that the amount of space that people feel is necessary to set between themselves and others is modified according to what the other pedestrian looks like and how they walk. A vast body of literature regarding proxemics in real-world and VR suggests that how we perceive other individuals (e.g., poles vs people, age, gender, height) influences navigation behaviours [Berton et al. 2020; Bönsch et al. 2020; Fiset et al. 2023; Hayduk 1978, 1983; Hecht et al. 2019; Iachini et al. 2016; Olivier et al. 2018; Patotskaya et al. 2023; Podkosova et al. 2021; Souza Silva et al. 2018; Welsch et al.

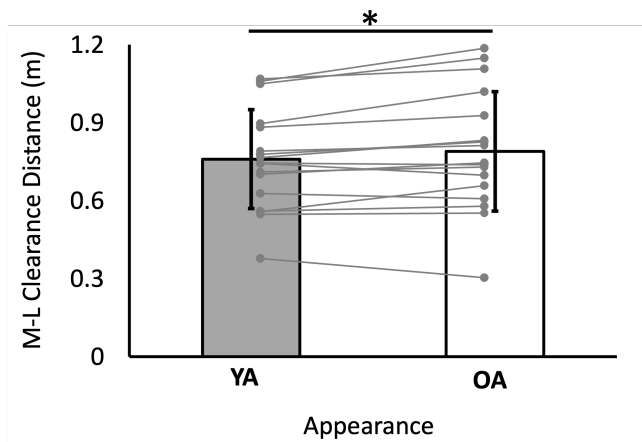


Figure 3: M-L clearance distance according to virtual pedestrian appearance. Individual data represented in grey circles.

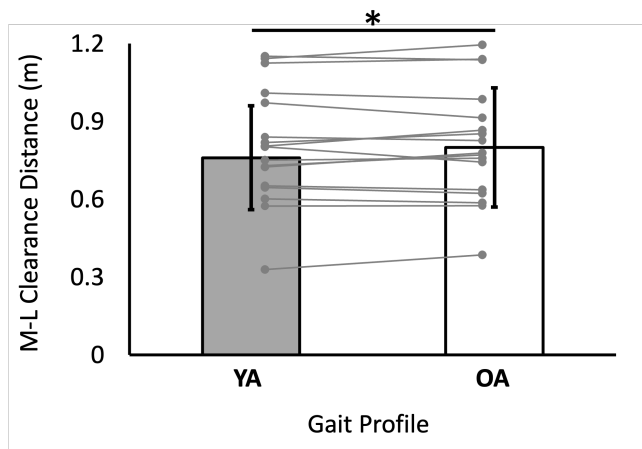


Figure 4: M-L clearance distance according to virtual pedestrian gait profile. Individual data represented in grey circles.

2021; Winogron 1981]. For example, during a stop-distance task (i.e., participants approached, or were approached by, a stationary person and stopped once a comfortable distance for conversation was reached). Iachini et al. [Iachini et al. 2014, 2016] observed an increase in the distance maintained between adult-adult vs adult-child vs child-child pairs, and further confirmed their real-world results in VR. Hecht et al. [Hecht et al. 2019] found similar effects in real-world and VR, with the addition of a mannequin and found that both men and women maintained the farthest distances with respect to the mannequin, suggesting that virtual characters are more life-like than mannequins. Here, we extend previous proxemics research into a navigation task and included OA-YA pairs and found that when avoiding a virtual pedestrian with OA characteristics (appearance or gait) individuals increased their clearance distance at the TOC.

For general pedestrian avoidance, OA are thought to use more cautious strategies compared to YA [Gérin-Lajoie et al. 2006], however it might be that during YA-OA interactions the YA is actually the one using a cautious strategy by providing more space at crossing. Recently, Rapos et al. [Rapos et al. 2021] compared collision avoidance between two walkers by forming duos of OA and YA and found that YA primarily contributed to the avoidance by adapting their behaviours. In the current study, participants were tasked with avoiding an approaching virtual pedestrian who was of the non-reactive type, where the virtual pedestrian did not engage in avoiding a collision. Therefore, when a contribution is made to the avoidance it can only be attributed to the participant. Whereas in the study of Rapos et al. [Rapos et al. 2021] YA-OA pairs were mutually avoiding one another and the task is performed collaboratively, such that the walker giving way (passing second) contributes more to the avoidance than the one passing first [Olivier et al. 2013]. By isolating the behaviours of only one individual, we observe how an individual's contribution to an avoidance is modulated based solely on the age-related characteristics of the virtual pedestrian, without any assumption of there being a reciprocation in avoidance. As such, our findings further support the findings of Rapos et al. [Rapos et al. 2021] and suggest that YA contribute more to successful collision avoidance when interacting with an OA.

Findings of the current study might be explained through the theory of affordances in social contexts [Fajen et al. 2008]. Early theories of ecological social psychology and social affordances were offered by Baron and Boudreau [Baron and Boudreau 1987], Baron and Misovich [Baron and Misovich 1993], and McArthur and Baron [McArthur and Baron 1983]. Three categories of social affordances can be described: affordances for another person (i.e., what actions another person can perform under a given set of environmental conditions), affordances for joint action (i.e., what actions can the perceiver and another agent or agents perform cooperatively), and affordances of another person (i.e., what actions another person afford the perceiver). The current study falls into the first category of social affordances for another person, given that the task did not involve mutual avoidance (i.e., no affordances for joint action) and the virtual pedestrian was non-reactive (i.e., no affordances of another person). The increase in clearance observed when individuals were interacting with the pedestrian possessing OA-like characteristics might reflect the YA's preconceived notions typically associated with OA walkers. For instance, a larger clearance distances observed with OA characteristics may be due to societal norms associated with the character of parental respect. Or perhaps YA leave more space at the TOC as a cautious strategy for any potential instability (wavering) in balance commonly observed in OA. These two thoughts could be linked to social affordances [Fajen et al. 2008], whereby young adults perceive the other person's possibilities for action and modulate their behaviours accordingly. Previous evidence indicates that people can accurately perceive what actions are possible for another person [Ramenzoni et al. 2008; Rochat 1995; Stoffregen et al. 1999]. For instance, Stoffregen et al. [Stoffregen et al. 1999] found using point-light displays of a walker that information contained within the movement kinematics was sufficient to support the visual perception of affordances of maximum and preferred sitting heights for the walker, provided

that the kinematic displays preserved information about the relation between the actor and the chair. When navigating, individuals need to be able to perceive affordances for other pedestrians to tailor their actions appropriately and result in situations where both parties can successfully avoid a collision. Given that the ability for an OA to perform certain adaptations may be limited [Gérin-Lajoie et al. 2006; Hackney and Cinelli 2011; Patla et al. 1996], an action boundary is established. As such, a YA may perceive the action boundaries of an OA and therefore compensate by contributing more to the avoidance and moving farther out of the way. Our results indicate that people are sensitive to affordances of others based on age-related characteristics, which may also be critical for the prospective control of joint action and mutual avoidance situations [Sebanz et al. 2006].

In VR, proxemics has established itself as a valuable resource for creating social behaviours. When designing crowds of characters, knowledge on proximity can help in creating appropriate social distances between them [Ennis and O'Sullivan 2012]. With the evolving use of VR for interactive collaboration (workspaces and conferences), gaming systems, and clinical tools, the knowledge of personal space could help design appropriate virtual environments. When interacting with a simulated virtual pedestrian in VR, proximity was identified as an indicator of social presence [Fox et al. 2014; Oh et al. 2018]. Furthermore, designing realistic virtual environments involves incorporating data obtained from real-world interactions between humans. Knowledge on real-world circumvention behaviours can help in creating appropriate social distances between virtual characters and with users. For users to feel immersed in VR, it is essential that the virtual pedestrians and their behaviours are realistic. Therefore, understanding how YA interact with OA during social interactions, and incorporating data obtained from OA is important for enhancing VR experiences and creating ecological virtual environments.

In addition to enhancing social presence and immersion, the findings of this study underscore the importance of incorporating age-related variations in appearance and gait profiles when designing virtual humans. By considering the diverse demographic characteristics of users, particularly older adults, in virtual environments, engineers can foster increased inclusivity and engagement. This approach not only enriches the authenticity of virtual interactions but also aligns with the principles of creating more ecologically valid virtual environments. Future work is needed to investigate the reciprocal relationship of how OA participants interact in virtual environments with virtual characters of various age-related characteristics. Furthermore, recent work demonstrates how spatial dimensions, like the height of a ceiling and floor area, can influence social interactions [Han et al. 2024]. Given that the current study was conducted on a virtual street (i.e., the sky acting as an unlimited ceiling), future studies should aim to examine how virtual environments influence OA/YA interactions when faced with various spatial constraints, such as a narrow hallway.

6 LIMITATIONS

There are some limitations to the current study. First, only female virtual pedestrians were used in this study. While the purpose

of the current study was to examine the influence of the virtual pedestrian's age characteristics and not sex, it limits the generalizability of our results to other YA and OA males. Second, it is arguable that the increase in clearance distance observed for the different pedestrian appearances and gait profiles may be the result of an uncanny valley effect [Moosa and Ud-Dean 2010; Mousas et al. 2021], occasionally observed with virtual characters. However, an interaction effect was not observed, and therefore we are confident that the results are not solely attributed to the strangeness of the virtual pedestrians' incongruent appearance and gait profile. Nonetheless, the absence of surveys means we cannot confirm participants' subjective experiences or perceptions of the virtual pedestrians. Third, only YA participants were recruited for the current study. It is unknown if OA are also sensitive to the age-related characteristics of an approaching person during a collision avoidance task. Given that OA are suggested to be less efficient at processing perceptual information [Mirelman et al. 2017; Patla et al. 1996], the current paradigm may result in riskier avoidance behaviours in an OA population compared to YA. Last, our sample included mainly participants from the same continent, which have similar cultural backgrounds related to social interaction. A sample of individuals from different cultural backgrounds could reveal alternative patterns, as previous research has suggested [Chattaraj et al. 2009; Hayduk 1983].

7 CONCLUSION

Age-related characteristics of an approaching pedestrian affect avoiding behaviours of young adults, where an older adult-like appearance and gait profile result in an increased ML clearance distance at the time of crossing. Findings provide support for the theory of affordances in social contexts [Fajen et al. 2008] as individuals' appear to account for the perceived affordances of OA pedestrians differently than YA pedestrians. Results also provide evidence to suggest that YA contribute more to avoidance than OA and are important for understanding the social factors that affect personal space during circumvention. Research should continue to attempt to understand how we perceive and navigate people differently, which is important for incorporating human-derived data as a means of enhancing the reality of crowd simulations, virtual environments, and video games.

ACKNOWLEDGMENTS

Thank you to Dr. Suzanne Martin (Victoria University, Australia) [Martin 2021] for providing the kinematic data to create the virtual pedestrian gait profiles.

This work was supported in part by the Natural Sciences and Engineering Council of Canada (NSERC#: 2019-05894 to MEC), the Inria-Rennes-Bretagne Atlantique, France BEAR Associate Team Grant (# EQA-031901), as well as the French National Research Agency grant PIA program (ANR-21-ESRE-0030 CONTINUUM). Thank you to Dr. Suzanne Martin (Victoria University, Australia) [Martin 2021] for providing the kinematic data to create the virtual pedestrian gait profiles.

REFERENCES

R.M. Baron and L.A. Boudreau. 1987. An ecological perspective on integrating personality and social psychology. *Journal of Personality and Social Psychology* 53 (1987),

- 1222–1228.
- R.M. Baron and S.J. Misovich. 1993. Dispositional knowing from an ecological perspective. *Personality and Social Psychology Bulletin* 19 (1993), 541–552.
- F. Berton, L. Hoyet, A.H. Olivier, J. Bruneau, O. Le Meur, and J. Pettré. 2020. Eye-gaze activity in crowds: impact of virtual reality and density. In *2020 IEEE conference on virtual reality and 3D user interfaces (VR)*. IEEE, IEEExplore, NY, USA, 322–331.
- J. Blascovich. 2002. *Social Influence within Immersive Virtual Environments*. Springer-Verlag, Berlin, Heidelberg.
- S. M. Bourgaize, B. J. McFadyen, and M. E. Cinelli. 2020. Collision avoidance behaviours when circumventing people of different sizes in various positions and locations. *J Mot Behav* 53, 2 (2020), 166–175. <https://doi.org/10.1080/00222895.2020.1742083>
- M. A. Buhler and A. Lamontagne. 2019. Locomotor circumvention strategies in response to static pedestrians in a virtual and physical environment. *Gait Posture* 68 (2019), 201–206. <https://doi.org/10.1016/j.gaitpost.2018.10.004>
- A. Bönsch, S. Radke, J. Ehret, U. Habel, and T.W. Kuhlen. 2020. The Impact of a Virtual Agent's Non-Verbal Emotional Expression on a User's Personal Space Preferences. In *Proceedings of the 20th ACM International Conference on Intelligent Virtual Agents*. Springer, Springer International Publishing, Cham, 1–8. <https://doi.org/10.1145/3383652.3423888>
- A. Camperio Ciani and M. Malaman. 2002. Where to sit in a waiting room: density, age and gender effects on proxemic choices. *Human Evolution* 17 (2002), 175–185.
- U. Chattaraj, A. Seyfried, and P. Chakroborty. 2009. Comparison of pedestrian fundamental diagram across cultures. *Advances in complex systems* 12, 03 (2009), 393–405.
- M.E. Cinelli and A.E. Patla. 2007. Travel path conditions dictate the manner in which individuals avoid collisions. *Gait Posture* 26, 2 (2007), 186–93. <https://doi.org/10.1016/j.gaitpost.2006.08.012>
- S. H. Creem-Regehr, K. T. Gagnon, M. N. Geuss, and J. K. Stefanucci. 2013. Relating spatial perspective taking to the perception of other's affordances: providing a foundation for predicting the future behavior of others. *Front Hum Neurosci* 7 (2013), 596. <https://doi.org/10.3389/fnhum.2013.00596>
- T. J. Davis, M. A. Riley, K. Shockley, and S. Cummins-Sebree. 2010. Perceiving affordances for joint actions. *Perception* 39, 12 (2010), 1624–44. <https://doi.org/10.1068/p6712>
- P. Dickinson, K. Gerling, L. Wilson, and A. Parke. 2020. Virtual reality as a platform for research in gambling behaviour. *Computers in Human Behavior* 107 (2020), 106293.
- C. Ennis and C. O'Sullivan. 2012. Perceptually plausible formations for virtual conversers. *Computer Animation and Virtual Worlds* 23, 3-4 (2012), 321–329. <https://doi.org/10.1002/cav.1453>
- B. R. Fajen, M. A. Riley, and M. T. Turvey. 2008. Information, affordances, and the control of action in sport. *Int J Sport Psychol* 40 (2008), 79–107.
- B. R. Fajen and W. H. Warren. 2007. Behavioral dynamics of intercepting a moving target. *Exp Brain Res* 180, 2 (2007), 303–19. <https://doi.org/10.1007/s00221-007-0859-6>
- F. Faul, E. Erdfelder, A.-G. Lang, and A. Buchner. 2007. G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods* 39 (2007), 175–191.
- F. Fiset, A. Lamontagne, and B.J. McFadyen. 2023. Effects of age on the visuo-locomotor control used to circumvent a virtual pedestrian with different limb movements. *Human Movement Science* 87 (2023), 103026. <https://doi.org/10.1016/j.humov.2022.103026>
- F. Fiset, A. Lamontagne, and B. J. McFadyen. 2020. Limb movements of another pedestrian affect crossing distance but not path planning during virtual over ground circumvention. *Neurosci Lett* 1, 736 (2020), 135278. <https://doi.org/10.1016/j.neulet.2020.135278>
- J. Fox, S.J. Ahn, J.H. Janssen, L. Yeckelis, K.Y. Segovia, and J.N. Bailenson. 2014. Avatars Versus Agents: A Meta-Analysis Quantifying the Effect of Agency on Social Influence. *Human-Computer Interaction* 30, 5 (2014), 401–432. <https://doi.org/10.1080/07370024.2014.921494>
- M. Gerin-Lajoie, C. L. Richards, J. Fung, and B. J. McFadyen. 2008. Characteristics of personal space during obstacle circumvention in physical and virtual environments. *Gait Posture* 27, 2 (2008), 239–47. <https://doi.org/10.1016/j.gaitpost.2007.03.015>
- E.C. Gioiella. 1978. The Relationships Between Slowness of Response, State Anxiety, Social Isolation and Self-Esteem, and Preferred Personal Space in the Elderly. *Journal of Gerontological Nursing* 4, 1 (1978), 40–43. <https://doi.org/10.3928/0098-9134-19780101-10>
- S.J. Guy, S. Kim, M.C. Lin, and D. Manocha. 2011. Simulating heterogeneous crowd behaviors using personality trait theory. In *Eurographics/ ACM SIGGRAPH Symposium on Computer Animation*, N. Spencer Stephen (Ed.). ACM, 2019406, 297.
- M. Gérin-Lajoie, C. L. Richards, and B. J. McFadyen. 2005. The Negotiation of Stationary and moving obstructions during walking: Anticipatory locomotor adaptations and preservation of personal space. *Motor Control* 9, 3 (2005), 242–269. <https://doi.org/10.1123/mcj.9.3.242>
- M. Gérin-Lajoie, C. L. Richards, and B. J. McFadyen. 2006. The circumvention of obstacles during walking in different environmental contexts: a comparison between older and younger adults. *Gait Posture* 24, 3 (2006), 364–9. <https://doi.org/10.1016/j.gaitpost.2005.11.001>
- A. L. Hackney and M. E. Cinelli. 2011. Action strategies of older adults walking through apertures. *Gait Posture* 33, 4 (2011), 733–6. <https://doi.org/10.1016/j.gaitpost.2011.02.019>
- E.G. Hall. 1959. *The Silent Language*. Double Day and Company, Garden City, New York.
- E. Han, C. DeVeaux, J.T. Hancock, N. Ram, G.M. Harari, and J.N. Bailenson. 2024. The influence of spatial dimensions of virtual environments on attitudes and nonverbal behaviors during social interactions. *Journal of Environmental Psychology* 95 (2024), 102269.
- L.A. Hayduk. 1978. Personal space: An evaluative and orienting overview. *Psychological Bulletin* 85, 1 (1978), 117–134.
- L.A. Hayduk. 1983. Personal space: Where we now stand. *Psychological Bulletin* 94, 2 (1983), 293–335.
- H. Hecht, R. Welsch, J. Viehoff, and M. R. Longo. 2019. The shape of personal space. *Acta Psychol (Amst)* 193 (2019), 113–122. <https://doi.org/10.1016/j.actpsy.2018.12.009>
- M. Huber, Y. H. Su, M. Kruger, K. Faschian, S. Glasauer, and J. Hermsdorfer. 2014. Adjustments of speed and path when avoiding collisions with another pedestrian. *PLoS One* 9, 2 (2014), e89589. <https://doi.org/10.1371/journal.pone.0089589>
- T. Iachini, Y. Coello, F. Frassinetti, and G. Ruggiero. 2014. Body space in social interactions: a comparison of reaching and comfort distance in immersive virtual reality. *PLoS One* 9, 11 (2014), e111511. <https://doi.org/10.1371/journal.pone.0111511>
- T. Iachini, Y. Coello, F. Frassinetti, V.P. Senese, F. Galante, and G. Ruggiero. 2016. Peripersonal and interpersonal space in virtual and real environments: Effects of gender and age. *Journal of Environmental Psychology* 45 (2016), 154–164. <https://doi.org/10.1016/j.jenvp.2016.01.004>
- G. Johansson. 1973. Visual perception of biological motion and a model for its analysis. *Perception & Psychophysics* 14, 2 (1973), 201–211.
- L. Johnston, S.M. Hudson, M.J. Richardson, R.E. Gunns, and M. Garner. 2004. Changing kinematics as a means of reducing vulnerability to physical attack. *Journal of Applied Social Psychology* 34, 3 (2004), 514–537.
- B. Keshavarz and H. Hecht. 2011. Validating an efficient method to quantify motion sickness. *Hum Factors* 53, 4 (2011), 415–26. <https://doi.org/10.1177/0018720811403736>
- A. G. Knorr, L. Willacker, J. Hermsdorfer, S. Glasauer, and M. Kruger. 2016. Influence of person- and situation-specific characteristics on collision avoidance behavior in human locomotion. *J Exp Psychol Hum Percept Perform* 42, 9 (2016), 1332–43. <https://doi.org/10.1037/xhp0000223>
- L.T. Kozlowski and J.E. Cutting. 1977. Recognizing the sex of a walker from a dynamic point-light display. *Perception & Psychophysics* 21, 6 (1977), 575–580.
- R. Michael Latta. 1978. Relation of Status Incongruence to Personal Space. *Personality and Social Psychology Bulletin* 4, 1 (1978), 143–146. <https://doi.org/10.1177/014616727800400131>
- F. Loula, S. Prasad, K. Harber, and M. Shiffrar. 2005. Recognizing people from their movement. *J Exp Psychol Hum Percept Perform* 31, 1 (2005), 210–220. <https://doi.org/10.1037/0096-1523.31.1.210>
- S. D. Lynch, R. Kulpa, L. A. Meerhoff, J. Pettré, A. Cretul, and A. H. Olivier. 2018. Collision Avoidance Behavior between Walkers: Global and Local Motion Cues. *IEEE Trans Vis Comput Graph* 24, 7 (2018), 2078–2088. <https://doi.org/10.1109/TVCG.2017.2718514>
- S. Martin. 2021. *Gait Adaptability and Biofeedback in Older Adults with Diabetes*. Ph.D. Dissertation. Victoria University.
- L.Z. McArthur and R.M. Baron. 1983. Toward an ecological theory of social perception. *Journal of Personality and Social Psychology* 90 (1983), 215–238.
- R. McDonnell, S. Jörg, J.K. Hodgins, F. Newell, and C. O'Sullivan. 2009. Evaluating the effect of motion and body shape on the perceived sex of virtual characters. *ACM Transactions on Applied Perception* 5, 4 (2009), 1–14. <https://doi.org/10.1145/1462048.1462051>
- A. Mirelman, I. Maidan, H. Bernad-Elazari, S. Shustack, N. Giladi, and J. M. Hausdorff. 2017. Effects of aging on prefrontal brain activation during challenging walking conditions. *Brain Cogn* 115 (2017), 41–46.
- B. L. Mishara, P. Brawley, M. Cheevers, R. M. Kitover, A. M. Knowles, P. Rautiala, and A. Suvajian. 1974. Encroachments upon the body buffer zones of the young and old woman: a naturalistic study. *Int J Aging Hum Dev* 5, 1 (1974), 3–5. <https://doi.org/10.2190/PGL7-TAQ3-XHBW-C36X>
- J.M. Montepare and L. Zebrowitz-McArthur. 1988. Impressions of people created by age-related qualities of their gait. *Journal of Personality and Social Psychology* 55, 4 (1988), 547–556.
- M.M. Moosa and S.M.M. Ud-Dean. 2010. Danger Avoidance: An Evolutionary Explanation of Uncanny Valley. *Biol Theory* 5 (2010), 12–14.
- Christos Mousas, Alexandros Koiliias, Banafsheh Rekabdar, Dominic Kao, and Dimitris Anastaslou. 2021. Toward Understanding the Effects of Virtual Character Appearance on Avoidance Movement Behavior. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*. IEEE, IEEExplore, NY, USA, 40–49. <https://doi.org/10.1109/vr50410.2021.00024>
- C. S. Oh, J. N. Bailenson, and G. F. Welch. 2018. A Systematic Review of Social Presence: Definition, Antecedents, and Implications. *Front Robot AI* 5 (2018), 114. <https://doi.org/10.3389/frobt.2018.00114>
- A. H. Olivier, J. Bruneau, R. Kulpa, and J. Pettré. 2018. Walking with Virtual People: Evaluation of Locomotion Interfaces in Dynamic Environments. *IEEE Trans Vis*

- Comput Graph* 24, 7 (2018), 2251–2263. <https://doi.org/10.1109/TVCG.2017.2714665>
- A. H. Olivier, A. Marin, A. Cretual, A. Berthoz, and J. Pettré. 2013. Collision avoidance between two walkers: role-dependent strategies. *Gait Posture* 38, 4 (2013), 751–6. <https://doi.org/10.1016/j.gaitpost.2013.03.017>
- A. H. Olivier, A. Marin, A. Cretual, and J. Pettré. 2012. Minimal predicted distance: a common metric for collision avoidance during pairwise interactions between walkers. *Gait Posture* 36, 3 (2012), 399–404. <https://doi.org/10.1016/j.gaitpost.2012.03.021>
- X. Pan and A.F.C. Hamilton. 2018. Why and how to use virtual reality to study human social interaction: The challenges of exploring a new research landscape. *British Journal of Psychology* 109, 3 (2018), 395–417.
- A. E. Patla, A.L. Adkin, C. Martin, R. Holden, and S.D. Prentice. 1996. Characteristics of voluntary visual sampling of the environment for safe locomotion over different terrains. *Exp Brain Res* 112, 3 (1996), 513–522.
- Y. Patotskaya, L. Hoyet, A.H. Olivier, J. Pettré, and K. Zibrek. 2023. Avoiding virtual humans in a constrained environment: Exploration of novel behavioural measures. *Computers & Graphics* 110 (2023), 162–172. <https://doi.org/10.1016/j.cag.2023.01.001>
- L.M. Pfaff and M.E. Cinelli. 2018. Avoidance behaviours of young adults during a head-on collision course with an approaching person. *Exp Brain Res* 236, 12 (2018), 3169–3179. <https://doi.org/10.1007/s00221-018-5371-7>
- I. Podkosova and H. Kaufmann. 2018. Mutual collision avoidance during walking in real and collaborative virtual environments. In *Proceedings of the ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games*. Association for Computing Machinery, New York, NY, USA, 1–9.
- I. Podkosova, K. Zibrek, J. Pettré, L. Hoyet, and A.H. Olivier. 2021. Exploring behaviour towards avatars and agents in immersive virtual environments with mixed-agency interactions. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE, IEEEExplore, NY, USA, 140–143.
- P. Raimbaud, A. Jovane, K. Zibrek, C. Pacchierotti, M. Christie, L. Hoyet, J. Pettré, and A.H. Olivier. 2023. The Stare-in-the-Crowd Effect When Navigating a Crowd in Virtual Reality. In *ACM Symposium on Applied Perception 2023*. Association for Computing Machinery, New York, NY, USA, 1–10.
- V. Ramenzoni, M. A. Riley, T. Davis, K. Shockley, and R. Armstrong. 2008. Tuning in to another person's action capabilities: perceiving maximal jumping-reach height from walking kinematics. *J Exp Psychol Hum Percept Perform* 34, 4 (2008), 919–28. <https://doi.org/10.1037/0096-1523.34.4.919>
- V. Rapos, M. E. Cinelli, R. Grunberg, S. Bourgaize, A. Cretual, and A. H. Olivier. 2021. Collision avoidance behaviours between older adult and young adult walkers. *Gait Posture* 88 (2021), 210–215. <https://doi.org/10.1016/j.gaitpost.2021.05.033>
- M.S. Remland, T.S. Jones, and H. Brinkman. 1995. Interpersonal distance, body orientation, and touch: effects of culture, gender, and age. *Journal of Social Psychology* 135, 135 (1995), 281–297.
- P. Rochat. 1995. Perceived reachability for self and for others by 3- to 5-year old children and adults. *Journal of Child Psychology* 59 (1995), 317–333.
- N. Sebanz, H. Bekkering, and G. Knoblich. 2006. Joint action: bodies and minds moving together. *Trends Cogn Sci* 10, 2 (2006), 70–6. <https://doi.org/10.1016/j.tics.2005.12.009>
- R. Sommer. 1959. On writing “little papers.”. *American Psychologist* 14 (1959), 235–237.
- W. Souza Silva, G. Aravind, S. Sangani, and A. Lamontagne. 2018. Healthy young adults implement distinctive avoidance strategies while walking and circumventing virtual human vs. non-human obstacles in a virtual environment. *Gait Posture* 61 (2018), 294–300. <https://doi.org/10.1016/j.gaitpost.2018.01.028>
- T.A. Stoffregen, K.M. Gorday, Y-Y. Sheng, and S.B. Flynn. 1999. Perceiving affordances for another person's actions. *Journal of Experimental Psychology* 25 (1999), 120–136.
- H. Trivedi and C. Mousas. 2023. Human-virtual crowd interaction: Towards understanding the effects of crowd avoidance proximity in an immersive virtual environment. *Computer Animation and Virtual Worlds* 34, 3-4 (2023), e2169.
- L. A. Vallis and B. J. McFadyen. 2003. Locomotor adjustments for circumvention of an obstacle in the travel path. *Exp Brain Res* 152, 3 (2003), 409–14. <https://doi.org/10.1007/s00221-003-1558-6>
- B.J. Van Basten, S.E. Jansen, and I. Karamouzas. 2009. In Motion in Games. *Second International Workshop, MIG 2009, Proceedings* 5884 (2009), 29–40.
- R. Welsch, M. Wessels, C. Bernhard, Sven Thönes, and C. von Castell. 2021. Physical distancing and the perception of interpersonal distance in the COVID-19 crisis. *Scientific reports* 11, 1 (2021), 11485.
- I. R. Winogrand. 1981. A comparison of interpersonal distancing behavior in young and elderly adults. *Int J Aging Hum Dev* 13, 1 (1981), 53–60. <https://doi.org/10.2190/tt33-d5jk-n23n-6ymt>
- K. Zibrek, B. Niay, A.H. Olivier, L. Hoyet, J. Pettré, and R. McDonnell. 2020. The Effect of Gender and Attractiveness of Motion on Proximity in Virtual Reality. *ACM Transactions on Applied Perception* 17, 4 (2020), 1–15. <https://doi.org/10.1145/3419985>