



HAL
open science

The Stare-in-the-Crowd Effect When Navigating a Crowd in Virtual Reality

Pierre Raimbaud, Alberto Jovane, Katja Zibrek, Claudio Pacchierotti, Marc Christie, Ludovic Hoyet, Julien Pettré, Anne-Hélène Olivier

► **To cite this version:**

Pierre Raimbaud, Alberto Jovane, Katja Zibrek, Claudio Pacchierotti, Marc Christie, et al.. The Stare-in-the-Crowd Effect When Navigating a Crowd in Virtual Reality. SAP 2023 - ACM Symposium on Applied Perception, Aug 2023, Los Angeles, United States. pp.1-10, 10.1145/3605495.3605796 . hal-04150082

HAL Id: hal-04150082

<https://inria.hal.science/hal-04150082v1>

Submitted on 4 Jul 2023

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

The Stare-in-the-Crowd Effect When Navigating a Crowd in Virtual Reality

Pierre Raimbaud
pierre.raimbaud@ec-lyon.fr
Univ Lyon, Centrale Lyon, CNRS,
INSA Lyon, UCBL, LIRIS, UMR5205
Inria, Univ Rennes, CNRS, IRISA
Saint-Etienne and Rennes, France

Alberto Jovane
alberto.jovane@inria.fr
Inria, Univ Rennes, CNRS, IRISA
Rennes, France

Katja Zibrek
katja.zibrek@inria.fr
Inria, Univ Rennes, CNRS, IRISA
Rennes, France

Claudio Pacchierotti
claudio.pacchierotti@irisa.fr
CNRS, Univ Rennes, Inria, IRISA
Rennes, France

Marc Christie
marc.christie@irisa.fr
Univ Rennes, CNRS, IRISA, Inria
Rennes, France

Ludovic Hoyet
ludovic.hoyet@inria.fr
Inria, Univ Rennes, CNRS, IRISA
Rennes, France

Julien Pettré
julien.pettre@inria.fr
Inria, Univ Rennes, CNRS, IRISA
Rennes, France

Anne-Hélène Olivier
anne-helene.olivier@univ-rennes2.fr
Univ Rennes, Inria, CNRS, IRISA, M2S
Rennes, France



Figure 1: Participants navigate a virtual crowd (left). We evaluated the effect of virtual agents gaze behaviour, looking or not at the participants (middle), on their gaze and locomotor behaviour (right - the colors depict which virtual agent was looked at).

ABSTRACT

Nonverbal communication is paramount in daily life, as well as in populated virtual reality (VR) environments. In this paper, we focused on gaze behaviour, which is key to initiate and drive social interactions. Previous work on photographs and on virtual agents showed the importance of gaze, even in the presence of multiple stimuli, by demonstrating the stare-in-the-crowd effect: humans detect faster and observe gazes directed towards them longer than the averted ones. While previous studies focused on static scenarios, which fail in representing the complexity of real-life social interactions, we propose to explore the stare-in-the-crowd effect in dynamic situations. To this end, we designed a within-subject experiment where 21 users navigated a virtual street through an idle or moving crowd of virtual agents. Agents' gaze was manipulated to display averted, directed, or shifting gaze. We analysed the user's gaze (fixations, dwell time) and locomotor behaviours

(path decisions, proximity to agents) as well as their social anxiety. Results showed that the stare-in-the-crowd effect is preserved when walking through both types of crowd, and that social anxiety decreases gaze interaction time and affects proximity behaviours in case of agents with directed gazes. However, virtual agents' gaze did not elicit significant changes on users' locomotion. These findings highlight the importance of considering virtual agents' gaze when creating VR environments, and open future work perspectives to better understand factors that would strengthen or decrease this effect at gaze and locomotor levels.

CCS CONCEPTS

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

KEYWORDS

gaze, social interaction, crowd, locomotion, virtual agents, virtual reality

ACM Reference Format:

Pierre Raimbaud, Alberto Jovane, Katja Zibrek, Claudio Pacchierotti, Marc Christie, Ludovic Hoyet, Julien Pettré, and Anne-Hélène Olivier. 2023. The Stare-in-the-Crowd Effect When Navigating a Crowd in Virtual Reality. In *ACM Symposium on Applied Perception 2023 (SAP '23), August 5–6, 2023, Los Angeles, CA, USA*. ACM, New York, NY, USA, 10 pages. <https://doi.org/10.1145/3605495.3605796>

1 INTRODUCTION

Facing an audience or navigating public spaces are daily situations that involve nonverbal communication, a key feature of social interactions. It refers to any interpersonal exchange that does not use the spoken language and transmit, voluntarily or not, meaningful messages. Rather than with words, these are conveyed with facial expression, arm gestures, the distance between people in a shared space (proximity) [Hall and Hall 1966], limb posture, and gaze [Harrigan et al. 2008]. Then, studying nonverbal communication here has not only fundamental applications to the understanding of social interactions, but also to the design of populated Virtual Reality (VR) environments where a user interacts with virtual agents.

Gaze is an important cue when interacting with others. For this reason, a gaze directed towards an individual can be particularly perceptible to that person, even when this gaze is “hidden” in a crowd of people. This effect called stare-in-the-crowd has been demonstrated when both the observer and crowd was static [Colombatto et al. 2020; Crehan and Althoff 2015; Von Grünau and Anston 1995] and has been confirmed in VR with virtual agents [Raimbaud et al. 2022]. These studies featured only a static condition, where both the participant and the crowd were not moving. Here, we ask the question if the effect generalises to more complex situations where the observer, the crowd or even both are moving. Our first objective is thus to assess the presence of the stare-in-the-crowd effect in dynamic situations in VR, more precisely when users perform a walking task through a crowd that is either standing idle or moving forward walking in a straight line against users’ walking direction.

Previous work in VR showed that mutual gaze can affect behavioural parameters of social interactions such as interpersonal distances between a user and a virtual agent [Bailenson et al. 2001]. In case of collision avoidance uncertainty, the gaze direction of an agent can contribute to the user’s avoidance decision and to the choice of the opposite side in the pathway [Nummenmaa et al. 2009], since gaze is an important predictor of where one might navigate [Hessels et al. 2020]. As these studies are difficult to organise and control in real life, VR is often used to investigate gaze-related avoidance. Our second objective was thus to evaluate whether the gaze of the virtual agents can affect participants’ locomotion behaviour, in terms of path decisions and proximity to agents in VR.

Understanding users’ individual characteristics is also relevant when studying their behaviour in crowds. Studies showed that our behavioural reactions (eye and body motions, posture etc.) to mutual gaze during social interactions can be influenced by personality traits, and particularly by our level of social anxiety [Schulze et al. 2013]. As these reactions have also been observed with virtual agents [Lange and Pauli 2019; Wieser et al. 2010], our third objective was to assess whether social anxiety level will modulate participants’ gaze and motion behaviours in response to eye-contact.

2 RELATED WORK**2.1 Eye-contact and gaze behaviour**

Gaze is paramount for social interactions since it helps one to interpret the intentions and feelings of the others. It serves many functions, including information gathering, signalling interest and emotional state, regulating conversations [Argyle and Cook 1976] and intimacy [Abele 1986], or even referring to objects in shared space [Gergle and Clark 2011]. Studies with virtual agents have considered the use of eyes, head, body and locomotive direction [Peters 2005] to orient observers’ attention. Gaze may be a powerful means for this, but more studies are needed to understand such effect.

Gaze behaviour, with all its intricacy, is extremely difficult to model for artificial faces, be it robots or virtual human agents (see [Ruhland et al. 2015] for an in-depth overview of artificial gaze modelling). Moreover, natural gaze behaviour was identified as superior in avatar-mediated environments [Roth et al. 2018]. However, even a simple gaze behaviour (directed gaze, avoidance when meeting the eyes of the user) can be a strong social cue.

Previous work showed the presence of the stare-in-the-crowd effect, a gaze behaviour effect that reflects the existence of a search asymmetry between directed and averted gazes when one faces a crowd [Von Grünau and Anston 1995]: directed gazes are detected faster than averted ones and cause more frequent and longer fixations. This has been found with photographs of people [Doi and Ueda 2007; Ramamoorthy et al. 2019], 3D geometric shapes [Colombatto et al. 2020], and virtual agents [Palanica and Itier 2011]. Nonetheless, some studies mitigated the existence of this effect, according to gaze positions [Palanica and Itier 2011] and user task [Cooper et al. 2013]. Recent studies proposed a new paradigm that relies on the use of eye-tracking and an observation task, rather than a detection task: they demonstrated again the stare-in-the-crowd effect, and showed that shifting gazes (averted to directed, vice-versa) produce it, with pictures [Crehan and Althoff 2015], and virtual agents in VR [Raimbaud et al. 2022]. Finally, directed gazes also draw more attention than averted ones between conversational dyads (gaze frequency and duration) [Dobre et al. 2021].

2.2 Eye-contact, proximity and avoidance

Mutual gaze behaviours affect interpersonal distances, a phenomena called the equilibrium theory [Argyle and Dean 1965]. Bailenson et al. [2001] showed its preservation in VR between dyads, notably with women who maintained more interpersonal distance with agents that engaged mutual gazes with them compared to the others. In real life and in VR, humans have different proximity behaviours depending on the others’ gender [Brady and Walker 1978]. Moreover, women have a further proximity towards others in general, compared to men [Iachini et al. 2016; Zibrek et al. 2020].

Nonetheless, daily-life situations also include more complex situations, such as interactions with crowds, and the need of collision avoidance. Humans rely on their gaze to analyse collision risks and navigate through a crowd, both in real life and VR [Meerhoff et al. 2018]. Hessels et al. [2022] showed that mutual gaze was not required to navigate a crowd. However, the same study reports that the importance of mutual gaze seems to remain context-dependent. For example, Murakami et al. [2022] showed that body motion cues seem to be sufficient for mutual anticipation to avoid collision

when navigating a crowd. This was explained since mutual gazes were strongly modulated by the uncertainty of the oncoming pedestrian's motion. Similar results have been found in VR for dyads, where participants avoided a virtual walker based on its motion, without any effect of its gaze, in absence of uncertainty on the agent's trajectory [Lynch et al. 2018]. Nummenmaa et al. [2009] did find an effect of the gaze behaviour of a virtual walker, by adding uncertainty on the side of its gaze behaviour (averted to the left or the right, and the possibility to shift just before the collision). Participants looked to the opposite side of the gaze, and chose this side for collision avoidance. However, the study was not conducted in VR but on a computer screen, and participants were not performing real avoidance but indicating the side they would have chosen. Finally, Mousas et al. [2019] noted an effect of an agent's gaze in VR on the length, duration, and deviation of collision avoidance with a static agent. Directed gaze behaviour increased the metrics, but significant differences were attributed more to the presence or absence of embodiment rather than the agents' gaze behaviours.

2.3 Eye-contact and individual traits

Even though external factors such as the gaze of others affect one's gaze behaviour, gaze interactions and their perception remain complex, social but individual processes [Hadders-Algra 2022]. Individual traits affect one's gazes, e.g., extraversion increases one's gaze frequency towards the others [Ijuin and Jokinen 2020], and openness increases fixation duration [Rauthmann et al. 2012].

Nonetheless, among many existing individual characteristics, social anxiety is the one most affected by gaze [Hessels et al. 2018]. Social anxiety is related to discomfort and avoidance of social situations due to one's fear of negative evaluation from the others [Clark 1995]. Physiological events, such as heart rate increase, can be triggered when situations are felt as socially anxious by one, both in real and virtual environments [Kahlon et al. 2019; Pittig et al. 2013]. Sensitivity to eye-contact, and elevated fear of direct gaze behaviours, is another common trait of socially anxious people [Baker and Edelman 2002]. Emotional expressions associated to interactants' gaze can modulate its effects: anger expressed with a direct gaze can induce fear [Horley et al. 2003], whereas averted gazes, while carrying no emotional message, can frighten socially anxious people since it can be perceived as disinterest [Wieser et al. 2009].

Virtual agents can also increase the discomfort of socially anxious people through directed gazes, thus affecting their gaze [Lange and Pauli 2019]. This study also found that these gazes affected proximity in correlation with social anxiety, enhancing the avoidance behaviour of socially anxious people towards virtual agents. These effects can be modulated by gender [Wieser et al. 2010], either of the VR users or the virtual agents: interpersonal distances increase for female users [Bailenson et al. 2001], as well as when VR users interact with male agents [Iachini et al. 2016].

For the above mentioned reasons, our study considered the potential effects of the individual traits of our participants on their behavioural responses to the virtual stimuli displayed.

3 OBJECTIVES AND HYPOTHESES

We designed a VR experiment to explore the effects of eye-contact within a virtual crowd on the nonverbal behaviours of the participants. We refer to the studies, which found the presence of the stare-in-the-crowd effect in VR, but only focused on static conditions [Palanica and Itier 2011; Raimbaud et al. 2022]. Here, we propose to study the gaze behaviours in dynamic situations, where the participant, the crowd or both are moving. Then, our first hypothesis **H1** is that the stare-in-the-crowd effect is present when walking through an idle or walking crowd in VR, i.e., participants will spend more time looking at directed gazes than averted ones.

We also aim to explore eye-contact effects on locomotor behaviours. For global path decision, conflicting evidence for collision avoidance behaviour in the literature suggests that this behaviour is task-dependent [Lynch et al. 2018; Mousas et al. 2019; Nummenmaa et al. 2009; Varma et al. 2017]. For more controlled conditions, we designed in this study a crowd with predictable behaviours, either idle or walking straight forward, without deviation. As a result, according to the literature, we did not expect an effect of agents' gazes on the participant's global path decision. We hypothesised that **H2**: *participants will not change their path trajectories by facing an agent who is making eye-contact with them or an agent whose gaze is averted*. However, we did anticipate local behavioural changes according to previous studies about the effect of mutual gaze on proximity behaviour [Bailenson et al. 2001]. We hypothesised that **H3**: *participants will move (interpersonal distance) and turn (interpersonal orientation) their bodies more to avoid the virtual agents with directed gazes than the ones with averted gazes*.

Finally, another objective of the study is to evaluate the interplay of an individual characteristic on the aforementioned behavioural interactions: the participants' social anxiety. It is indeed a factor that influences both people's gaze [Wieser et al. 2010] and avoidance behaviour [Lange and Pauli 2019] with virtual agents. Therefore, we hypothesised that **H4**: *a higher level of social anxiety will be associated with decreased gaze and increased local avoidance (distance, orientation) towards the agents with mutual gaze behaviours*.

4 EXPERIMENT

4.1 Crowd stimuli creation

4.1.1 Virtual environment and agents' models. We created our populated virtual environment in Unity 2021.3.9f1, which was composed of a 3D digital twin model of a pedestrian street and a crowd of 28 virtual agents. We designed our crowd from 28 male models of the Microsoft RocketBox adult avatar collection [Gonzalez-Franco et al. 2020]. We chose only one gender (male) for our virtual models to avoid the potential effects of gender on eye-gaze and proximity responses of our participants [Wieser et al. 2009], because these effects are out of the scope of this paper. We also anticipated that male virtual agents might induce higher social anxiety and intensify gaze behaviour effects on highly social anxious participants, as suggested in the literature [Donovan and Leavitt 1980; Kleinke and Pohlen 1971; Schmitz et al. 2012]. Finally, we avoided using particularly distinctive agent models, which could stand out from the crowd and influence participants' interactions, and thus chose slightly uniformed agent appearances (no garish color on clothes, same visibility of agents' eyes, height, stature etc.).

4.1.2 Crowd gaze behaviours. We designed four different gaze behaviour conditions, in line with previous studies [Crehan and Althoff 2015; Raimbaud et al. 2022; Von Grünau and Anston 1995], which we applied here to some lines of four agents in our crowd:

- **Averted gaze - A:** this condition is composed of the whole line of agents which avoid looking towards the participant, even by moving the head to the opposite side when necessary, e.g., if the participant moved (see Fig. 2.1);
- **Directed gaze - D:** this condition is composed of three agents with an averted gaze and one that stares at and follows the participant, even when both are moving (see Fig. 2.2);
- **Averted-then-Directed - AD:** this condition is composed of three agents with an averted gaze and one that starts avoiding the participant's gaze, but switches to the directed gaze described above as soon as looked at, and remain with this behaviour regardless next gaze exchanges (see Fig. 2.3);
- **Directed-then-Averted - DA:** this condition is composed of three agents with an averted gaze and one with that starts staring at the participant, but switches to the averted gaze previously described as soon as looked at, and remain with this behaviour regardless next gaze exchanges (see Fig. 2.4).

For the D, AD and DA conditions, we also created another variation of these three crowd gaze behaviours, where two agents from the same side (left or right, separated by a space) had a Directed, Averted-then-Directed, or Directed-then-Averted gaze. The gaze model we developed relied on eye-head coordination (eyes moving first until 30° , then head plus eyes adjustment), thus all our gaze behaviours (even averted) included these motions, avoiding any perceptual bias due to a lack of motions and increasing the naturalness. A blinking animation was also applied on agents' eyes.



Figure 2: Our gaze conditions: 1) averted gaze - A, 2) directed gaze - D, 3) and 4) directed-then-averted gaze - DA, and averted-then-directed gaze- AD. Agents with averted gazes are highlighted in yellow, and green for directed gazes.

4.1.3 Crowd spatial layout. To explore participants' walking path decisions, we needed to capture clear, distinct but controlled trajectory changes. For these reasons, we designed the following layout for our crowd, shown in Fig. 3: seven horizontal lines of four agents,

the third and sixth lines being gaze-manipulated, with available path decision through two available spaces of 70 cm that require a left or right deviation. These lines will be referred later as the *active lines*, and the others as the *passive lines*. The purpose of the passive ones was to ensure that participants faced the active lines in the same conditions, bringing them back to the center of the street.

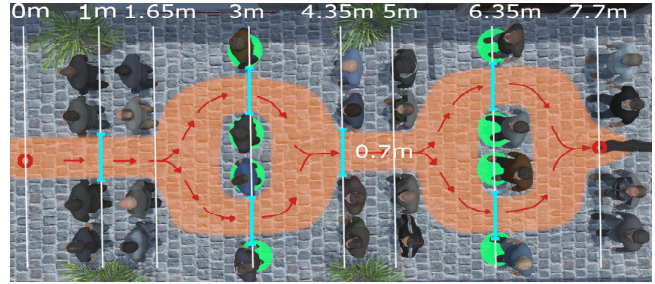


Figure 3: Crowd top-view (idle condition distances). The estimated walkable area is represented in orange, red arrows show the path possibilities, red circles initial/ending points. Active line agents are highlighted in green, and gaps in blue.

The position and gaps between agents were designed to prevent participants from: i) going through the crowd by walking on the street borders, or ii) going through an active line without choosing the gap between the two agents of the left or right side. Decorative elements were added on the street sides to limit the walking area without reducing its realism. The target end of the walking path was materialised by a tree placed in the middle of the last line of agents, at 8 m from the starting point (see Fig. 3 for all details). Finally, all the virtual agents' models were randomly switched between each trial, so that models' appearance would not influence our results.

4.1.4 Crowd gaze distribution. We applied on our two active lines the gaze behaviours described in Sec. 4.1.2. All the agents of passive lines had a *default averted gaze*, designed as a straight forward look on a distant point, so participants do not feel concerned by it, and it was not involving reactive head motions unlike our studied gazes.

As in previous stare-in-the-crowd-effect studies [Colombatto et al. 2020; Von Grünau and Anston 1995], the manipulation of which virtual agent is looking or not at the participant must remain unpredictable to participants. Therefore, across the trials of the experiment, we balanced the spatial distribution of the gazes in each line. It also helped us avoiding any effects of position on the results [Doi and Ueda 2007; Palanica and Itier 2011]

4.1.5 Crowd locomotor behaviour. We created two types of crowd: one with idle standing agents, and one with agents walking in the opposite direction of the participant – referred later as *idle crowd* and *moving crowd*. We applied motion captured animations to our agents. In both cases, the crowd was unresponsive to any collision risk with participants and did not show any avoidance behaviour. This allowed to standardise conditions across trials and participants.

Agents of the moving crowd were all walking straight at 0.7 m/s , with a desynchronisation of their foot movements to increase the behavioural naturalness of the crowd. We chose a walking speed lower

than a more commonly used human comfort speed of 1.4 *m/s* [Bohannon 1997], as pre-tests demonstrated that it was too difficult for participants to navigate a virtual crowd that had this speed (participants were only taking side steps to avoid the oncoming crowd without walking forward). In addition, participants' distance to the first line of agents, as well as distance between agent lines, were doubled compared to the idle crowd condition. The size of the gaps inside agents' lines were nonetheless remaining the same.

4.2 Participants and Apparatus

Twenty-one participants voluntarily took part in our experiment, without compensation, and with normal or corrected-to-normal vision (5 females, 16 males; age: aver. 31.8, SD: 6.9; VR experience from 1 to 5: aver. 3.2, SD: 1.1; computer games experience from 1 to 5: aver. 3.7, SD: 1.2). Our study complied with the Declaration of Helsinki and was approved by our local ethics committee (COERLE).

Participants were asked to wear a backpack computer and the HTC Vive Pro Eye VR head-mounted display (HMD). They carried two HTC Vive controller in their hands, and two Vive trackers were positioned on their shoulders. Participants' behavioural data were recorded through all these devices. The eye-tracking system of the VR HMD used here has a maximum eye-tracking sampling rate of 120 Hz, recording eye motions in a 110° field of view with an advertised precision between 0.5 and 1.1°. Its video display field of view is 110°, with a maximum refresh rate of 90 Hz. The tracking space area of the experiment was 10 *m* x 10 *m*. Participants were told to stand and walk during the experiment, and did not have more hardware limits than the available tracked space – e.g., no cable.

4.3 Experimental procedure

First, an informative document about the study was given to the participants, along with the informed consent form and oral explanations. It was explained to them that their task was to navigate a populated virtual street, and to reach a tree 8 *m* farther. They were told to follow their natural behaviours in such social situations. No information about the agents' gaze behaviours were provided.

Once ready, they were equipped with the backpack computer, the VR HMD, controllers, and trackers. A calibration of the eye-tracking system was performed to ensure the quality of gaze data. In addition, the participant eye-height in the virtual environment was calibrated and adjusted to the one of the virtual agents' so that all participants had the same visibility to exchange gaze behaviours.

Then, participants were immersed in our virtual environment for a brief training phase, where they had time to familiarise with the virtual pedestrian street and the setup. This training was composed of 6 trials. Participants could always control the beginning and end of the trials, through buttons on the VR controllers; black screens showing the current trial number and the total of trials were displayed between each trial. No further action was required using the controllers, as navigation was done by natural walking. Between each trial, the street was flipped during the black screen view, thus allowing participants to virtually perform the next trial in the same conditions after they turned back. The first two training trials were performed in a virtual environment empty from virtual agents. Then, two additional training trials with a crowd were displayed to the participants before they faced each type of crowd.

In both cases, all the virtual agents displayed the *default averted gaze* (straight forward look towards a distant point).

After that, participants were asked to perform 64 trials, under all our crowd behaviour conditions (see Sec. 4.1.2): 4 gaze behaviours × (4 one-agent gaze case position + 4 two-agents gaze case i.e., twice left and twice right for each of the two cases) × 2 types of crowd. It should be noted that the number of observations was 64 × 2 = 128 since each trial contained two active lines (see Sec. 4.1.3). The order of sequences of gaze behaviour composition, within and between trials, was randomised and balanced for all our participants.

The idle and moving crowd trials were separated into two blocks of 32 trials split by a mandatory break, to minimise fatigue. Extra breaks were proposed to participants inside each block, who could also stop at any moment. To control motion sickness issues, we used the Fast Motion Sickness scale [Keshavarz and Hecht 2011], reporting participants' state every 16 trials. None of them suffered from high motion sickness, and all integrally completed the study.

Finally, participants were asked to fill post-experiment questionnaires: i) a demographic questionnaire (age, gender, experience with VR and games), ii) the Lateral Preference Inventory questionnaire [Coren 1993], iii) the Liebowitz Social Anxiety Scale that measures the level of social anxiety as a trait expressed in daily life [Liebowitz 1987], and iv) the Bailenson et al. [2003] social presence questionnaire. There was also a semi-directed space for comments, asking participants their walking and collision avoidance strategy, and their guess and feeling about manipulated factors.

4.4 Data collection

We collected two types of data, both quantitative: i) continuous participant's nonverbal behaviours during the VR experience, and ii) participant's responses to the questionnaires. We also got qualitative data by collecting participants' comments after the study.

For i), gaze behaviour was collected using the HMD embedded eye-tracking system, and global and local locomotion behaviours through the VR tracking system. At each frame, participant's gaze data were logged, indicating the presence of a hit on virtual agents' heads, as well as the participant's head, hand and shoulder positions.

For ii), data was collected through post-experiment questionnaires: demographics (age, gender, experience with VR and games), eye, hand, feet, and ear lateral preferences (using the Lateral Preference Inventory with scores ranging from -16 to 16 i.e., from left to right [Coren 1993]), self-estimated social presence felt during VR experiment (with scores ranging from 5 to 35 i.e., from low to high social presence [Bailenson et al. 2003]), self-estimated social anxiety (using the Liebowitz Social Anxiety Scale [Liebowitz 1987] that ranges from 0: not socially anxious to 144: very socially anxious).

4.5 Dependent variables

To assess H1 hypothesis, we computed dependent variables linked to participants' gaze behaviour towards virtual agents, from eye-tracking data. Gaze activity was split between saccades when shorter than 150 *ms*, and fixations when longer [Manor and Gordon 2003; Westheimer 1954]. For each trial, we considered these metrics, previously identified as appropriate to detect the stare-in-the-crowd effect [Crehan and Althoff 2015; Von Grünau and Anston 1995] :

- Dwell time: the total time spent looking at a virtual agent;

- Fixation count: the total number of fixations on an agent;
- First fixation duration: the length of the first fixation.

We computed these variables with the same method used in previous studies [Crehan and Althoff 2015; Raimbaud et al. 2022]). For condition A, for fair comparison with other conditions, dependent variables were averaged over the four agents of a line.

Then, to assess H2 we computed the following dependent variables from the participant locomotion data, according to the crowd composition and the gaze spatial distribution we chose:

- Crossing-side percentage: the percentage of left and right side choices when passing through a line of agents (any side can be chosen indifferently for analysis).

To assess H3, we computed metrics used for proximity and collision avoidance studies [Berton et al. 2020; Patotskaya et al. 2023]. We only considered the trials where the participant chose to cross the line through the side of a studied agent, focusing on central gazing agents only (not the ones on the extreme parts of a four-agents line – most of our metrics could not be computed correctly), and omitting the trials with two gazing agents – local deviations in distance/orientation could not be firmly attributed to one of them.

- Lateral crossing distance: the lateral distance at the agent’s left or right side (when crossing the line its belongs to);
- Frontal crossing distance: the frontal distance to the agent after starting the deviation towards its side;
- Minimum distance: the closest distance to the crossed agent;
- Mean distance: the mean of the distance to the crossed agent in the crossing zone (the zone between the frontal crossing point and the lateral crossing one);
- Minimum shoulder angle: the shoulder angle rotated the most towards the crossed agent in the crossing zone (negative when oriented towards the agent, 0 when the shoulders are horizontally aligned, positive when outwardly oriented)
- Maximum shoulder angle: the shoulder angle rotated the least towards the crossed agent (same spatial zone and scale)
- Mean percentage of outwardly-oriented shoulder angle: the mean percent of time when the shoulder angle was not oriented towards the crossed agent (same spatial zone).

To assess H4, we computed and analysed participants’ level of social anxiety from Liebowitz questionnaire, the lateral preference score, the social presence score, and demographic variables.

In order to assess the effect of eye-contact when navigating a crowd, we used separate one-way repeated-measures ANOVAs for idle and moving crowd conditions. ANOVAs had 4 levels (A, D, AD, and DA) except for crossing-side percentage where it had 7 levels (A, D gaze on the left side of the virtual agents’ line, D on the right one, AD left, AD right, DA left, and DA right). We set the level of significance to $\alpha = 0.05$. Results are reported as mean \pm SD. We verified the normality and sphericity assumptions (checked with Shapiro-Wilk’s and Mauchly’s tests) for all variables, and excluded outliers (values below the 1st quartile - 3 * interquartile range (IQR) or above the 3rd quartile + 3 * IQR). In case of a significant effect, we performed pairwise post-hoc comparisons with Bonferroni correction. Finally, to evaluate the link between social anxiety and gaze or locomotor variables, we performed Pearson correlations.

5 RESULTS

The analysis of demographic data did not reveal any particular effect on behavioural data, neither did lateral preferences (eye, feet, total). The social presence score felt in VR was 19.4 ± 4.3 (average, SD), showing a medium level of social presence with the crowd.

5.1 Gaze behaviour

Fig. 4 shows the mean and standard deviations of our gaze variables. The dwell time was significantly affected by the agents’ gaze condition, both for the idle crowd ($F(3,57) = 17.47$, $p < 0.00001^{***}$, $\eta_p^2 = 0.48$) and the walking one ($F(3,57) = 8.74$, $p = 0.00007^{***}$, $\eta_p^2 = 0.32$). Post-hoc tests revealed that this variable was significantly lower in the A condition compared to D, AD and DA ones for both crowds (see Table 1), and that there were no other significant differences.

The fixation count was significantly different depending on the agents’ gaze condition, both for the idle crowd ($F(3,57) = 17.48$, $p < 0.00001^{***}$, $\eta_p^2 = 0.48$) and the walking one ($F(3,57) = 10.67$, $p = 0.00001^{***}$, $\eta_p^2 = 0.36$). Post-hoc tests revealed that this metric was significantly lower in the A condition compared to D, AD and DA ones, for both crowds (see Table 1). For the idle crowd, we found significantly higher results in the AD condition than in the DA one.

The first fixation duration was significantly different depending on the agents’ gaze, for the idle crowd ($F(3,51) = 20.63$, $p < 0.00001^{***}$, $\eta_p^2 = 0.55$) and the walking one ($F(3,54) = 8.74$, $p = 0.00004^{***}$, $\eta_p^2 = 0.34$). Post-hoc tests showed that the metric was significantly lower in the A condition compared to D, AD and DA ones (see Table 1), for both crowds, and that there were no other significant differences.

Table 1: Effect of virtual agents’ gaze behaviours on dwell time, fixation count and first fixation duration: post-hoc comparisons with significant differences.

	Idle Crowd			Moving Crowd		
	t	p bonf	η_p^2	t	p bonf	η_p^2
Dwell time						
A vs. D	-4.74	0.00086 ***	0.54	-3.86	0.00626 **	0.44
A vs. AD	-5.95	0.00006 ***	0.65	-4.51	0.00145 **	0.52
A vs. DA	-5.95	0.00006 ***	0.65	-4.35	0.00201 **	0.50
Fixation count						
A vs. D	-4.79	0.00077 ***	0.55	-4.16	0.00322 **	0.48
A vs. AD	-5.90	0.00007 ***	0.65	-4.54	0.00134 **	0.52
A vs. DA	-4.68	0.00099 ***	0.54	-4.48	0.00154 **	0.51
AD vs. DA	3.40	0.01803 *	0.38	-	-	-
First fixation duration						
A vs. D	-5.97	0.00009 ***	0.68	-4.93	0.00066 ***	0.57
A vs. AD	-6.15	0.00006 ***	0.69	-3.65	0.0110 *	0.43
A vs. DA	-7.32	<0.00001***	0.76	-4.32	0.00246 **	0.51

* for p-values < 0.05, ** < 0.01 and *** < 0.001. Time and duration in seconds.

5.2 Locomotor behaviours

5.2.1 Global path decision behaviours. Analyses on participants’ left-side crossing percentages are given here – right-side crossing analyses are equivalent. Results were not significantly different

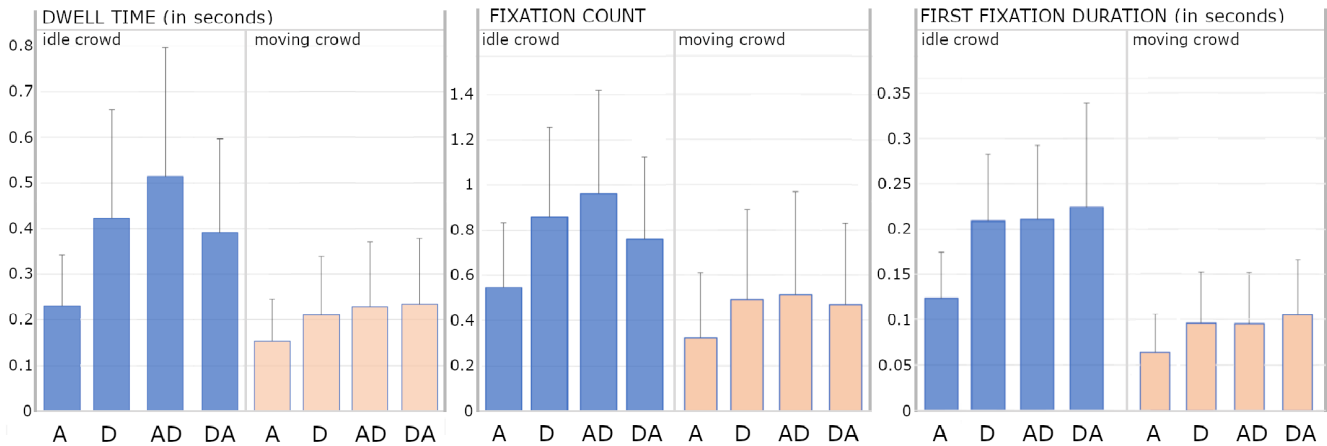


Figure 4: Mean ± SD of participants' gaze behavioural data depending on gaze and crowd conditions

across gaze conditions, nor for the idle crowd ($F(6,120) = 0.58, p = 0.75$), neither for the moving crowd ($F(6,120) = 1.80, p = 0.10$).

5.2.2 Local body interaction behaviours. For each participant, we computed all our dependent variable values as the means of such values when crossing the relevant virtual agent, for each gaze condition (or a missing value in absence of any crossing towards the evaluated gaze condition over all the associated trials). We found that the results were not significantly different across gaze conditions, for both crowd conditions. For example, for the minimum distance, results were ($F(3,48) = 0.55, p = 0.65$) with the idle crowd, and ($F(3,54) = 0.63, p = 0.60$) with the moving crowd, and for the maximum shoulder angle, results were ($F(3,48) = 2.32, p = 0.09$) with the idle crowd, and ($F(3,54) = 2.71, p = 0.06$) with the moving crowd.

5.3 Social anxiety and nonverbal behaviours

Results showed negative correlations between the social anxiety level and our three variables in D condition, for both crowds. Fig. 5 illustrates it for the dwell time variable, and Table 2 provides all detailed values. We also found a negative correlation with the AD condition in the moving crowd ($r = -0.39, p = 0.0445^*$) for our three variables, as well as an interesting but not significant trend in the A condition for the first fixation duration ($r = -0.39, p = 0.0518$).

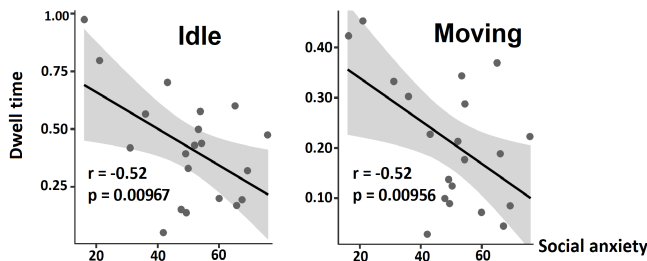


Figure 5: Significant negative correlations between participants' social anxiety and dwell time towards directed gazes.

There was no correlation between social anxiety and the cross-side percentage in any gaze condition for the idle crowd. However,

Table 2: Correlations between participants' gaze behaviour and social anxiety level, in D condition, for both crowds.

	Idle crowd, D		Moving crowd, D	
	r	p	r	p
Dwell time	-0.52	0.00967 **	-0.52	0.00956 **
Fixation count	-0.42	0.03118 *	-0.39	0.04516 *
First fixation dur.	-0.40	0.04437 *	-0.55	0.00710 **

* for p-values < 0.05, ** < 0.01 and *** < 0.001.

in the case of the moving crowd, we did find a negative correlation in all gaze conditions (A, D on the left and on the right side, AD left/right, DA left/right), when considering the left-side frequencies – positive if considering the right ones. Details are given in Table 3.

Table 3: Participants' left-side crossing percentage and social anxiety correlations, all gaze conditions, moving crowd only.

	Moving crowd						
	A	D left	D right	AD left	AD right	DA left	DA right
r	-0.46	-0.61	-0.71	-0.42	-0.50	-0.49	-0.43
p	0.017*	0.0018**	0.0002***	0.029*	0.010*	0.013*	0.025*

* for p-values < 0.05, ** < 0.01 and *** < 0.001.

Finally, there was no correlation between social anxiety level and distance metrics in any of the gaze conditions, for both types of crowds. However, we found positive correlations between social anxiety level and our four shoulder orientation metrics in the D and AD gaze conditions for the idle crowd (see Table 4). For the moving crowd, results for D and AD were close to significant positive correlations (p-values between 0.05 and 0.10), but interestingly we found positive correlations in the DA condition for minimum angle ($r = 0.45, p = 0.020$), and maximum angle ($r = 0.45, p = 0.021$).

Table 4: Participants' shoulder rotations and social anxiety correlations in D and AD conditions, for idle crowd only.

	Idle crowd, D		Idle crowd, AD	
	r	p	r	p
Min. shoulder angle	0.61	0.00277 **	0.39	0.04989 *
Max. shoulder angle	0.46	0.02474 *	0.39	0.04927 *
Mean perc. outw. ang.	0.56	0.00591 **	0.29	0.115 (ns)

* for p-values < 0.05, ** < 0.01 and *** < 0.001.

6 DISCUSSION

We investigated here the presence of the stare-in-the-crowd effect and other changes to global and local locomotor behaviour, as well as participants' individual characteristics when they move through an idle or moving crowd where virtual agents looked or not at them.

First, our results revealed different gaze behaviours of participants towards averted (A) and directed (D) gazes of agents, based on significant differences between these conditions for all our metrics (dwell time, fixation count, first fixation duration, see Table 1), for both types of crowds. Moreover, shifting gaze behaviour conditions (AD and DA), which also contain directed gaze behaviours, showed the same asymmetry when compared to the A condition. Therefore, our **hypothesis H1 is verified**, meaning that the stare-in-the-crowd effect is still valid in more complex situations where an individual navigates a crowd. Regarding the complexity of the situation, we found the presence of the stare-in-the-crowd effect in the idle and the moving crowd conditions, observing in both cases a large effect size (partial eta squared), similarly to Raimbaud et al. [2022] study. In a study without gaze manipulation, Hessels et al. [2020] did not find any particular fixation on faces compared to other elements of the environment when moving through a crowd, which would indicate that the attention to gazes and the stare-in-the-crowd effect could be diminished in dynamic conditions. This suggests that the stare-in-the-crowd effect might be modulated by the interplay between social cues (looking or not at the participant) and physical integrity preservation, when participants have to avoid collisions. As suggested by Meerhoff et al. [2018], when navigating a crowd of virtual agents without any eye representation, participants looked at the ones showing the highest risk of collision. Information about the gaze of the other walkers might be essential in that context when uncertainty exists [Nummenmaa et al. 2009; Varma et al. 2017] or in no major collision risk situations.

Second, **we also verified the hypothesis H2**, since our analysis of the participants' locomotor behaviours did not show any effect of gaze conditions on path decision. This was expected due to the specifics of our task, where the movement of the crowd was not unpredictable (either idle behaviour or moving in straight line without any motion adaptation), thus reducing the importance of mutual gaze for navigation. However, the local interactions to agents in the form of proximity and shoulder angle changes according to gaze conditions for our two types of crowds were also not affected (see 5.2), even though this goes against the evidence that there is a link between proximity and gaze [Bailenson et al. 2001]. Therefore, **our hypothesis H3 is not verified**. We did find a trend in the idle

crowd condition, where the directed gaze condition was associated with the increased outward rotation of the shoulder. While the effect was not significant, it still provided an indication of a local behaviour change in the expected direction (increasing distance to the agent while passing them). The reasons for absence of these effects could be due to constricted space – since participants had a relatively limited space for avoidance of the agents while walking, they could have compromised their walking trajectory to be equally spaced between obstacles, a known strategy when passing between two human obstacles [Hackney et al. 2015]. It is important to note that in our experiment, we did not embody the participant in an avatar, but used VR controllers as references of the body in the virtual space, which gave a sense of agency to the participant. In the paper of Mousas et al., the effect of gaze on the path length, duration, and deviation of collision avoidance with a static agent was found but only when the participants were embodied in an avatar, thus showing the importance of the presence of the virtual body when exploring gaze effects on avoidance [Mousas et al. 2019]. The lack of gaze effects on global and local behaviours in our experiment could thus have been due to the lack of visual cues of one's own body in VR. Further studies are needed to explore the effect of gaze in a crowd while the user is embodied in a human avatar.

Third, the participants' social anxiety level analysis as well as our behavioural metrics analysis with respect to crowd gaze conditions revealed several significant correlations. Notably, in the case of directed and averted-then-directed gaze conditions, the variables related to reactive behaviours of socially anxious participants towards the studied agent showed: i) negatives correlations for time-related gaze metrics, in line with Raimbaud et al. [2022], for both crowds; ii) positive correlations for avoiding-angle metrics for the idle crowd. In this respect, **H4 is partly verified**. Some post-experiment comments also highlighted this relation between social anxiety and behaviours: *"I was stressed a lot. I tried to squeeze my shoulders"*. Interestingly, only socially anxious participants mentioned their shoulders for their navigation strategy *"I turned my shoulders to avoid people"*; *"I rotated my shoulder to smoothly pass"*.

Lastly, we also found other effects of the agents' gaze behaviours. First, the DA gaze condition is interesting: for the idle crowd, the effect on the participant's gaze behaviour was significantly lower than in the AD condition; however, for the moving crowd condition, the DA condition was the only one where the maximum and minimum shoulder orientations were correlated to the participant's social anxiety level, with larger avoidance. One explanation could be that when the crowd is moving, participants interpreted DA gazes as an increase of the absence of cooperation from the agent to avoid the upcoming collision [Olivier et al. 2013]. Then, we found an interesting effect of social anxiety on the global path decision: for moving crowds, we found significant negative correlations in the left side, under all agents' gaze conditions (see Table 3). This might be explained by the fact that under the stress of the upcoming crowd, socially anxious people went to their "default path" choice, the right one in many countries [Chattaraj et al. 2009]. Moreover, still in the moving crowd condition, we observed a negative correlation between the social anxiety level and the participants' gaze behaviours towards agents under the A condition, although not significant, in line with the literature about the fact that averted gaze can induce discomfort in the socially anxious individuals too [Raimbaud et al.

2022; Wieser et al. 2009]. Finally, we did not find any evidence that supports the claim that females generally keep further distances from the agents in VR compared to males [Iachini et al. 2016; Zibrek et al. 2020]. This could be because our sample of participants was not well balanced in terms of gender, therefore, effect could not be detected. Future studies are needed to investigate the gender effect on the local behaviour while walking through a virtual crowd.

7 CONCLUSIONS AND FUTURE WORK

The results of our study show that gaze of virtual agents when walking through an idle or moving crowd affects VR users' attention to mutual gaze but does not affect navigation. Additionally, we found that social anxiety is an important characteristic that reduces the attention to gazes but also affects local navigation behaviours in terms of body orientation between the socially anxious individual and the virtual agent. These insights suggest that VR developers that aim to create realistic crowds should proceed to a trade-off between gaze realism and its (possibly unwanted) effects on participants.

In the future, more challenging navigation situations could be considered, such as moving through a crowd that moves in different directions and where a virtual agent's behaviour is more unpredictable. Increasing the avoidance area for the users, e.g., with wider gaps between agents in the crowd, could also potentially show more differences in navigation behaviours due to a reduction of physical constraints for the user. Exploring these and potential other factors in future research could be beneficial to understand the complex nature of the effect of an agent's gaze on the user's social behaviour.

ACKNOWLEDGMENTS

We would like to thank the participants of our experiment. This work received funding from the European Union (No 856879, H2020 ICT-25 RIA PRESENT project), the Brittany Region (No 19023, SAD-2019-REACTIVE project), the French government (Investments for the Future program PIA, French National Research Agency, ANR-21-ESRE-0030, CONTINUUM project), and the French National Centre for Scientific Research CNRS (INS2I, ETC-RAS-RV project).

REFERENCES

- Andrea Abele. 1986. Functions of gaze in social interaction: Communication and monitoring. *Journal of Nonverbal Behavior* 10 (1986), 83–101.
- Michael Argyle and Mark Cook. 1976. *Gaze and mutual gaze*. Cambridge U Press, Cambridge, UK.
- Michael Argyle and Janet Dean. 1965. Eye-contact, distance and affiliation. *Sociometry* 28, 3 (1965), 289–304.
- Jeremy N Bailenson, Jim Blascovich, Andrew C Beall, and Jack M Loomis. 2001. Equilibrium theory revisited: Mutual gaze and personal space in virtual environments. *Presence: Teleoperators & Virtual Environments* 10, 6 (2001), 583–598.
- Jeremy N Bailenson, Jim Blascovich, Andrew C Beall, and Jack M Loomis. 2003. Interpersonal distance in immersive virtual environments. *Personality and social psychology bulletin* 29, 7 (2003), 819–833.
- Sarah R Baker and Robert J Edelman. 2002. Is social phobia related to lack of social skills? Duration of skill-related behaviours and ratings of behavioural adequacy. *British Journal of Clinical Psychology* 41, 3 (2002), 243–257.
- Florian Berton, Fabien Grzeskowiak, Alexandre Bonneau, Alberto Jovane, Marco Aggravi, Ludovic Hoyet, Anne-Helene Olivier, Claudio Pacchierotti, and Julien Pettre. 2020. Crowd navigation in vr: exploring haptic rendering of collisions. *IEEE Transactions on Visualization and Computer Graphics* 28, 7 (2020), 2589–2601.
- Richard W Bohannon. 1997. Comfortable and maximum walking speed of adults aged 20–79 years: reference values and determinants. *Age and ageing* 26, 1 (1997), 15–19.
- Adele T Brady and Michael B Walker. 1978. Interpersonal distance as a function of situationally induced anxiety. *British Journal of Social and Clinical Psychology* 17, 2 (1978), 127–133.
- Ujjal Chattaraj, Armin Seyfried, and Partha Chakroborty. 2009. Comparison of pedestrian fundamental diagram across cultures. *Advances in complex systems* 12, 03 (2009), 393–405.
- David M Clark. 1995. A cognitive model of social phobia. *Social phobia: Diagnosis, assessment, and treatment* 1, 1 (1995), 69–73.
- Clara Colombatto, Benjamin van Buren, and Brian J Scholl. 2020. Gazing Without Eyes: A “Stare-in-the-Crowd” Effect Induced by Simple Geometric Shapes. *Perception* 49, 7 (2020), 782–792.
- Robbie M Cooper, Anna S Law, and Stephen RH Langton. 2013. Looking back at the stare-in-the-crowd effect: Staring eyes do not capture attention in visual search. *Journal of vision* 13, 6 (2013), 10–10.
- Stanley Coren. 1993. The lateral preference inventory for measurement of handedness, footedness, eyedness, and earedness: Norms for young adults. *Bulletin of the Psychonomic Society* 31, 1 (1993), 1–3.
- Eileen T Crehan and Robert R Althoff. 2015. Measuring the stare-in-the-crowd effect: a new paradigm to study social perception. *Behavior research methods* 47, 4 (2015), 994–1003.
- Georgiana Cristina Dobre, Marco Gillies, Patrick Falk, Jamie A Ward, Antonia F de C Hamilton, and Xueni Pan. 2021. Direct gaze triggers higher frequency of gaze change: An automatic analysis of dyads in unstructured conversation. In *Proceedings of the 2021 International Conference on Multimodal Interaction*. Association for Computing Machinery, New York, NY, USA, 735–739. <https://doi.org/10.1145/3462244.3479962>
- Hirokazu Doi and Kazuhiro Ueda. 2007. Searching for a perceived stare in the crowd. *Perception* 36, 5 (2007), 773–780.
- Wilberta L Donovan and Lewis A Leavitt. 1980. Physiologic correlates of direct and averted gaze. *Biological Psychology* 10, 3 (1980), 189–199.
- Darren Gergle and Alan T Clark. 2011. See what I'm saying? Using dyadic mobile eye tracking to study collaborative reference. In *Proceedings of the ACM 2011 conference on Computer supported cooperative work*. Association for Computing Machinery, New York, NY, USA, 435–444.
- Mar Gonzalez-Franco, Eyal Ofek, Ye Pan, Angus Antley, Anthony Steed, Bernhard Spanlang, Antonella Maselli, Domna Banakou, Núria Pelechano Gómez, Sergio Orts-Escolano, et al. 2020. The rocketbox library and the utility of freely available rigged avatars. *Frontiers in virtual reality* 1, 561558 (2020), 1–23.
- Amy L Hackney, Michael E Cinelli, and James S Frank. 2015. Does the passability of apertures change when walking through human versus pole obstacles? *Acta psychologica* 162 (2015), 62–68. <https://doi.org/10.1016/j.actpsy.2015.10.007>
- Mijna Hadders-Algra. 2022. Human face and gaze perception is highly context specific and involves bottom-up and top-down neural processing. *Neuroscience & Biobehavioral Reviews* 132 (2022), 304–323.
- Edmund T Hall and Edward T Hall. 1966. *The hidden dimension*. Vol. 609. Anchor, NY, USA.
- Jimi Harrigan, Robert Rosenthal, Klaus R Scherer, and Klaus Scherer. 2008. *New handbook of methods in nonverbal behavior research*. Oxford University Press, Oxford, United Kingdom.
- Roy S Hessels, Jeroen S Benjamins, Diederick C Niehorster, Andrea J van Doorn, Jan J Koenderink, Gijs A Holleman, Yentl JR de Kloof, Niilo V Valtakari, Sebas van Hal, and Ignace TC Hooge. 2022. Eye contact avoidance in crowds: A large wearable eye-tracking study. *Attention, Perception, & Psychophysics* 84, 8 (2022), 2623–2640.
- Roy S Hessels, Gijs A Holleman, Tim HW Cornelissen, Ignace TC Hooge, and Chantal Kemmer. 2018. Eye contact takes two—autistic and social anxiety traits predict gaze behavior in dyadic interaction. *Journal of Experimental Psychopathology* 9, 2 (2018), jep-062917.
- Roy S Hessels, Andrea J van Doorn, Jeroen S Benjamins, Gijs A Holleman, and Ignace TC Hooge. 2020. Task-related gaze control in human crowd navigation. *Attention, Perception, & Psychophysics* 82 (2020), 2482–2501.
- Kaye Horley, Lea M Williams, Craig Gonsalvez, and Evian Gordon. 2003. Social phobics do not see eye to eye: A visual scanpath study of emotional expression processing. *Journal of anxiety disorders* 17, 1 (2003), 33–44.
- Tina Iachini, Yann Coello, Francesca Frassinetti, Vincenzo Paolo Senese, Francesco Galante, and Gennaro Ruggiero. 2016. Peripersonal and interpersonal space in virtual and real environments: Effects of gender and age. *Journal of Environmental Psychology* 45 (2016), 154–164.
- Koki Ijuin and Kristiina Jokinen. 2020. Exploring gaze behaviour and perceived personality traits. In *Social Computing and Social Media. Design, Ethics, User Behavior, and Social Network Analysis: 12th International Conference, SCISM 2020, Held as Part of the 22nd HCI International Conference, HCII 2020, Copenhagen, Denmark, July 19–24, 2020, Proceedings, Part I 22*. Springer, Springer International Publishing, Cham, 504–512.
- Smiti Kahlon, Philip Lindner, and Tine Nordgreen. 2019. Virtual reality exposure therapy for adolescents with fear of public speaking: a non-randomized feasibility and pilot study. *Child and adolescent psychiatry and mental health* 13, 1 (2019), 1–10.
- Behrang Keshavarz and Heiko Hecht. 2011. Validating an efficient method to quantify motion sickness. *Human factors* 53, 4 (2011), 415–426.
- Chris L Kleinke and Paul D Pohlen. 1971. Affective and emotional responses as a function of other person's gaze and cooperativeness in a two-person game. *Journal*

- of *Personality and Social Psychology* 17, 3 (1971), 308.
- Bastian Lange and Paul Pauli. 2019. Social anxiety changes the way we move—A social approach-avoidance task in a virtual reality CAVE system. *PLoS One* 14, 12 (2019), e0226805.
- Michael R Liebowitz. 1987. Social phobia. *Modern problems of pharmacopsychiatry* 22 (1987), 141–173.
- Sean D Lynch, Julien Pettré, Julien Bruneau, Richard Kulpa, Armel Crétual, and Anne-Hélène Olivier. 2018. Effect of virtual human gaze behaviour during an orthogonal collision avoidance walking task. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, IEEExplore, NY, USA, 136–142.
- Barry R. Manor and Evian Gordon. 2003. Defining the temporal threshold for ocular fixation in free-viewing visuo-cognitive tasks. *Journal of Neuroscience Methods* 128, 1 (2003), 85–93. <https://www.sciencedirect.com/science/article/pii/S0165027003001511>
- Laurentius Antonius Meerhoff, Julien Bruneau, Alexandre Vu, A-H Olivier, and Julien Pettré. 2018. Guided by gaze: Prioritization strategy when navigating through a virtual crowd can be assessed through gaze activity. *Acta psychologica* 190 (2018), 248–257.
- Christos Mousas, Alexandros Koiliias, Dimitris Anastasiou, Banafsheh Rekabdar, and Christos-Nikolaos Anagnostopoulos. 2019. Effects of self-avatar and gaze on avoidance movement behavior. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, IEEExplore, NY, USA, 726–734.
- Hisashi Murakami, Takenori Tomaru, Claudio Feliciani, and Yuta Nishiyama. 2022. Spontaneous behavioral coordination between avoiding pedestrians requires mutual anticipation rather than mutual gaze. *IScience* 25, 11 (2022), 105474.
- Lauri Nummenmaa, Jukka Hyönä, and Jari K Hietanen. 2009. I'll walk this way: Eyes reveal the direction of locomotion and make passersby look and go the other way. *Psychological science* 20, 12 (2009), 1454–1458.
- Anne-Hélène Olivier, Antoine Marin, Armel Crétual, Alain Berthoz, and Julien Pettré. 2013. Collision avoidance between two walkers: Role-dependent strategies. *Gait & posture* 38, 4 (2013), 751–756.
- Adam Palanica and Roxane J Itier. 2011. Searching for a perceived gaze direction using eye tracking. *Journal of Vision* 11, 2 (2011), 19–19.
- Yuliya Patotskaya, Ludovic Hoyet, Anne-Hélène Olivier, Julien Pettré, and Katja 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>
- Christopher Peters. 2005. Direction of attention perception for conversation initiation in virtual environments. In *Intelligent Virtual Agents: 5th International Working Conference, IVA 2005, Kos, Greece, September 12-14, 2005. Proceedings 5*. Springer, Springer International Publishing, Cham, 215–228.
- Andre Pittig, Joanna J Arch, Chi WR Lam, and Michelle G Craske. 2013. Heart rate and heart rate variability in panic, social anxiety, obsessive-compulsive, and generalized anxiety disorders at baseline and in response to relaxation and hyperventilation. *International journal of psychophysiology* 87, 1 (2013), 19–27.
- Pierre Raimbaud, Alberto Jovane, Katja Zibrek, Claudio Pacchierotti, Marc Christie, Ludovic Hoyet, Julien Pettré, and Anne-Hélène Olivier. 2022. The Stare-in-the-Crowd Effect in Virtual Reality. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, IEEExplore, NY, USA, 281–290.
- Nayantara Ramamoorthy, Kate Plaisted-Grant, and Greg Davis. 2019. Fractionating the stare-in-the-crowd effect: Two distinct, obligatory biases in search for gaze. *Journal of Experimental Psychology: Human Perception and Performance* 45, 8 (2019), 1015.
- John F Rauthmann, Christian T Seubert, Pierre Sachse, and Marco R Furtner. 2012. Eyes as windows to the soul: Gazing behavior is related to personality. *Journal of Research in Personality* 46, 2 (2012), 147–156.
- Daniel Roth, Peter Kullmann, Gary Bente, Dominik Gall, and Marc Erich Latoschik. 2018. Effects of hybrid and synthetic social gaze in avatar-mediated interactions. In *2018 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*. IEEE, IEEExplore, NY, USA, 103–108.
- K. Ruhland, C. E. Peters, S. Andrist, J. B. Badler, N. I. Badler, M. Gleicher, B. Mutlu, and R. McDonnell. 2015. A Review of Eye Gaze in Virtual Agents, Social Robotics and HCI: Behaviour Generation, User Interaction and Perception. *Computer Graphics Forum* 34, 6 (2015), 299–326. <https://doi.org/10.1111/cgf.12603>
- Julian Schmitz, Corinna N Scheel, Alessandro Rigon, James J Gross, and Jens Blechert. 2012. You don't like me, do you? Enhanced ERP responses to averted eye gaze in social anxiety. *Biological psychology* 91, 2 (2012), 263–269.
- Lars Schulze, Janek S. Lobmaier, Manuel Arnold, and Babette Renneberg. 2013. All eyes on me?! Social anxiety and self-directed perception of eye gaze. *Cognition and Emotion* 27, 7 (2013), 1305–1313. <https://doi.org/10.1080/02699931.2013.773881> PMID: 23438447.
- Kamala Varma, Stephen J Guy, and Victoria Interrante. 2017. Assessing the relevance of eye gaze patterns during collision avoidance in virtual reality. In *Proceedings of the 27th International Conference on Artificial Reality and Telexistence and 22nd Eurographics Symposium on Virtual Environments*. The Eurographics Association, Groene Loper 3, 5612AE Eindhoven, Netherlands, 149–152.
- Michael Von Grünau and Christina Anston. 1995. The detection of gaze direction: A stare-in-the-crowd effect. *Perception* 24, 11 (1995), 1297–1313.
- Gerald Westheimer. 1954. Eye movement responses to a horizontally moving visual stimulus. *AMA archives of ophthalmology* 52, 6 (1954), 932–941.
- Matthias J Wieser, Paul Pauli, Georg W Alpers, and Andreas Mühlberger. 2009. Is eye to eye contact really threatening and avoided in social anxiety?—An eye-tracking and psychophysiology study. *Journal of anxiety disorders* 23, 1 (2009), 93–103.
- Matthias J Wieser, Paul Pauli, Miriam Grosseibl, Ina Molzow, and Andreas Mühlberger. 2010. Virtual social interactions in social anxiety—the impact of sex, gaze, and interpersonal distance. *Cyberpsychology, Behavior, and Social Networking* 13, 5 (2010), 547–554.
- Katja Zibrek, Benjamin Niay, Anne-Hélène Olivier, Ludovic Hoyet, Julien Pettré, and Rachel McDonnell. 2020. The effect of gender and attractiveness of motion on proximity in virtual reality. *ACM Transactions on Applied Perception (TAP)* 17, 4 (2020), 1–15.