Computers & Graphics (2022)

Contents lists available at ScienceDirect

Computers & Graphics

journal homepage: www.elsevier.com/locate/cag

Avoiding virtual humans in a constrained environment: exploration of novel behavioural measures

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ARTICLE INFO

Article history:
Received December 31, 2022

Keywords: Perception, VR, Personality, Virtual Characters, Trajectory Analysis

ABSTRACT

In computer animation, the creation of believable and engaging virtual characters has been a long-lasting endeavour. While researchers investigated several aspects of character design, not many studies focused on the qualities of biological human motion itself. We approached the perception of motion from the perspective of distinct movement patterns which can be observed on people with neurotic and emotionally stable personality traits. We designed an experiment in virtual reality, using a photo-realistic metro scenario, where we studied the avoidance behaviour of participants when encountering these two types of virtual characters in a constrained environment. We also make a contribution by successfully implementing two behavioural measures in particular: a choice task, and a novel 'turning point' metric, which calculates the point in the trajectory when people turned to avoid the character. Our results indicate that users' behaviour is affected by character's motion and we propose the use of these behavioural measures to investigate other aspects of character motion in future research.

1. Introduction

As the every-day exposure to virtual humans is increasing, there is more incentive to understand their effect on people's perception. Animation is an important part of the character design and a considerable amount of research in computer animation is studying the traits of biological motion to create realistic characters. The aim of such studies is often to generate artificial motion which appears natural, while distinct movement patterns are analysed with the intent to create variety in motion.

Not many studies focus on exploring the behavioural effect of biological human motion, applied to virtual characters, on the observers. Particularly when used for serious applications, such as psychotherapy [1], medical rehabilitation [2] and training in VR, understanding how characters affect people's responses is highly relevant. For example, characters who are considered pleasant to observe could inspire positive emotions, engagement and cooperative behaviour of people [3, 4]. In our study, we make a novel contribution by exploring people's responses to 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. [5]. As both personalities have distinct movement patterns, we anticipated that only by observing the character's movement, the users will react to these motions with a particular behavioural response which would signal positive or negative attitude towards them.

Current work contributes to the understanding of how the virtual characters with distinct personalities can influence the behaviour of an observer immersed in a highly constrained [6], enclosed virtual environment. The interest to investigate this type of environment is motivated with many real-life-inspired scenarios which have constrained-space nature, for example shops, transport, bars, etc. We explore if we can outline specific be-

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Fig. 1. Metro scene from our experiment with virtual characters: "Cooper" (*left*) expressing the neurotic personality with body and facial motion, and "Yuri" (*right*) expressing the emotionally stable personality.

havioural features, particularly in the participant's walking trajectory, or would these differences be fully extinguished due to constraints of their maneuver space. Our proposed constrained environment revealed some significant features in users' locomotion, showing specific meaningful patterns in their behavior depending on the character's personality in their proximity. To measure this, we analyse the participant's trajectory data, which contains rich information about participant's behaviour. In addition, the highly-constrained environment enabled us to create a simple decision making task, where we could easily categorise peoples' preferences.

We designed a simple task in VR, where the user walked through the metro and exited by selecting one of the doors to the right or left (see Figure 1). In front of each door, there was either a neurotic or emotionally stable virtual character. The user had to first pass between both characters and then avoid one of the characters to exit. We anticipated that in doing so, the user's choice of doors and walking trajectory will be impacted: we expected people will try to maintain a larger personal space around the neurotic character or choose to exit by passing the emotionally stable character when given a choice. To identify the behavioral changes, we implemented a novel trajectory analysis approach (turning point), which would identify the distance at which the user would turn around the character to avoid it. This measure is similar to the deviation point (see, e.g., Bourgaize et al. [7]) but is specifically designed for a constrained space. In smaller spaces users need to avoid collisions while maintaining personal space, as described in Bönsch et al. [6], so we propose that the turning point could capture subtle aspects of human behaviour in this restricted space. We also implemented several well-known metrics for evaluation of the interaction experience in VR, most of them based on the use of personal space (e.g., proximity or clearance distance).

Our main contributions in this paper are: a) the successful implementation of a simple choice task (exiting the metro), b) a novel metrics for trajectory analysis, suitable for constrained spaces (turning point), and c) using these behavioral measures to show a greater avoidance behaviour when in close proximity to a character with neurotic motion as opposed to an emotionally stable one.

The paper is organized as follows: we first introduce the Related Work (Section 2), followed by the Experiment (Section 3), where we begin by explaining our approach to the trajectory analysis, describe how we created our stimuli and designed the experiment, measures, and the protocol for participants we used. In Results (Section 4), we analyse the responses to the subjective and behavioral measures of participants in our experiment. We discuss our findings in the Discussion (Section 5) and conclude the paper in the Conclusion (Section 6).

2. Related Work

2.1. Perception of Human Body Motion

Several studies focused on the perception of human motion. Early work in this area [8, 9] showed that people are very sensitive to the perception of human motion and can perceive complex information from it (gender, emotions, etc.). With the development of 3D graphics, studies analysed human motion by applying it to virtual human models. It was found that the body representation of virtual characters can additionally affect the perception of motion, for example, in a way that it obscures naturalness [10].

There have been attempts to classify or describe human body motions, e.g., expressivity [11, 12], emotions [13], aesthetics [14, 15] or distinctiveness [16]. Rudolf Laban [17] developed a method for categorising quality of human movements called the Laban Movement Analysis (LMA) with descriptors such as timing, space used, posture and intention.

Body motion can also reveal personality traits. The "Big Five" personality theory [18] describes a hierarchical model of personality traits with five broad factors (Extraversion, Agreeableness, Conscientiousness, Openness to Experience, and Emotional Stability). There have been attempts to describe body motion and gaze behaviour related to these personality traits [19, 20, 21, 22]. A subset of these factors have distinctive movement patterns. For example, neuroticism is the polar opposite of emotional stability, where neuroticism is described as being anxious, easily upset, negative and oversensitive. Neff et al. [23] found that neuroticism is associated with body movement, which include rapid movement, indirect gaze and gestures, and self touch. On the contrary, emotionally stable people exhibit calm, controlled and directed gestures.

While people can recognise and categorise the information from body motion of virtual characters, not many studies evaluated their effect on perceived *appeal*. Appealing characters are likable, induce pleasant emotions, are trustworthy and inspire cooperation [4]. Studies in VR found that characters with attractive motion are allowed closer into the user's personal space [24] and characters exhibiting positive emotions facilitate interaction [3]. A non-VR based study by Hoyet et al. [16] found that symmetrical walking motions were perceived to be more attractive than distinctive ones. Another study in VR by Bönsch et al. [25] demonstrated that expressions of negative emotion (anger) increase the users' personal space, signaling a discomfort with the character.

To our knowledge, the effect of the character's motion depending on its personality traits has not been directly investigated yet. Neuroticism (as opposed to emotional stability) was found to be a less pleasant trait of the person or virtual character [26, 5]. For this reason, the use of personal space and locomotion trajectory of the user could be affected. We describe these behavioral measures in more detail below.

2.2. Behavioral measures in VR

Since VR can enable a relatively controlled and ecologically valid experimental environment, behavioral measures are often used in VR to study human perception [27]. These measures are considered to be objective as people cannot control these types of responses, since most are not available to conscious interpretation. Behavioral responses can be reflected in the choice the person makes in the experimental condition, e.g., approaches a specific virtual character in a crowd of characters [3]. Other examples of behavioral measures include analysis of eye-gaze behavior (e.g., number of gaze fixations onto a character) [28, 29, 30] and analysis of human locomotion.

The experiments based on locomotion in VR are becoming more frequently used as a participant's trajectory contains rich information about his experience while performing daily tasks, encountered in physical reality. The unconstrained trajectories produced during virtual walking can be analyzed geometrically and temporally, where task completion time, traveled distance, number of collisions [31, 30] can potentially reflect participants' confidence in their decision, emotional comfort, etc. In the study of Perrinet et al. [32], where a participant walked alongside an emotionally expressive virtual character, metrics such as walking speed, interpersonal distances and relative position of a real to a virtual human, were proposed. The avoidance and maintenance of personal space around virtual characters allows us to understand how people generate their locomotion trajectory in a social situation [33, 7, 34, 35]. This is reflected in the trajectory length [36], average trajectory curvature, maximal lateral deviation and clearance distance [34, 33, 37, 30], i.e. the shortest distance between the participant and the virtual character found during the avoidance task.

These studies in VR have identified some distinctive locomotion patterns of humans in interaction with virtual characters [6, 37, 36]. For example, people avoid virtual humans with a larger clearance distance than virtual obstacles [34], likely because of anticipation of movement [38]. Indeed, a study by Lee et al. [39] showed changes in walking speed and observation ratio when avoiding a moving obstacle, however, the avoidance was shorter when passing repetitive (jumping) behaviour since it was predictable. Other studies by Iachini et al. [40] have shown importance of sex and age of the virtual human, and a study by Zibrek et al. [24] found that a character with an attractive walking motion will be allowed closer into one's personal space.

In this overview of the research, which studied the perception of virtual characters in VR, the experiments often lacked naturalness. For example, a participant needed to stop an approaching virtual character by pulling the trigger of the controller [24]. In our experiment, we are proposing a familiar daily task, where people could use natural locomotion to walk through the virtual environment while avoiding virtual characters.

3. Experiment

The aim of this experiment was to use behavioral measures to evaluate the response to virtual characters who display different personalities. We chose a scenario, where participants would not need to interact but only observe and avoid the characters in a small, restricted space. We also wanted the task to resemble a daily-life scenario, therefore, the 'metro scenario' was chosen, since in a metro people need to make their way to the exit door while avoiding other people. Due to a constrained environment, we anticipated the user's trajectory would be affected and some of the previously used metrics inefficient. For this reason, we developed our own trajectory analysis approach (see Section 3.1), to explore the behaviour of the user engaged with virtual characters in VR.

3.1. Trajectory Analysis

In order to find the approach to the trajectory analysis which would best fit our requirements, we first explored already existing metrics.

Turning Point is a novel metric similar to the deviation point [7]. The deviation point is a point on the walking path, when a participant's medial-lateral centre of mass deviates from the straight path by a threshold distance. The rationale behind this metric is that the deviation point will appear earlier in the trajectory, when people feel uncomfortable of approaching the obstacle in close proximity [7, 34]. This approach was not suitable in our case, since we intended to conduct our experiment in a smaller space with a restricted walking area of $2m \times 3.5m$. Contrary to the deviation point, where the user deviates from a straight line to avoid collision with the virtual character, the goal in our task is not in front of the participant but to left or right, forcing the participant to turn in one direction and avoid the character. We thus anticipated the deviation point will have a different pattern – the participants would walk further to pass the unappealing character. Therefore, we renamed our measure to *Turning Point* and calculated it as an intersection point between two linear functions approximating a path curve of the participants' trajectories of the HMD position in the virtual space. We identified only one turn event, so the path could be approximated with only two lines (see Figure 5).

Minimum distance (or clearance distance [34, 30, 37]) is calculated as the Euclidian distance between the center of mass of the character (in our case, center of mass of the bounding box of the character in the virtual environment) to the closest point in the user's walking trajectory [24].

Clearance area is similar to clearance distance and is based on a concept of personal space across environment factors [41]. But instead of it being one point in the trajectory, it describes the area between the character and part of the participant's trajectory. Clearance area is calculated as the area of a sector bounded with a curve of trajectory and two perpendicular lines, crossing the center of mass of each character in parallel with the axes x and y correspondingly, as shown on Figure 4. We indent $25cm$ from the center of mass of each character along the y-axis and cut off the end of all the trajectories, as pre-experimental trials showed that participants tend to make supplementary movements due to the fact that they are going out from the metro, so the end of trajectory contained non-predictable artefacts as speed decrease, head motions, etc.

We expected that the clearance area will be a more suitable metric than the minimum distance, since it also incorporates the differences in clearance distance when passing the character frontally or laterally [34]. Also, the trajectory of the participant when avoiding the obstacle can occasionally be corrupted with walking oscillations. This was particularly the case in our restricted space scenario, where the trajectory was significantly shorter and not straight as in [34], where the participants had to walk a total path of 8m. Therefore, we expected that the accumulative information represented by the clearance area would more accurately represent the personal space preserved by a participant.

Completion time was measured in milliseconds from one meter on x-axis after the start trajectory and to the end of the trajectory used to calculate clearance area [31]. We cut off the first meter of the trajectory to ensure that walking speed is not affected with secondary factors, such as hesitation at the start of the task.

Before analysing the trajectory, we applied some standard treatment to the trajectory data we collected, e.g., removing artefacts such as medio-lateral oscillations due to stepping activity and frame drops from the raw trajectory path. Since the simulation did not have a constant rate, we temporally re-sampled the data at 40 fps and applied a Butterworth low-pass filter with a cutoff frequency of 1 Hz [28].

3.2. Stimuli Creation

Environment. We used the latest version of Unreal Engine (5.0.1) and a freely available asset at the Unreal Marketplace "City Subway Train Modular" [1]. We used the interior of the metro (see Figure 1) with some adjustments to the original scene to make it appropriate for VR (e.g., remove excessive and dynamic lighting, deleting 3D objects in the background, etc.) but aimed to keep realistic materials and reflections to preserve the realistic appearance. We also added an HDRI backdrop of a train station [2]. We added the animation of exit doors opening accompanied with a green light and a sound. The time from the start of the condition to the door opening event was 20 seconds. We also used unintelligible conversation audio to increase the realism of the scene and to mask any sounds from outside of the experience. The transition between the conditions was seamless, indicated only by the appearance of virtual boards in the environment which instructed the participant to turn and walk back to the initial position (marked on the floor). This way, the participant had an impression of remaining in the same part of the metro during the entire experiment.

[1]https://www.unrealengine.com/marketplace/en-US/product/city-subway-train-modular

[2]https://polyhaven.com/a/dresden_station_night

	Description	Body Motion	Gaze & Head Motion
Emotionally Stable	Calm, not easily upset, low in self-consciousness.	Smooth transitions from one peak activity to the next, no big amplitudes in movement patterns. Directed, measured gestures.	Gaze towards the speaker, mainly in the center, medium amount of blinks. Head motion not frequent, moving from left to right.
Neurotic	Anxious, easily upset, highly self-conscious.	Rapid transitions from low to peak movement, trying to camouflage true emotions and intentions, indirected gestures.	Avoids eye-contact, frequent movements in all directions except upwards, high amount of blinks. Frequent movements of the head.

Table 1. Descriptors for emotionally stable and neurotic personality traits and their corresponding body, gaze and head motion behaviour.

Characters. MetaHuman([3]) characters were downloaded to our project via Unreal Bridge, which enables free access to photo-realistic, fully rigged virtual humans for body and facial animation. Several MetaHuman characters were downloaded and used to populate the metro in the training condition. In the experimental trials, we used two male characters named Cooper and Yuri in the MetaHuman creator (see Figure 1). Male characters were used to match the gender of the performing actor.

Animations. To record the animations, we invited an actor to perform a series of motions while wearing the Xsens 3D motion tracking suit. We asked him to portray two types of personalities, neurotic and an emotionally stable, by focusing on the nonverbal behavior. We gave specific instructions on the type of motions he needs to include in his performance (see Table 1). The descriptions of personality were based on the studies of personality trait descriptions [18], head and gaze behaviour [21, 20] and body motion [42, 23]. The actor acted out a dialogue between the neurotic and emotionally stable character by switching the roles, where the neurotic character was asking for a phone and the emotionally stable character did not wish to give it to him. We did not record the voice of the actor. The facial animations were recorded using the iPhone Live Link Face app. The app uses the iPhone's depth camera to detect the actor's face, overlays it with a virtual facial mesh and sends and stores the deformation data in the form of action units directly onto the MetaHuman character in Unreal 5. Recordings were approx. 1 minute long.

While facial animation was recorded directly on the MetaHuman characters in Unreal, the body animation was retargeted from the default Xsens skeleton to the MetaHuman skeleton. We reviewed the neurotic and emotionally stable recordings and selected the ones which were the most representative of the descriptors presented in Table 1. We used Maya 2022 to clean the animations for jitters and other tracking issues then exported the final animations in the proprietary file format Filmbox ($.fbx$)

[3]https://www.unrealengine.com/en-US/Metahuman

files to the Unreal project, where they were applied to the characters and looped.

We also recorded and retargeted some idle motions of female and male actors standing or sitting in the metro to populate the training condition of the experiment. This was done in order to display a populated metro scene to increase the presence in VR. We used several MetaHuman characters of different gender, which matched the actors', to display these animations. The scene was only used for the training trial and at the middle of the experiment (participants could remove or readjust their headset, etc.), since analysing participant's data with more than two characters was out of scope of this experiment. In the experimental trials, only the Yuri and Cooper characters were featured.

We assigned the neurotic animation either to the Yuri character and emotionally stable to the Cooper character or vice versa before the start for each participant in order to control for any effects of appearance on motion perception. After, this assignment was kept constant for the participant throughout the experiment. We did this so the participants would have a sense that the characters possess distinct personalities (humans do not tend to change personalities in the physical world).

3.3. Experimental Design

To explore how the motion related to personalities of virtual characters influences the users' responses in VR, we set up different experimental conditions in the virtual metro. We used the characters Cooper and Yuri, to which we applied either the neurotic (NE) or emotionally stable (ES) animation, with one participant seeing one combination throughout the whole experiment trial (e.g., NE on Cooper and ES on Yuri). In some conditions, the metro would be empty but in others, the characters were partially obstructing the left and right exit door, so people would need to avoid the character to exit. We also included free choice of exit (both doors open) and forced choice (only left or right door open).

In total, this resulted in 9 combinations (see Table 2):

Conditions 1-3: empty metro, with either free or forced choice of doors (left or right). We used these conditions to investigate the walking trajectory of the participants when there was no character obstructing the exit. This would give us initial information if participants were behaving differently when the metro was empty to when the characters were present, and if they were selecting one side of the metro more readily than the other.

Conditions 4-5: free choice of doors with the characters NE obstructing either the left or right door, and ES placed at the opposite side (see Figure 1). These conditions would indicate if participants chose to avoid a particular character more often than the other one.

Conditions 6-9: forced choice of doors where participants were forced to walk around each character personality on each side. These conditions were designed to study the trajectory around a particular character (NE or ES) and identify potential differences in the trajectory when exiting left or right.

We hypothesised that:

Table 2. Experimental conditions.

Condition	Choice	Character Left	Character Right
1	Free	x	x
2	Forced	x	x
3	Forced	x	x
4	Free	NE	ES
5	Free	ES	NE
6	Forced	NE	ES
7	Forced	NE	ES
8	Forced	ES	NE
9	Forced	ES	NE

Side of the opened door NE - Neurotic ES - Emotionally Stable

H1: character's personality expressed with body and facial motion will affect the choice of exit. We expected that participants will choose the exit behind the ES character more often than the NE in conditions 4-5.

H2: character's personality expressed with body and facial motion will affect the trajectory. We expected that participants will avoid the NE character to a greater extent than the ES in conditions 6-9.

H3: gender affects the trajectory. Female participants will avoid all characters to a greater extent than male participants.

In order limit the exposure time, we avoided having too many repetitions of conditions. For this reason, 2 repetitions were chosen for each condition. The repetitions were organised in blocks, where participants saw one repetition of a random condition in the first block and the second repetition randomized in the second block. The repetitions were included in the analysis to identify if the responses to characters changed through time. The experiment was approx. 25 minutes long.

3.4. Measures

In our experiment, we collected subjective and behavioral responses from participants.

In order to validate that participants can recognise the intended personality traits, we used **subjective responses** in the form of a questionnaire constituting of 7-point Likert scale items (1 - Not at all, 7 - Extremely). We used 2 items from the Ten Item Personality Questionnaire [43] which measure the personality traits of neuroticism and emotional stability. We reformulated the questions to address the personality of the character (see Table 3).

We also measured the feeling of presence, social presence and embodiment (described in Table 3), again on the 7-point Likert scale. We included these measures to collect more information about the VR experience of the participants. We used the Social presence questionnaire [44], with the modified question 2 where we omitted the words "watching me" as we did not implement the eye-gaze of characters. We added one custom question about the presence in the virtual environment. We did not implement the whole questionnaire since we only used it as a control question which was not a part of our statistical analysis. We anticipated that the behavioral response itself will be a strong predictor of presence, or rather place and plausibility illusions as discussed in Slater et al. [45]. Similarly, we selected only the relevant questions of agency and body ownership from the Embodiment Questionnaire [46] as embodiment was not the focus of our study.

Table 3. Subjective response questions arranged by questionnaire and items.

Questionnaire	Item
Personality	This character is anxious or easily upset.
	This character is calm, emotionally stable.
Presence	I had the sensation of being in a real metro.
Social Presence	Throughout the experience, it felt as if I was in the presence of another person (people) in the metro.
	It felt as if the person was aware of my presence.
	The thought that the people in the metro were not real crossed my mind often.
	The people appeared to be alive.
	The people were only computerized images, not real people.
Embodiment	When I looked down on my hands I felt like the virtual hands were my own hands.
	I felt as if the movements of the virtual hands were caused by my movements.

At the end of the questionnaire, we added an open-ended question where the participants could comment on the characters and their VR experience. We also asked if they experienced any dizziness or sickness after the VR experience.

For the **behavioral responses**, we were interested in two responses: choice of exit doors and kinematics of the trajectory. We already described our approach to the trajectory analysis in Section 3.1. The choice response was labelled as “left” or “right”, depending on the side of the door chosen in each experimental condition. This measure was used primarily to test the first hypothesis (H1).

3.5. Participants

38 participants took part in our experiment, 14 females and 25 males, with an average age of 28 years (+/ − 6.6). Participants were predominantly European (32), with the exception of 4 Canadian and two Chinese participants. 15 participants had a high level of familiarity with computer generated characters and 19 of them had a high level of experience with VR. 4 participants reported to have no prior experience with computer generated characters or VR. The rest estimated their experience with characters and VR to be medium. All participants signed the consent form which was approved by the internal ethics committee.

Exclusion Criteria. Among the behavioral responses, 15 participants had tracking issues for one repetition from the 9 conditions, and 2 participants were missing 1 full condition completely. Even though most of these participants had at least one repetition for one condition, we chose to have a strict approach and only include data of 21 participants (7 females and 14 males) in the final analysis. We compared this analysis with

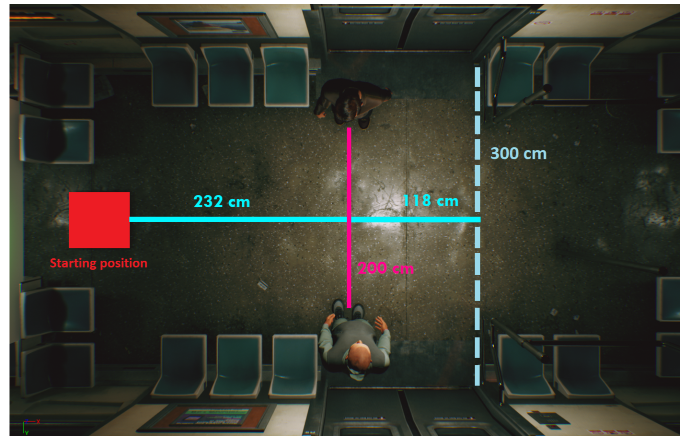

Fig. 2. Top view of the virtual environment space and distances from the starting position, towards the exit doors and between the two character positions.

the analysis on the sample of N = 37 with missing values and found similar results. Therefore, while lower in power [4], the analysis on the reduced sample is representative and we do not report the analysis on the full set of participants in this paper.

3.6. Apparatus

The participants were wearing the HTC Vive Pro headset with controllers. In the VR environment, they could see the controllers with realistic virtual hands attached to them - this was to ensure some reference of their body in the virtual space as this could affect avoidance behaviour. They were moving through the virtual metro by walking in physical space while their headset was tracked. The walking distances were limited to the tracking area and the length of the headset cable ($10m$) in order to enable a comfortable and non-restrained locomotion of the participant (Figure 2). Their eye-height was set to be on the eye-level of the characters to avoid the height affecting the avoidance pattern and we also did not include eye-contact of the character with the participants since this could also affect avoidance behaviour [44]. We also reset the position of the headset in each condition to have exactly the same starting position for the analysis of the trajectory.

3.7. Procedure

The participants first signed the consent form and were then explained the task before they entered the VR environment. The task was to remain in the starting position until the doors of the metro open. Then, they have to walk towards one of the exits doors on the left or right side of the metro. They were told that sometimes the metro would be empty and other times the scene will contain some characters. They were asked to pay attention to these characters before exiting. They were also told that in some cases they could choose which side to exit from, but they might encounter only one open door, giving them no choice but

[4] An a priori N size calculated with G*Power for ANOVA repeated measures, within-between interactions, with the effect size = 0.2, was 34 subjects.

to exit there. The first scene was a training scene where participants were familiarised with the environment and the task. It also contained multiple characters and participants could freely explore the metro until they exited the door. They could also see their virtual hands. At the exit, they were told they are not actually leaving the metro but need to turn around and go back to the initial position marked on the floor with a green "X". Boards also appeared in the environment to guide them through the task. When they arrived at the starting position, their headset location in the virtual environment was reset and they were asked to remain in the same place until the doors opened. After these instructions, the participant put on the headset with the controllers and completed the tasks independently. After the VR trial, they removed the headset and controllers and were asked to answer the questionnaire.

4. Results

The procedure of analysing results was the following: where the normality assumptions tested with Kolmogorov-Smirnov & Lilliefors test were satisfied, we used the parametric statistical analysis to explore potential differences between conditions (paired sample T-test, repeated measures ANOVA) or used their non-parametric equivalent if the assumptions were not met. We also corrected the p-values if the sphericity assumptions were not met for the repeated measures ANOVA using the Greenhouse-Geisser correction.

4.1. Subjective Responses

As mentioned previously, for consistency, we report only the results on a sample of 21 participants which have complete behavioral data. One participant did not answer the questionnaire so we included the data of 20 participants in the following analysis.

4.1.1. Personality Perception

First, we inverted the value of the item measuring neuroticism for all participants and calculated the Cronbach's Alpha level for both neuroticism and emotional stability and found them to be sufficient (neuroticism: $\alpha = 0.73$, emotional stability: $\alpha = 0.85$). We proceeded by averaging over the two items and tested the normality of distribution for the NE and ES characters. Since the distribution of data was normal, we conducted a t-test which showed that the NE character ($\bar{x} = 2.03, SD = 0.70$) was perceived as significantly less emotionally stable than the ES character ($\bar{x} = 3.57, SD = 1.07$), as anticipated ($t(19) = -4.35, p = 0.000$).

While we designed the personality of characters based on motion alone, the appearance of the characters could have affected the perception of their personality traits. We therefore evaluated if there was a difference in perception of the personality traits based on the character model. The number of participants with reversed models was not balanced: 12 participants saw Cooper with neurotic motion while 8 participants saw Yuri with neurotic motion. Therefore, we conducted a Kolmogorov-Smirnov Two-Sample test for the ratings of emotional stability separately for the NE and ES character depending on character model (Yuri NE: $\bar{x} = 2.25, SD = 0.89$ vs. Cooper NE: $\bar{x} = 1.88, SD = 0.53$; Yuri ES: $\bar{x} = 3.54, SD = 1.16$, vs. Cooper ES $\bar{x} = 3.63, SD = 0.99$) but no significant differences were found.

There was also no effect of Gender (N females: 6, N males: 14) on the personality ratings with the Kolmogorov-Smirnov Two-Sample test (ES character: Females: $\bar{x} = 3.83, SD = 0.81$ vs. Males: $\bar{x} = 3.46, SD = 1.17$, NE character: Females: $\bar{x} = 1.92.0, SD = 0.38$ vs. Males: $\bar{x} = 2.07, SD = 0.81$). The proportion of female to males is not balanced therefore the results should be interpreted with caution.

4.1.2. Presence

Participants reported a realistic feeling of being in an actual metro in their free form comments and with the Presence question analysed by the Wilcoxon Signed-rank test with the test value 3 ($\bar{x} = 3.80, SD = 0.83$, $W = 138, p < 0.002$).

4.1.3. Social Presence

For Social Presence, we calculated the final score for each participant over 5 scales (Cronbach's $\alpha = 0.84$). The scores were normally distributed, therefore, we conducted a one sample t-test with the mid-score value of 20 (min = 5, max = 35) and found that Social Presence was low ($\bar{x} = 13.8, SD = 3.37, t(19) = -8.24, p = 0.001$).

4.1.4. Embodiment

We used two scales, Ownership and Agency, which we added to a final score of Embodiment (Cronbach's $\alpha = 0.71$). The Wilcoxon Signed-rank test with the test mid-score value 6 (min = 2, max = 10) showed that Embodiment level was significantly higher than the test value, showing that participants had a feeling of embodiment in the virtual environment ($\bar{x} = 7.3, SD = 1.94, W = 501, p < 0.001$).

4.2. Exit Choice

Conditions analysed here are all the free choice conditions (1, 4, 5), see Table 2. The data was treated in the following manner: if participants chose the same door in both repetitions, we labeled the response 'Left' or 'Right', depending on which side of the metro they exited. If participants chose different doors in each repetition, we marked them as 'Mixed'. We analysed the percentage of participants in each label.

For Condition 1, we got similar percentages for all three labels, showing that there was no particular preference for the side of doors when the metro was empty (see Figure 3), Chi-square Proportion test for N samples showed no significant difference between the proportions ($\chi^2(2) = 0.89, p = 0.64$).

In Condition 4, we see a stronger preference for the right door as opposed to the left (see Figure 3), but also a high amount of mixed choice, however, the Chi-square showed a significant difference between the percentages ($\chi^2(2) = 8.67, p = 0.031$).

In Condition 5, we registered a stronger preference for the left door (see Figure 3), with Chi-square showing a significant difference between the three conditions ($\chi^2(2) = 10.9, p = 0.004$).

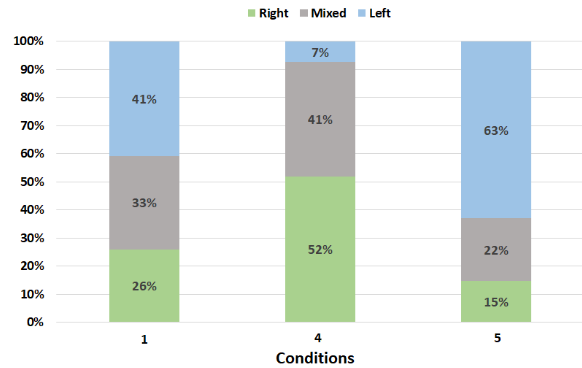

Fig. 3. Percentages of choices for the door on the left or right, as well as mixed choices for the conditions 1 (empty metro), 4 (NE left) and 5 (NE right).

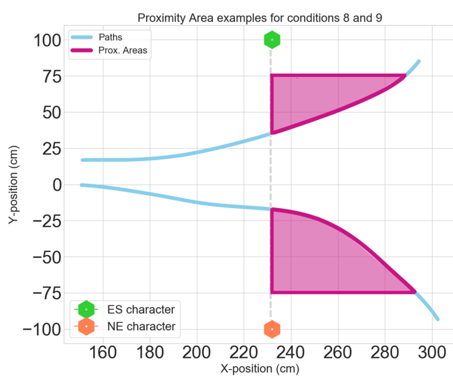

Fig. 4. Clearance area computation example for two paths of avoiding of ES and NE character (conditions 8 and 9). We can see that the clearance area is larger when a participant is forced to turn close to NE character than to ES character.

We were also interested to know if the choices of exit would depend on Gender of the participant. We conducted a $\chi^2(2)$ test of association where we compared the percentage differences in choices depending on Gender and found that for all three Conditions, there were no significant differences between the choices of females and males.

4.3. Trajectory

Turning Point. To analyse the turning point, we first evaluated the normality assumption in order to determine whether to use a parametric analysis. The data was distributed normally, therefore, we conducted a repeated measure ANOVA with within factors Repetition (2 levels) and Condition (9 levels) and Gender as a between group factor. We found no difference in Repetition or Gender but a main effect of Condition was found ($F(8, 152) = 43.713, p = 0.000, \eta_p^2 = 0.697$). A closer investigation with the Bonferroni post-hoc showed that the first three conditions (the ones not including the character in the scene) had a turning point earlier in the trajectory (see Figure 6 for descriptive statistics). This was expected since the participants moved directly to the exit doors which were not obstructed, therefore, turning earlier. There was no significant difference in the turning point between the first three conditions analysed with repeated measure ANOVA but there were significant differences between the first three Conditions and the last six, containing characters ($p < 0.000$).

Since the trajectory path of the empty conditions was very different to the ones with characters, we analysed the turning points for the conditions with characters in a separate analysis and chose a Bonferroni correction of the alpha level for two separate tests ($p = 0.025$). A new repeated measure ANOVA was conducted on the remaining 6 conditions and we found a main effect of Condition ($F(5, 95) = 4.238, p = 0.002, \eta_p^2 = 0.182$). We then conducted a Bonferroni post-hoc and investigated significant differences. It revealed that the turning point in Condition 6 was significantly further in the scene compared to the Condition 8 ($p < 0.021$). This shows that participants walked further before turning to exit the left door when the NE character was obstructing it compared to when the ES character was obstructing their way, but only on the left side, so both the character and side of the exit affected the turning point.

There was also a significant difference between 6 (forced left exit with NE character) and 5 (free choice, NE on the right side)($p < 0.014$). The freedom to choose any door made it possible to walk around the character of their choice but we also found a significant difference depending on which side the characters were obstructing. Condition 4 had the turning point significantly further away than Condition 5 ($p < 0.014$). This could be because we found that participants chose to go around the NE character more often in Condition 4 (see Figure 3). It is important to note that due to free choice of exit, we do not have a balanced dataset of turning points for NE and ES characters. In order to compare these turning points to the ones where participants were forced to walk around the assigned characters, we could only do a non-parametric evaluation. This was to determine whether the turning point around a particular character was different when participants had a choice as opposed to when they did not. We conducted a Wilcoxon Matched Pairs Test between conditions 4 and 6 (NE on left), 5 and 9 (NE on the right), 4 and 7 (ES on the right), as well as 5 and 8 (ES on the left), per repetition. No significant differences were found. We conclude, that forcing the participant to avoid a particular character as opposed to the participant choosing the character freely, did not change their turning point significantly.

Minimum Distance. In order to analyse the minimum distances, we selected the conditions where participants were forced to walk around a particular character and conducted the repeated measures ANOVA with factors Repetition (2) and Condition (4), and a between factor Gender (2). We got a main effect of Condition ($F(3, 57) = 2.837, p = 0.046, \eta_p^2 = 0.129$), see Figure 7. The Bonferroni post-hoc showed no significant differences between minimum distances in any of the conditions.

Similarly as in the turning point analysis, we could not reliably test the comparison between the distances when participants were free to choose the exit door, since the amount of time they chose the door with the NE character obstructing it, was low. However, we conducted the same analysis as described in 4.3, where we found that when the NE character was on the right side (Conditions 4 and 9) in the second repetition, the free choice had a slightly further Minimum Distance than the forced

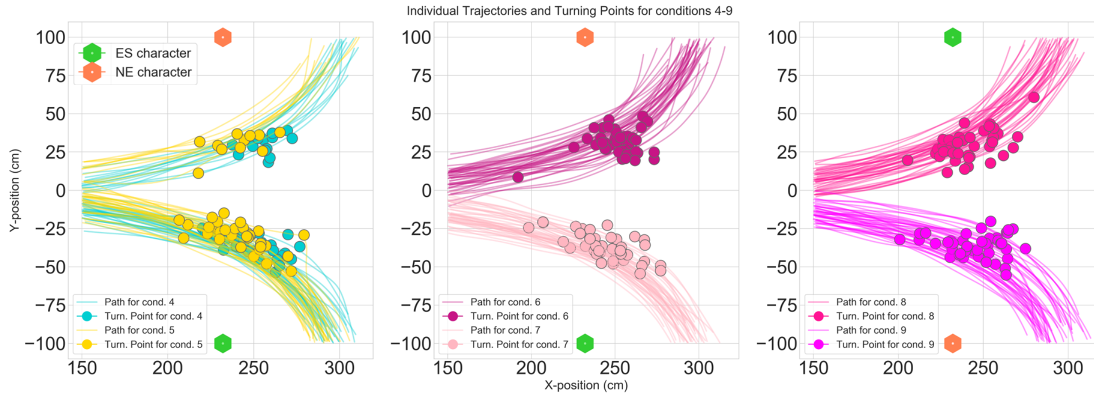

Fig. 5. Individual paths of participants and Turning (Deviation) Points for levels 4-9 (we cut off the initial 1.5 meter of the trajectories). Figure 1: participant is free to choose one of the doors to exit; Figure 2,3: Only one door is open.

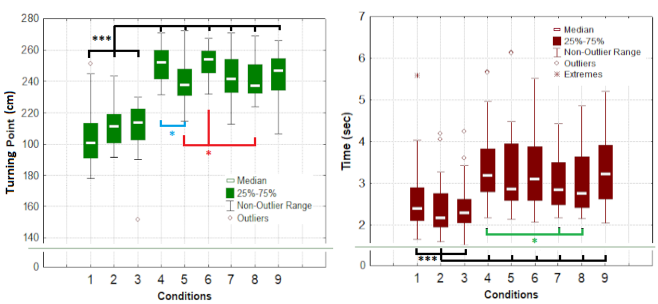

Fig. 6. Box plots for all the individual conditions in turning points analysis and completion time. The mark * represents the significance on the level $p < 0.05$**, and *** on the level** $p < 0.0001$.

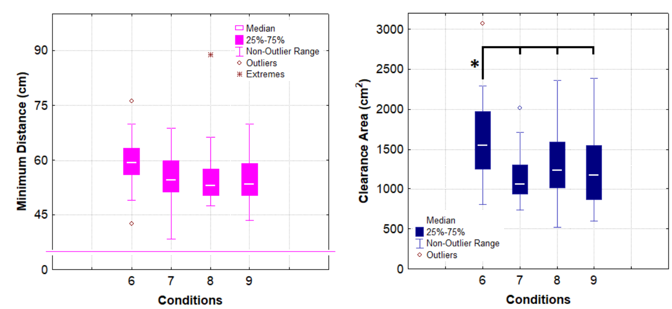

Fig. 7. Box plots for Minimum Distance and Clearance Area for the selected conditions. Lines marked with * denote significant differences at $p < 0.05$.

condition ($Z(8) = 2.38, p = 0.017$). Due to significantly less data in Condition 4, this result should be interpreted with caution.

Clearance Area. We conducted the same analysis as for the Minimum Distance (the results were distributed normally and we conducted a repeated measure ANOVA with within factors Repetition (2 levels) and Condition (4 levels) and Gender as a between factor). We found a main effect of Condition ($F(3, 57) = 7.183, p = 0.0004, \eta_p^2 = 0.274$), see Figure 7. Similarly as for Deviation Point, the clearance areas were larger in Condition 6, compared to all other conditions ($p < 0.02$ for all comparisons).

There was also a three-way interaction with Gender, Repetition and Condition ($F(3, 57) = 2.95, p = 0.04, \eta_p^2 = 0.134$), however, the post-hoc showed no significant differences between males and females in each individual condition.

Finally, we conducted a Wilcoxon Matched Pairs Test to test the Clearance Area of forced or free choice for each matching condition and per repetition. We found no significant differences except in the second repetition, the free choice to go around the NE character on the left side was significantly larger than in the forced choice condition ($Z(15) = 2.61, p = 0.009$).

Completion Time. For completion time, we again included all 9 conditions in the analysis and found a main effect of Repetition: $F(1, 19) = 12.774, p = 0.003, \eta_p^2 = 0.401$, where in the second repetition, participants walked faster. We also found a main effect of Condition ($F(8, 152) = 16.915, p = 0.000, \eta_p^2 = 0.471$). Apart from the first three conditions taking significantly shorter time to complete as opposed to others ($p < 0.000$), the post-hoc also showed that Condition 4 was significantly different to the time in Conditions 7 and 8 ($p < 0.05$). For descriptive statistics, see Figure 6.

5. Discussion

In this paper, we presented a study on the effect of a character's motion on peoples' behaviour in VR. We were interested if the type of motion which is associated with the personality traits of neuroticism and emotional stability would affect people's personal space preferences. A neurotic personality would be seen as less appealing than the emotionally stable character, which would increase the distance towards it [24].

In the first hypothesis (H1), we anticipated that participants would more readily choose to exit through the door obstructed by the emotionally stable character. We showed that this was indeed the case, signified by lower levels of selection for the door with the neurotic character. Participants would still choose doors with a neurotic character; however, this was done to a significantly lesser extent. Participants gave some insights about their experience of the two characters in their free form comments: "*I had the feeling that the black shirt character motion was less predictable, and I was more careful getting closer to* him", *"one character was very scary and I did not want to be close to him"* and *"thinking about it, I am wondering whether the agitated character is occupying more space with his motion"*. This indicates participants could notice the difference in the behavior of the characters and some explained their discomfort with the neurotic character was due to his unpredictable movements and the space he was occupying.

The second hypothesis (H2) proposed that the avoiding behaviour in the form of walking trajectory would also be affected by the type of personality of the obstructing character. We found evidence to support this - a larger clearance area was found around the neurotic character as opposed to the emotionally stable one when exiting the metro. Minimum distance was less sensitive to capture this effect. Associated with H2, we also tested our new metric, the turning point. We found that for the neurotic character, it was calculated to be further on the path line as opposed to the emotionally stable character. The significant difference was again seen only when the neurotic character was standing on the left side, but not when it was on the right of the participant, a similar result we got for the clearance area. Since we did not get a difference in the empty metro condition, this effect may not be due to perceptual differences according to side (e.g., laterality). It could be due to the limitations of the tethered headset. While we ensured that the cable was long enough to span from the starting point to both exit doors, participants might have felt a slight pull on their headset when exiting right, and this may have affected the trajectory. A wireless headset would undoubtedly be a better choice for non-restrictive locomotion but it could also limit the graphics performance needed to render our complex environment. In future research, a portable computer could help solving the issue of cable length restrictions and poor graphics performance.

The last hypothesis (H3) was formulated based on previous research which showed that gender of the participant affects the size of personal space [40, 24], where females tend to leave more space between virtual humans than males. In our study, this was not evident; however, our participant sample was not balanced in gender and any conclusions based on gender could be misleading. The sample was also small, mainly of European background. It is known that gender and cultural background impact personal space preferences (see for example [47]). Having a more representative sample would be beneficial in future work.

Other results gave us more insight into the experiment outcomes. First, we found that participants felt that the metro was realistic but the social presence was low. As we did not make our characters responsive to the presence of the user, this result is not surprising. Adding more interactive behaviour (e.g., eye-gaze) in future work could increase social presence, impacting the walking trajectory of people. Second, task completion time analysis revealed some expected results (task completed faster in second repetition, longer time when having the choice of exit). However, no significant difference was found for forced exit conditions, possibly since participants had to pass between both characters at the same time, which was shown in Hackney et al. [38] to affect walking speed. In order to study the effect of character's personality on completion time, only one character should be positioned at a time in the scene, which could be part of future work investigation. Third, even though participants recognised the intended personality traits of characters, we cannot conclude that it was the personality which affected the behaviour of the participants. Different performances of the neurotic and emotionally stable traits should be investigated to asses the perceptual effect of these traits. Since perception of movement cannot be completely separated from appearance [10] and since it was found appearance can affect the trajectory of the user [37], more virtual models, diverse in appearance, should be explored in future work.

In addition to the already mentioned limitations, we acknowledge that the animations we created for the virtual characters had considerable amount of glitches and retargeting issues. We also did not have finger motion capture, which resulted in the stiffness of fingers, however, we created a neutral hand pose by slightly bending the joints of the fingers. Some of these errors were innate to the MetaHuman retargeting pipeline and we spent a considerable amount of time solving the issues but our final animation result was compromised. While the motion artefacts could have impacted the perceived naturalness of the characters' movements, participants were rating the personality of the characters as we intented - neurotic character was rated as more neurotic than emotionally stable one. Since we were interested in creating specific gestures which would reflect either emotionally stable or neurotic personality, our priority was to make sure that these personality traits would be recognised from motion regardless of the glitches, which were present in both types of motions. Regardless, the errors could have impacted the personality ratings and our results showed that the perceived emotional stability for the character with the corresponding personality was relatively low (the average rating on Emotional Stability was mid-range, 3.6 out of a maximum 5). Indeed, in the free form comments, some participants indicated they felt uncomfortable with both characters. They also noticed that both characters moved strangely and were doing some weird behaviour. We stress that in spite of these issues, our results showed a difference between the perceived personalities but this could point to another problem. We created quite exaggerated expressions of both motion styles to ascertain that a participant recognised the difference in behaviour. In turn, this could have reduced the naturalness of the character's behaviour. These limitations show that the design of natural and realistic motions remains a challenging target and motivates the interest for future research. Future methods should also include evaluation of perceived realism or naturalness of motion.

Another limitation of our study is that we only included participant's gender in the analysis but not other possible characteristics which could affect their behaviour. For example, participant's own personality, their current emotional state, or social anxiety [35], could have influenced the results. We only focused on participant's gender due to sufficient evidence that it affects the proximity measure and since we included 40% of females in our sample, we had a reasonable suspicion that this will affect our results. However, adding the analysis of other participants' traits could indeed be beneficial in the future work.

Our study shows that both the decision task (choice of doors) and walking trajectory path in a spatially restricted environment provide insights into human perception and behaviour. Both behavioral tasks are complimentary and give different results. For example, in our study, participants could try to control their behavior and would choose the door with the neurotic character even when it made them uncomfortable. However, with the added trajectory path analysis, we were able to identify that participants kept a larger distance to the neurotic character when passing it compared to the emotionally stable character. Other ideas for future work include using the same metrics to explore more subtle and complex body motions in a realistic virtual environment, but also to study other aspects of character design (appearance, voice, interaction, etc.).

6. Conclusion

This paper focuses on an underrepresented problem of studying the quality of human motion related to personality types, and its ability to affect the behaviour of users in VR. We make important contributions to the perception of character motion while using a realistic, daily-life scenario in VR. We also introduce a novel measure (turning point) and an avoidance decision task. Both measures showed to be effective when studying avoidance behaviour in constricted spaces. Our results have implications for research and creative industry in the area of virtual characters and populated virtual spaces for various VR applications. VR developers can use the outcomes of our study as a guideline for animation of virtual humans. Depending on the application, the current work can provide design guidelines for virtual reality. For example, the character's motion can be used to direct the locomotion of the users in the virtual environment. We also showed that creating characters with neurotic motion (rapid movement, indirect gestures) will induce a feeling of discomfort in enclosed spaces and should be avoided if the goal is a positive user experience.

References

[1] Seinfeld, S, Arroyo-Palacios, J, Iruretagoyena, G, Hortensius, R, Zapata, LE, Borland, D, et al. Offenders become the victim in virtual reality: impact of changing perspective in domestic violence. Scientific reports 2018;8(1). doi:10.1038/s41598-018-19987-7.

[2] Sharar, SR, Miller, W, Teeley, A, Soltani, M, Hoffman, HG, Jensen, MP, et al. Applications of virtual reality for pain management in burn-injured patients. Expert Review of Neurotherapeutics 2008;8(11):1667–1674. doi:10.1586/14737175.8.11.1667.

[3] Volonte, M, Hsu, YC, Liu, KY, Mazer, JP, Wong, SK, Babu, SV. Effects of interacting with a crowd of emotional virtual humans on users' affective and non-verbal behaviors. In: 2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR). IEEE; 2020, p. 293–302. doi:10.1109/VR46266.2020.00049.

[4] Torre, I, Carrigan, E, Domijan, K, McDonnell, R, Harte, N. The effect of audio-visual smiles on social influence in a cooperative human–agent interaction task. ACM Transactions on Computer-Human Interaction (TOCHI) 2021;28(6):1–38. doi:10.1145/3469232.

[5] Zibrek, K, McDonnell, R. Does render style affect perception of personality in virtual humans? In: Bailey, R, Kuhl, S, Mohler, BJ, Singh, K, editors. Proceedings of the ACM Symposium on Applied Perception, SAP '14. ACM; 2014, p. 111–115. doi:10.1145/2628257.2628270.

[6] Bönsch, A, Weyers, B, Wendt, J, Freitag, S, Kuhlen, TW. Collision avoidance in the presence of a virtual agent in small-scale virtual environments. In: IEEE Symposium on 3D User Interfaces. 2016, p. 145–148.

[7] Bourgaize, SM, McFadyen, BJ, Cinelli, ME. Collision avoidance behaviours when circumventing people of different sizes in various positions and locations. Journal of Motor Behavior 2021;53(2):166–175. doi:10.1080/00222895.2020.1742083.

[8] Johansson, G. Visual perception of biological motion and a model for its analysis. Perception & psychophysics 1973;14(2):201–211. doi:10.3758/BF03212378.

[9] Kozlowski, LT, Cutting, JE. Recognizing the sex of a walker from a dynamic point-light display. Perception & psychophysics 1977;21(6):575–580. doi:doi.org/10.3758/BF03198740.

[10] Chaminade, T, Hodgins, J, Kawato, M. Anthropomorphism influences perception of computer-animated characters' actions. Social cognitive and affective neuroscience 2007;2(3):206–216. doi:10.1093/scan/nsm017.

[11] Guay, M, Ronfard, R, Gleicher, M, Cani, MP. Adding dynamics to sketch-based character animations. In: Sketch-Based Interfaces and Modeling (SBIM) 2015. Eurographics Association; 2015, p. 27–34.

[12] Ahuja, K, Ofek, E, Gonzalez-Franco, M, Holz, C, Wilson, AD. Coolmoves: User motion accentuation in virtual reality. Proc ACM Interact Mob Wearable Ubiquitous Technol 2021;5(2). doi:10.1145/3463499.

[13] De Gelder, B. Towards the neurobiology of emotional body language. Nature Reviews Neuroscience 2006;7(3):242–249. doi:10.1038/nrn1872.

[14] Choi, B, i Ribera, RB, Lewis, JP, Seol, Y, Hong, S, Eom, H, et al. Sketchimo: Sketch-based motion editing for articulated characters. ACM Trans Graph 2016;35(4). doi:10.1145/2897824.2925970.

[15] Neff, M, Fiume, E. Aesthetic edits for character animation. In: Proceedings of the 2003 ACM SIGGRAPH/Eurographics symposium on Computer animation. 2003, p. 239–244.

[16] Hoyet, L, Ryall, K, Zibrek, K, Park, H, Lee, J, Hodgins, J, et al. Evaluating the distinctiveness and attractiveness of human motions on realistic virtual bodies. ACM Transactions on Graphics (TOG) 2013;32(6):1–11. doi:10.1145/2508363.2508367.

[17] Laban, R. The mastery of movement on the stage. Macdonald & Evans; 1950.

[18] Goldberg, LR. The development of markers for the big-five factor structure. Psychological assessment 1992;4(1):26. doi:10.1037/1040-3590.4.1.26.

[19] Argyle, M. Bodily communication new york: Methuen & co. 1988. doi:10.1007/978-94-017-2367-1_2.

[20] Fukayama, A, Ohno, T, Mukawa, N, Sawaki, M, Hagita, N. Messages embedded in gaze of interface agents—impression management with agent's gaze. In: Proceedings of the SIGCHI conference on Human factors in computing systems. 2002,doi:10.1145/503376.503385.

[21] Matsumoto, K, Shibata, S, Seiji, S, Mori, C, Shioe, K. Factors influencing the processing of visual information from non-verbal communications. Psychiatry and clinical neurosciences 2010;64(3):299–308. doi:10.1111/j.1440-1819.2010.02077.x.

[22] Durupinar, F, Kapadia, M, Deutsch, S, Neff, M, Badler, NI. Perform: Perceptual approach for adding ocean personality to human motion using laban movement analysis. ACM Trans Graph 2016;36(1). doi:10.1145/2983620.

[23] Neff, M, Toothman, N, Bowmani, R, Fox Tree, JE, Walker, MA. Don't scratch! self-adaptors reflect emotional stability. In: International Workshop on Intelligent Virtual Agents. Springer; 2011, p. 398–411. doi:10.1007/978-3-642-23974-8_43.

[24] Zibrek, K, Niay, B, Olivier, AH, Hoyet, L, Pettre, J, McDonnell, R. The effect of gender and attractiveness of motion on proximity in virtual reality. ACM Transactions on Applied Perception (TAP) 2020;17(4):1–15. doi:10.1109/VRW55335.2022.00187.

[25] Bönsch, A, Radke, S, Overath, H, Asché, LM, Wendt, J, Vierjahn, T, et al. Social vr: How personal space is affected by virtual agents' emotions. In: 2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR). IEEE; 2018,doi:10.1109/VR.2018.8446480.

[26] Mathes, EW, Kahn, A. Physical attractiveness, happiness, neuroticism, and self-esteem. The Journal of psychology 1975;90(1):27–30. doi:10.1080/00223980.1975.9923921.

[27] Pan, X, Hamilton, AFdC. Why and how to use virtual reality to study human social interaction: The challenges of exploring a new research landscape. British Journal of Psychology 2018;109(3):395–417. doi:10.1111/bjop.12290.

[28] Brument, H, Marchal, M, Olivier, AH, Argelaguet, F. Influence of

dynamic field of view restrictions on rotation gain perception in virtual environments. In: International Conference on Virtual Reality and Augmented Reality. Springer; 2020,doi:10.1007/978-3-030-62655-6_2.

[29] Berton, F, Hoyet, L, Olivier, AH, Bruneau, J, Le Meur, O, Pettré, J. Eye-gaze activity in crowds: impact of virtual reality and density. In: 2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR). IEEE; 2020, p. 322–331. doi:10.1109/VR46266.2020.00052.

[30] Berton, F, Olivier, AH, Bruneau, J, Hoyet, L, Pettre, J. Studying gaze behaviour during collision avoidance with a virtual walker: Influence of the virtual reality setup. 2019, p. 717–725. doi:10.1109/VR.2019.8798204.

[31] Cirio, G, Olivier, AH, Marchal, M, Pettré, J. Kinematic evaluation of virtual walking trajectories. IEEE transactions on visualization and computer graphics 2013;19(4):671–680. doi:10.1109/TVCG.2013.34.

[32] Perrinet, J, Olivier, AH, Pettré, J. Walk with me: Interactions in emotional walking situations, a pilot study. In: Proceedings of the ACM Symposium on Applied Perception. SAP '13; Association for Computing Machinery. ISBN 9781450322621; 2013,doi:10.1145/2492494.2492507.

[33] Mousas, C, Kao, D, Koilias, A, Rekabdar, B. Evaluating virtual reality locomotion interfaces on collision avoidance task with a virtual character. Vis Comput 2021;37:2823–2839. doi:10.1007/s00371-021-02202-6.

[34] Sanz, FA, Olivier, AH, Bruder, G, Pettré, J, Lécuyer, A. Virtual proxemics: Locomotion in the presence of obstacles in large immersive projection environments. In: 2015 IEEE Virtual Reality (VR). 2015, p. 75–80. doi:10.1109/VR.2015.7223327.

[35] Lange, B, Pauli, P. Social anxiety changes the way we move—a social approach-avoidance task in a virtual reality cave system. PLOS ONE 2019;14:e0226805. doi:10.1371/journal.pone.0226805.

[36] Mousas, C, Koilias, A, Anastasiou, D, Rekabdar, B, Anagnostopoulos, CNE. Effects of self-avatar and gaze on avoidance movement behavior. 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR) 2019;:726–734.

[37] Mousas, C, Koilias, A, Rekabdar, B, Kao, D, Anastasiou, D. Toward understanding the effects of virtual character appearance on avoidance movement behavior. 2021, p. 40–49. doi:10.1109/VR50410.2021.00024.

[38] Hackney, AL, Cinelli, ME, Frank, JS. Does the passability of apertures change when walking through human versus pole obstacles? Acta psychologica 2015;162:62–68. doi:10.1016/j.actpsy.2015.10.007.

[39] Lee, M, Bruder, G, Höllerer, T, Welch, G. Effects of unaugmented periphery and vibrotactile feedback on proxemics with virtual humans in ar. IEEE transactions on visualization and computer graphics 2018;24(4):1525–1534. doi:10.1109/TVCG.2018.2794074.

[40] Iachini, T, Coello, Y, Frassinetti, F, Senese, VP, Galante, F, Ruggiero, G. Peripersonal and interpersonal space in virtual and real environments: Effects of gender and age. Journal of Environmental Psychology 2016;45:154–164. doi:10.1016/j.jenvp.2016.01.004.

[41] Gérin-Lajoie, M, Richards, C, McFadyen, B. The negotiation of stationary and moving obstructions during walking: Anticipatory locomotor adaptations and preservation of personal space. Motor control 2005;9:242–69.

[42] Neff, M, Wang, Y, Abbott, R, Walker, M. Evaluating the effect of gesture and language on personality perception in conversational agents. In: International Conference on Intelligent Virtual Agents. Springer; 2010,doi:10.1007/978-3-642-15892-6_24.

[43] Gosling, SD, Rentfrow, PJ, Swann Jr, WB. A very brief measure of the big-five personality domains. Journal of Research in personality 2003;37(6):504–528.

[44] Bailenson, JN, Blascovich, J, Beall, AC, Loomis, JM. Interpersonal distance in immersive virtual environments. Personality and social psychology bulletin 2003;29(7):819–833. doi:10.1177/0146167203029007002.

[45] Slater, M, Cabriera, C, Senel, G, Banakou, D, Beacco, A, Oliva, R, et al. The sentiment of a virtual rock concert. Virtual Reality 2022;doi:10.1007/s10055-022-00685-9.

[46] Gonzalez-Franco, M, Peck, TC. Avatar embodiment. towards a standardized questionnaire. Frontiers in Robotics and AI 2018;5:74. doi:10.3389/frobt.2018.00074.

[47] Hall, ET. The hidden dimension. 1969.