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The influence of body expression, group affiliation and threat proximity on interactions in virtual reality

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ABSTRACT

Social threat requires fast adaptive reactions. One prominent threat-coping behavior present in both humans and other species is freezing, of which heart rate deceleration and reduced postural mobility are two key components. Previous studies mostly focused on freezing reactions in rodents, but now virtual reality offers unique possibilities for controlled and ecologically valid lab-based experiments in humans. This immersive virtual reality study examined how several understudied aspects of social threat, i.e., emotional body expressions, group affiliation, and physical distance from the potential threat, affect freezing behavior in humans. We hypothesized that freezing would be observed for approaching aggressive-looking virtual characters and for virtual characters situated in close proximity. Furthermore, we predicted an enhanced freezing response for approaching, aggressive outgroup members. As expected, reduced heart rate and postural mobility were observed in participants when they faced aggressive-looking and proximal virtual characters. Freezing was also observed for ingroup aggression, specifically when participants were embodied in a black-skinned virtual body and faced black-skinned aggressive and proximal virtual characters. Our results provide novel evidence on the social factors that elicit freezing behavior in humans. Importantly, this evidence is based on a highly ecological virtual reality paradigm that enables people to experience a threatening scenario "as if" it was actually happening to them.

Introduction

The ability to detect threat and react adaptively is a major evolutionary endowment in many species (Blanchard et al., 1986). Freezing has been defined as a threat-anticipatory state whereby an individual is hyperattentive to a potentially threatening stimulus to enhance its processing (Terburg et al., 2018; Livermore et al., 2021). This adaptive response to threat is characterized by two principal components, i.e., a reduction in one's heart rate (bradycardia) and a reduction in one's postural mobility (Roelofs, 2017; Livermore et al., 2021). While extensive research on freezing has been carried out in non-human animals, and especially rodents (e.g., Blanchard et al., 1986; Fanselow, 1994), research on freeze-like reactions to threat in humans is still limited. Previous work has investigated freezing in humans using threat-related social stimuli, such as facial expressions (Roelofs et al., 2010; Stins et al., 2011), affective films (Hagenaars et al., 2014), and computer-based tasks (e.g., a gun shooting task, Gladwin et al., 2016). These studies, however, have tended to maximize experimental control at the expense of ecological validity. In this study, we took advantage of immersive virtual reality (IVR) – a highly ecological technique (Parsons et al., 2017; Monti and Aglioti, 2018) – to examine the effect of underexplored social factors on freezing responses in humans. These factors were: body expressions, group affiliation, and physical proximity.

Roelofs and colleagues (2010) demonstrated that social threat signals conveyed by facial expressions can elicit freeze-like responses in humans, as indexed by reduced heart rate and body sway (Roelofs et al., 2010). It is not yet known, however, whether this adaptive response is affected by the perception of whole-body, threatening expressions. Ob-

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serving an aggressive body expression triggers fear and prepares the observer for adaptive action (de Gelder et al., 2004, 2006; Grezes et al., 2007; Pichon et al., 2012), and a threat-anticipatory freezing state plays a key role in the detection and processing of such social threat (Roelofs, 2017; Livermore et al., 2021). So far, a major obstacle in research on human defensive behavior relates to the difficulty of rendering threatening situations in a realistic manner. The use of IVR now opens unique chances (Sanchez-Vives and Slater, 2005; Parsons et al., 2017; Monti and Aglioti, 2018) as it allows participants to experience a threatening event in a controlled laboratory environment "as if" it was actually happening to them (de Borst et al., 2020; Mello et al., 2022).

The potential of IVR studies is substantially increased by capitalizing on the phenomenon of body ownership (BO), i.e., the feeling that the body and its parts belong to the "self" (Botvinick and Cohen, 1998; Berlucchi and Aglioti, 2010). BO illusion paradigms, e.g., the full-body illusion (Maselli and Slater, 2013), have demonstrated that the feeling of BO is a crucial aspect to consider when studying reactions to threatening stimuli (Tieri et al., 2015; Fusaro et al., 2016). When the virtual body is experienced in first-person perspective (1PP) and/or visuomotor synchrony between the real and the artificial body is provided, strong BO feelings can be experienced for avatars representing a different ethnic group (Peck et al., 2013; Banakou et al., 2016), a different age group (Banakou et al., 2013), or a different sex (de Borst et al., 2020; Mello et al., 2022). We used this opportunity to examine the effect of ethnic group affiliation on freezing by having white people embody, in two different sessions, either a white-skinned or a black-skinned virtual body (VB) and confront either white-skinned or black-skinned virtual characters. Group affiliation based on ethnicity is a prominent aspect of social life and it has been linked to cognitive bias and implicit attitudes and to behavioral and physiological reactivity associated with threat perception when facing outgroup individuals (Correll et al., 2011; Boyer et al., 2015; Amodio and Cikara, 2021). For instance, Correll and colleagues (2006, 2007), using a first-person-shooter task, showed that white men typically shoot black targets more frequently and faster compared to white targets. The authors linked these findings to automatic activation of racial stereotypes including the concept of danger (Correll et al., 2011). Similarly, Maner and colleagues (2005) have hypothesized that participants rate outgroup people as angrier when they are in a self-protective state of mind. Based on this evidence, we asked whether facing ethnic outgroup individuals would be associated with increased reactivity to threat.

One crucial factor that can influence human social encounters is physical proximity, i.e., the actual distance between two or more individuals, which can have important effects on social interactions and relations (Stopczynski et al., 2018) and modulates our perception and processing of threat (Xiao et al., 2016). Freezing reactions in non-human animals are highly dependent on the proximity of the threat. When a menace is detected and it enters an individual's proximal space, a freezing state of fear bradycardia and motor immobility helps to allocate attentional resources to the threat. When the threat is most imminent, defensive behavior may switch from passive (e.g., freezing) to active (e.g., fight or flight) (Blanchard et al., 1986; Fanselow, 1994; Lang et al., 1997). Recent studies have confirmed this proximity-related pattern of behavioral strategies when facing a threat in humans (Mobbs et al., 2007; Löw et al., 2015; Wendt et al., 2017; Rosén et al., 2019). Specifically, when the threat is proximal but inescapable, attentive freezing predominates (Löw et al., 2015; Wendt et al., 2017). On the other hand, if participants are given the opportunity to escape the approaching threat, the defensive behavior switches from passive freezing to active avoidance (Löw et al., 2015; Wendt et al., 2017). However, the studies on threat proximity described above have implemented non-social threatening stimuli and have used paradigms that maximize experimental control at the expense of ecological validity. In the present study, we focussed on human social encounters as a source of potential threat, and we balanced experimental control and ecological validity by utilizing approaching virtual characters that walked towards the participants until reaching close proximity.

To summarize, we took advantage of VR techniques to create virtual characters showing an aggressive or neutral body expression and we investigated their effect on freezing. We predicted a reduction in heart rate and postural mobility when facing aggressive- compared to neutral-looking approaching virtual characters. Based on the group affiliation literature, we also expected a reduction of heart rate and postural mobility when participants embodied a white-skinned VB and encountered a black-skinned virtual character and similarly when they embodied a black-skinned VB and faced white-skinned virtual characters. Moreover, we tested whether embodiment in a VB of a different ethnicity would lead to a reduction in participants' implicit biases towards people of that specific ethnicity, measured via the implicit association test (IAT) (Peck et al., 2013; Banakou et al., 2016). Finally, we predicted that proximal virtual characters would elicit an enhanced freezing response as compared to distal virtual characters and we hypothesized an enhanced freezing response to aggressive virtual characters and outgroup members when they reached close proximity.

Materials and methods

Participants

Thirty healthy volunteers participated in this study (17 men, 13 women; age range 20-31 years, M = 24.8; SD = 5.13). Participants were all white/Caucasian except for one white/Asian and had normal or corrected-to-normal vision. Four participants were excluded from the analyses because of technical problems during the electrocardiography (ECG) and postural mobility recordings. The sample size was based on that of similar previous studies (e.g., Gladwin et al., 2016) and on a sample size estimation using MorePower 6.0 software, which indicated that a sample of ~30 participants was sufficient to identify a medium effect (e.g., a three-way interaction) with at least 80% power.

General procedure and design

All participants took part in two experimental sessions that were separated by minimally five days to reduce carry-over effects from one session to the other. The sessions were similar, with the exception that in one session the participants were embodied in a black-skinned VB and, in the other, they were embodied in a white-skinned VB (Fig. 1). The order of embodiment type was randomized across participants. At the start of each session, participants completed the Race Implicit Association Test (race IAT, Greenwald et al., 1998). Before starting the experiment, participants were asked to stand barefoot on a force platform while ECG electrodes for measuring heart rate (HR) were attached to their chest. Next, they went through an immersive embodiment training using the first virtual environment (Fig. 1A). They viewed either a sex-matched white-skinned or a black-skinned avatar reflected in a mirror from 1PP and performed several movements (e.g., move the arms) intended to induce embodiment through visuomotor synchrony (e.g., Peck et al., 2013).

After this training, the experimental task started during which participants were immersed in a second virtual environment (Fig. 1B) and observed, in separate trials, virtual characters walking toward them one by one. The approaching virtual characters were either black-skinned or white-skinned and displayed either a neutral (arms down) or an aggressive (raised arms) body posture (Fig. 1B) (similar to the stimuli implemented in Pichon et al., 2009, Marrazzo et al., 2021). The virtual characters started walking from a remote position and stopped at a very close position, inside the participant's personal space. Each trial lasted six seconds. For the analyses, these 6-second trials were subdivided into three windows representing different distances between the approaching virtual characters and the participants – far, intermediate, and close

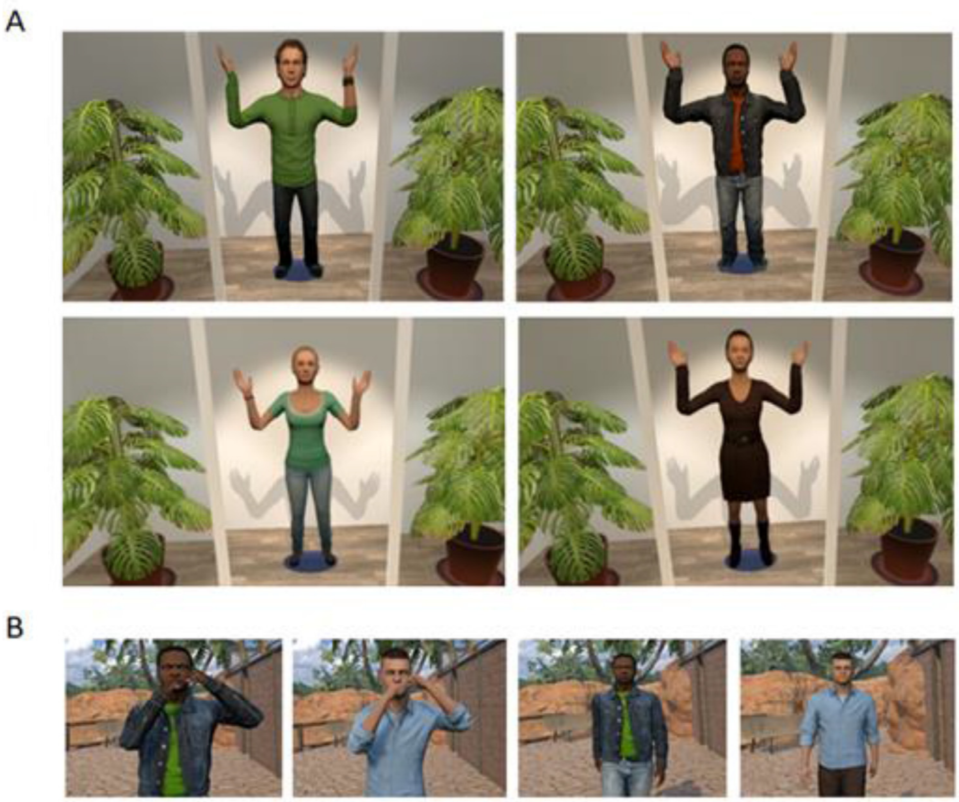

Fig. 1. **(A)** Embodiment environment and an example from the embodiment training task–*"Slightly lift your arms and wave to yourself in the mirror"*. Left. White-skinned embodiment; Right. Black-skinned embodiment. **(B)** Stimuli and environment from the main experiment. From left to right–Black-skinned virtual character with aggressive body posture (raised arms), white-skinned virtual character with aggressive body posture (raised arms), black-skinned virtual character with neutral body posture (arms down), white-skinned virtual character with neutral body posture (arms down). Note that the brightness of the embodied and approaching virtual characters' clothes was selected such that a dark piece of upper clothing (e. g., shirt) was matched with a light piece of lower clothing (e. g., trousers) and vice versa, irrespective of the virtual character's skin color".

Table 1
Embodiment questionnaire items.

Item	Type	Statement
Q1	*Mybody*	I felt as if the body I saw in the virtual world might be my body.
Q2	*Nervous*	I became nervous when the other avatars approached me.
Q3	*Control*	I felt like I controlled the avatar as if it was my own body.
Q4	*Notme*	I felt like the avatar was not me.
Q5	*Liked*	I liked being able to control the movements of the avatar.
Q6	*Greet*	I wanted to say hello to the avatars as they walked towards me.

proximity (see also *Baselined heart rate and postural mobility* section). Thus, the experimental variables consisted of the within-subject factors *Embodiment type* (black-skinned, white-skinned), *Virtual character skin color* (black-skinned, white-skinned), *Virtual character posture* (aggressive, neutral), and *Virtual character proximity* (far, intermediate, close). The experiment was divided into three blocks. A session consisted of 84 trials (28 per block), each lasting 6 seconds, with a 12-second intertrial interval (ITI). The order of trials was randomized across blocks and participants. After the main task, participants completed the race IAT again and filled out an embodiment questionnaire (Peck et al., 2013). Finally, at the end of the second session, participants were debriefed about the study and rewarded for their participation.

Data collection, pre-processing, and analysis

Virtual embodiment questionnaire. This questionnaire consisted of six statements answered on a 1–5 Likert scale, where 1 meant least and 5 greatest agreement (Table 1). The ownership scores for the VBs were obtained by combining the two questions that relate to body ownership, Q1 (*Mybody*) and Q4 (*Notme*), according to Peck et al. (2013): (Q1 + 6 – Q4)/2. A paired sample t-test was performed to test for differences in body ownership in black-skinned vs. white-skinned VB conditions using a significance threshold of $p = 0.05$.

Baselined heart rate and postural mobility. Participants' ECG was recorded using an EGI system (Electrical Geodesics, Inc., Eugene, USA), via two active alligator-connected electrodes, one placed at the centre of the sternum and the other placed at the ribs under the left breast. Raw ECG data were pre-processed in Matlab (see Supplementary information) and HR changes to the experimental conditions were computed as differential values between instantaneous HR (IHR) in three subsequent windows of 2000 ms, covering the 6000 ms trial duration (representing *Virtual character proximity*), and 2000 ms of baseline before stimulus onset. A preliminary data inspection showed the model residuals to have a slightly negatively skewed and leptokurtic distribution, therefore the baselined HR values were normalized with a Lambert W x F function using the package LambertW in R (Georg, 2015; Fig. S1). The normalized HR values were analysed with a linear mixed-effects approach in RStudio using the lmer function from the lme4 package (Bates et al., 2015), which allows to model dependency in the data (within-subjects factors) and to account for missing values. All the fitted models included by-subject intercepts. Graphical inspection of model residuals and fitted vs. predicted values revealed that normality of model residuals, homoscedasticity and linearity assumptions were met (Fig. S2).

Centre of pressure (COP) excursions were recorded with an AMTI AccuSway Force Platform (Advanced Mechanical Technology, Inc., Watertown, USA). The anterior-posterior (AP) and medial-lateral (ML) time series define the COP path relative to the origin of the force platform coordinate system (Prieto et al., 1996; see also Supplementary information). COP raw data were filtered with a low-pass Butterworth filter (cut-off frequency: 5 Hz, filter order: 4). Postural mobility (body sway) was calculated as the standard deviation of the COP in the AP and ML planes in three subsequent windows of 2000 ms, covering the 6000 ms post-stimulus onset (representing *Virtual character proximity*). 0.001% (~25 trials) of the data was manually removed as they represented clear technical artifacts. Scores were analysed with a generalized linear mixed-effects approach in RStudio using the glmer function from the lme4 package (Bates et al., 2015), which allows to model dependency in data with non-normal distributed model residuals and to account for missing values. The data were assumed to follow a gamma distribution. All the fitted models included by-subject intercepts.

For both baselined HR and postural mobility measures, model complexity was gradually increased by inserting fixed effects – *Embodiment type, Virtual character skin color, Virtual character posture*, and *Virtual character proximity* – and their interactions to check for the model that best fitted the data. The different statistical models were compared using the anova function from the stats package (R Core Team, 2019). AIC, BIC, and Chi-square statistics informed us on which model best fitted the data compared to the previous ones in the hierarchy. When relevant, Tukey-corrected post-hoc comparisons were performed with the R package lsmeans (Russel and Lenth, 2016). For all results, a threshold of p = 0.05 for statistical significance was used.

Race IAT. The IAT measures the strength of the automatic concept-attribute associations that are thought to underlie implicit biases and stereotypes (Greenwald et al., 1998). The critical blocks consisted in answering with the same keyword button to “bad” words (e.g., awful, nasty) *and* images of black-skinned individuals and with another keyword button (placed in the opposite direction, symmetrically) to “good” words (e.g., love, happy) *and* images of white-skinned individuals (Knutson et al., 2007; see also Table S1). Vice versa for non-critical blocks. Individual IAT D1 scores were extracted as the mean difference in reaction times between non-critical and critical blocks of the task, divided by the pooled standard deviation of the two types of blocks. These scores represent the strength of the implicit concept-attribute association that sees black people as “bad” and white people as “good”. We created an index subtracting the individual D1 scores for the IAT taken before the embodiment to those obtained with the IAT taken at the end of each session – we call this ΔD1. We then compared the ΔD1 scores across sessions (black and white embodiment) with a paired sample t-test.

Results

Embodiment questionnaire

In both sessions participants showed moderate body ownership of the avatar (white-skinned VB: M = 3.14, SD = 1.37; black-skinned VB: M = 2.93, SD = 1.49). Note that the levels of embodiment obtained in our study are comparable to those found in other studies on related topics and using similar experimental practices (Slater et al., 2010; Banakou et al., 2013; Mello et al., 2022). Participants’ ownership scores did not differ depending on the type of VB experienced during the two sessions (t = -0.66, p = 0.51) indicating that they experienced a similar amount of embodiment, regardless of the VB. These results are further supported by the significant positive correlation found between ownership scores for a white-skinned avatar and those for a black-skinned avatar (Pearson’s r = 0.44, p = 0.03), clearly indicating within-subject coherence in eliciting embodiment using immersive virtual reality.

Baselined HR

The linear model run with baselined heart rate values as outcome yielded main effects of *Embodiment type, Virtual character skin color, Virtual character posture*, and *Virtual character proximity*. Overall, HR was significantly lower when participants embodied a black-skinned VB, compared to a white-skinned one (estimate = 0.65; t = 2.96, p = 0.003); when they faced a black-skinned, compared to a white-skinned virtual character (estimate = 0.58; t = 2.44, p = 0.01); when they faced an aggressive, compared to a neutral virtual character (estimate = 0.51; t = 2.36, p = 0.01); and for close compared to both intermediate (estimate = 0.53; t = 2.44, p = 0.01) and far virtual character proximity (estimate = 0.42; t = 1.96, p = 0.04). *Embodiment type* further interacted with *Virtual character skin color* and *Virtual character posture*. In the first interaction, the effect represented by a reduced heart rate when facing a black-skinned virtual character, compared to a white-skinned one, was greater when participants embodied a black-skinned VB (estimate = -0.77; t = -3.07, p = 0.002). This effect was driven by a greater reduction in heart rate when facing a black-skinned virtual character and embodying a black-skinned VB. Similarly, the effect represented by a reduced heart rate when facing an aggressive virtual character, compared to a neutral one, was greater when participants embodied a black-skinned VB (estimate = -0.53; t = -2.12, p = 0.03). This effect was also driven by a greater reduction in heart rate when facing an aggressive virtual character and embodying a black-skinned VB. Importantly, we found a significant three-way interaction: *Embodiment type* interacted with *Virtual character skin color*, and *Virtual character posture* (estimate = 0.8; t = 2.26, p = 0.02). This interaction is explained by the reduction in heart rate when facing a black-skinned, aggressive virtual character, compared to a black-skinned, neutral virtual character, and when participants embodied a black-skinned VB themselves (Fig. 2).

Postural mobility

The generalized linear model run with the SDs in the AP plane (AP_SD) as outcome yielded main effects of *Virtual character skin color* and *Virtual character proximity*. AP_SD decreased when facing a black-skinned, compared to a white-skinned, virtual character (estimate = -1.34; t = -2.56, p = 0.01). Moreover, a decrease in AP_SD was observed for close virtual character proximity compared to both far (estimate = -2.03; t = -3-29, p = 0.001) and intermediate (estimate = -1.53; t = -2.45, p = 0.01) virtual character proximity. The factor *Virtual character proximity* further interacted with both *Embodiment type* and *Virtual character skin color*. As concerns the former interaction, the effects represented by a reduction in AP_SD for close versus far virtual character proximity (estimate = -1.41; t = -2.1, p = 0.03) and for close versus intermediate virtual character proximity (estimate = -2.56; t = -3.8, p < 0.001) were greater when participants embodied a white-skinned compared to a black-skinned VB. This effect was driven by an overall decrease in AP_SD when embodying a black-skinned VB (Fig. 3A). In fact, post hoc tests revealed that the embodiment in a black-skinned VB compared to white-skinned VB, was associated with reduced AP_SD for far virtual character proximity (estimate = 1.99; z = 4.66, p < 0.001) and intermediate virtual character proximity (estimate = 3.13; z = 7.38, p < 0.001). Finally, the same proximity effects, a reduction in AP_SD for close versus far virtual character proximity (estimate = 1.69; t = 2.57, p = 0.01) and for close versus intermediate virtual character proximity (estimate = 1.54; t = 2.42, p = 0.01) were greater when participants faced a black-skinned compared to a white-skinned virtual character. These effects were mainly driven by a reduced AP_SD when participants faced a black-skinned virtual character in the last 2 seconds of the condition (close proximity) (Fig. 3B). All other main effects and interactions were not significant.

The generalized linear model run with the SDs in the ML plane (ML_SD) as outcome yielded main effects of *Embodiment type, Virtual character skin color*, and *Virtual character posture*. We observed a reduction in ML_SD when embodying a black-skinned versus white-skinned VB (estimate = -2.08; t = -3.84, p < 0.001); when facing a black-skinned versus white-skinned virtual character (estimate = -1.31; t = -2.36, p = 0.01); and when facing an aggressive versus neutral virtual character (estimate = -1.32; t = -2.37, p = 0.01). We also found a set of two-way interactions – *Embodiment type* and *Virtual character skin color, Embodiment type* and *Virtual character posture, Virtual character skin color* and *Virtual character posture,* and *Virtual character skin color* and *Virtual character proximity* – that are better explained by the three-way and four-way interactions we observed. *Embodiment type* interacted with *Virtual character skin color* and *Virtual character posture*. ML_SD in response to a black-skinned, aggressive virtual character versus a black-skinned, neutral virtual character had an inverse relationship when embodying a black-skinned compared to a white-skinned VB. In fact, ML_SD decreased when facing a black-skinned, aggressive virtual character (com-

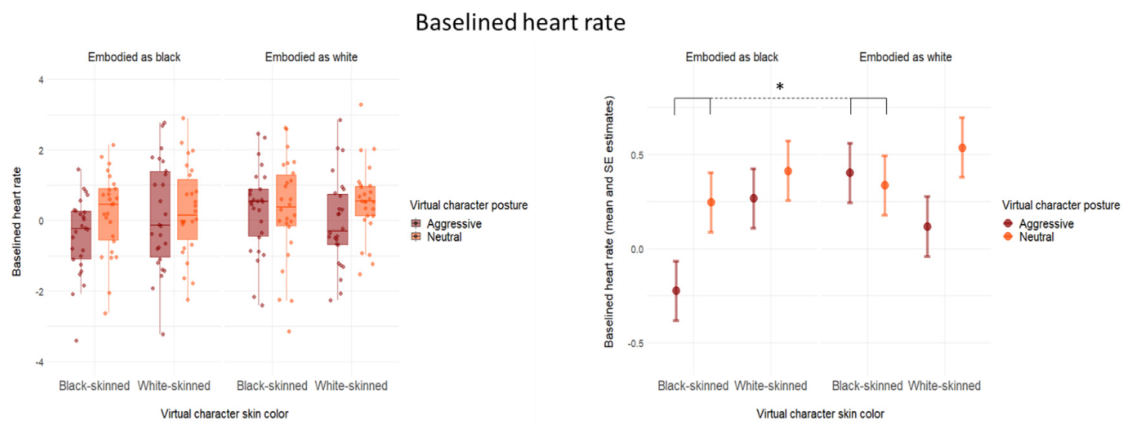

Fig. 2. Left. Baselined heart rate data averaged across participants. **Right.** Corresponding mean and SE model estimates showing a three-way interaction effect (Embodiment type*Virtual character skin color*Virtual character posture).

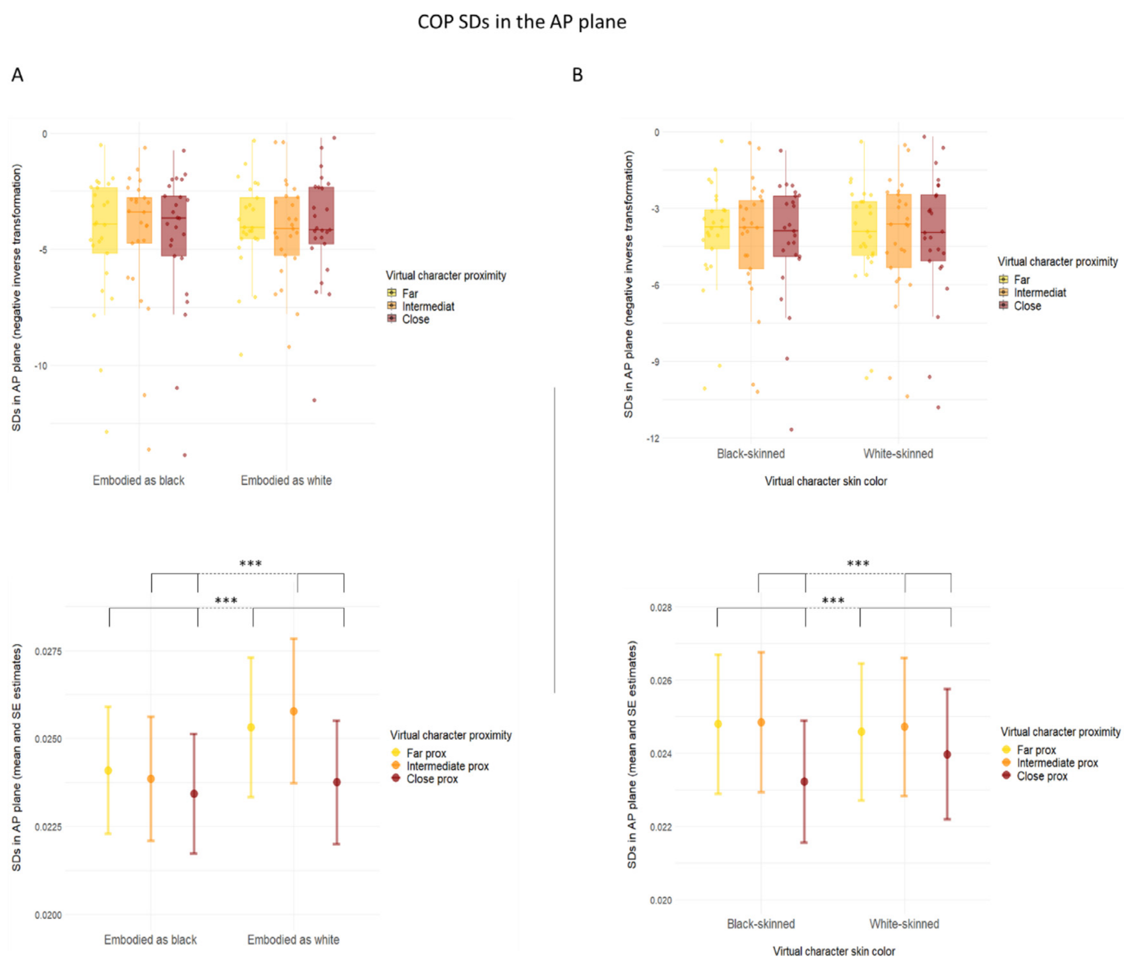

Fig. 3. (A) Top. Body sway in the AP plane data averaged across participants. **Bottom**. Corresponding mean and SE model estimates showing a two-way interaction effect (Embodiment type*Virtual character proximity). **(B) Top.** Body sway in the AP plane data averaged across participants. **Bottom**. Corresponding mean and SE model estimates showing a two-way interaction effect (Virtual character skin color*Virtual character proximity).

pared to neutral) and embodying a black-skinned VB, while it increased when facing a black-skinned, aggressive virtual character (compared to neutral) and embodying a white-skinned VB (estimate = -3.09; t = -3.1, p = 0.002) (Fig. 4). Supporting this, post hoc tests revealed that, when facing a black-skinned, aggressive virtual character, participants' ML_SD was significantly lower when embodying a black-skinned VB, compared to a white-skinned one (estimate = 1.77; z = 5.56, p < 0.001). Lastly, this three-way interaction effect was modulated by *Virtual character proximity*, being greater for close versus far virtual character proximity (four-way interaction: estimate = -3.91; t = 2.71, p = 0.006).

Race-IAT

Reaction times differed significantly for critical (M = 0.68, SD = 0.14) compared to non-critical blocks (M = 0.75, SD = 0.13) (averaged across sessions). Participants were faster in categorizing "bad"

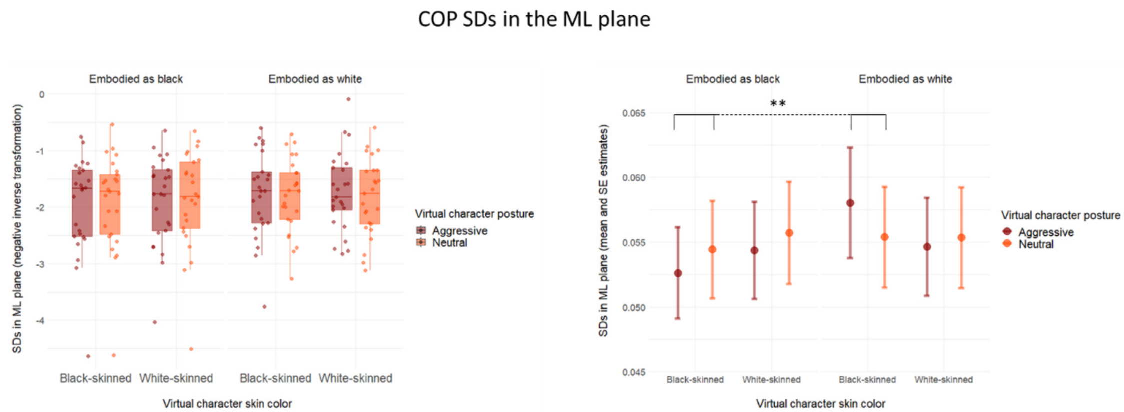

Fig. 4. Left. Body sway in the ML plane data averaged across participants. **Right**. Corresponding mean and SE model estimates showing a three-way interaction effect (Embodiment type*Virtual character skin color*Virtual character posture). Note–A four-way interaction effect (Embodiment type*Virtual character skin color*Virtual character posture*Virtual character proximity) was found, but a three-way effect is shown for simplicity.

words *with* images of black-skinned individuals and "good" words *with* images of white-skinned individuals compared to the opposite (t = -8.16, $p < 0.001$). This indicates that an implicit outgroup bias was present in our sample. ΔD1 scores did not differ across embodiment conditions (t = -0.49, $p = 0.62$).

Discussion

This study set out to test the effect of understudied aspects of social threat, namely body expression, group affiliation and proximity, on freezing. We hypothesized that aggressive and outgroup virtual characters approaching the participants would elicit a reduction in heart rate and body sway and that this would be enhanced when the virtual characters are closest to the participant. Our results partly confirm this hypothesis. We found that people freeze more when facing aggressive-looking virtual characters and when virtual characters are in close proximity, independent of their characteristics. In contrast to our prediction, freezing was stronger for ethnic ingroup members, i.e., for black-skinned aggressive virtual characters when participants embodied a black-skinned VB. Below, we discuss these findings against the relevant literature.

Our findings on freezing when facing aggressive virtual characters are in line with previous work reporting freezing for social threats in humans (Roelofs et al., 2010; Hagenaars et al., 2014; Gladwin et al., 2016). For instance, Roelofs and colleagues (2010) showed that the perception of angry facial expressions, compared to happy and neutral expressions, was associated with both reduced body sway and bradycardia. We report that a freezing state is triggered by threatening whole-body expressions as well. The notion that seeing expressive whole-body postures and movements triggers motor preparation was at the core of the earliest studies on body expressions (e.g., de Gelder et al., 2004) but no direct physiological or behavioral evidence was so far available. Consistent with this perspective, Borgomaneri and colleagues (2015) showed that watching fearful body expressions suppresses TMS-induced intracortical facilitation in the motor cortex and the authors interpreted this as an index of freezing response when observing a cue indicating a potential threat in the environment. We expand this at the behavioral and physiological levels by showing that facing an aggressive body posture is also associated with freezing.

The present work also clarifies the impact of the proximity of the social threat on freezing as we found an overall reduction of heart rate and body sway in the AP plane when participants faced a virtual character in close proximity. This situation represented an inescapable threat as participants were instructed to stand still on the force platform and to try not to react to the approaching stimuli. Our finding is consistent with previous studies showing that facing approaching inescapable threats results in augmentation of freezing, as represented by fear bradycardia, and increased skin conductance and startle reflex (Löw et al., 2015; Wendt et al., 2017). For instance, Wendt and colleagues (2017) showed that while facing approaching inescapable threats is associated with attentive freezing behavior, escapable threats elicit instead active avoidance. Thus, our results support the finding that, when people are not given the opportunity to actively avoid a threat, passive freezing is the predominant defensive strategy implemented by humans in the face of proximal threats. However, our paradigm could not dissociate passive from active defensive behavior, as escapable threats were not included. Future studies should address this limitation by implementing a paradigm in which a freezing-like reaction to virtual threatening stimuli is assessed in the face of both escapable and inescapable threats.

The other main aspect of our findings concerns the role of group affiliation, studied here by manipulating skin color. We showed that behavioral reactions and physiological activation differ as a function of the skin color of the threatening virtual character but also as a function of the type of embodiment. We observed enhanced freezing (reduction of heart rate and body sway in the ML plane) to black-skinned aggressive virtual characters when the participants embodied a black-skinned VB themselves. This effect was also greater for proximal virtual characters (only concerning the body sway in the ML plane). This finding is surprising considering results from studies on group affiliation and implicit bias. First, the literature on group affiliation bias and perception of threat (Amodio and Cikara, 2021) predicts that encountering a virtual character belonging to a different group (by skin color) under the above conditions exacerbates freezing. In fact, an approach based on the role of group dynamics, with 'group' here specified as skin color, would predict that behavior is consistent with the participants' group affiliation such that a black-skinned aggressor is more threatening when participants embody a white virtual character and vice versa. However, the group affiliation logic seems to fail here as our results show the opposite pattern and suggest that ingroup-outgroup dynamics and their influence on defensive behavior are not simply a matter of skin color (of both the offender and the offended).

Beyond simple group affiliation-based threat reactions (Boyer et al., 2015), the literature suggests various other explanations which we present as speculations consistent with our results. The fact that the minority (black-skinned) virtual character condition tends to be perceived by the participants as more threatening when they embody a black-skinned VB finds support in studies on internalized stereotypes. For example, black individuals consider black neighbourhoods as "less safe" if they believe the stereotype that black communities are dangerous (Bailey et al., 2011). This interpretation would be strengthened by the finding of an increase in ownership and other virtual embodiment indexes (e.g., agency) for black-skinned virtual bodies over time. We believe future studies should directly address this issue. A different possibility is that ingroup violence is perceived as more realistic and therefore more threatening because aggression from the same group member is likely to be more serious than random and less personal aggression from a stranger. Supporting this, and along with our main findings on black-skinned embodiment, our results (Fig. 2) show that the difference in heart rate between white-skinned aggressive and white-skinned neutral conditions is bigger when embodying a white-skinned virtual character, compared to a black-skinned one. However, the direct comparison between the conditions of interest – white embodiment, white-skinned aggressive virtual character compared to black embodiment, white-skinned aggressive virtual character – was not significant (Tukey-corrected, post-hoc comparison: $p > 0.05$).

Finally, it is worth noting that previous studies have shown that the embodiment of white people in a black-skinned VB is associated with reduced negative biases towards black people (Peck et al., 2013; Banakou et al., 2016). But we did not find such a reduction in IAT-measured implicit biases when participants embodied a black-skinned VB. We cannot exclude that a longer embodiment phase would have made a critical difference in eliciting the expected reduction in IAT-measured outgroup biases. Still, our results show that this condition caused the illusion of BO in the participants. Alternatively, the long exposure to repeated stimuli during the main experimental task might have weakened the initial strength of the embodied perspective-taking process.

Our findings show that group affiliation dynamics, skin color, implicit attitudes and behavior have complex relations with one another such that an explanation focusing on just one of them is unlikely to explain the data. More studies are needed to shed light on the dispositional and contextual factors that contribute to defensive behavior both in within-group and between-group situations and to gain a better understanding of the within-group dynamics that may have been neglected in favour of ingroup-outgroup difference.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Manuel Mello: Conceptualization, Methodology, Data curation, Investigation, Formal analysis, Writing – original draft, Visualization, Writing – review & editing. **Lennie Dupont:** Conceptualization, Methodology, Data curation, Investigation, Formal analysis, Writing – original draft, Visualization, Writing – review & editing. **Tahnée Engelen:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Adriano Acciarino:** Conceptualization, Methodology, Data curation, Investigation, Writing – review & editing. **Aline W. de Borst:** Conceptualization, Methodology, Writing – review & editing. **Beatrice de Gelder:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition, Supervision.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.crbeha.2022.100075.

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