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Running head: Electrodermal activity and social comfort distance

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Abstract

Interpersonal distance, an essential component of social interaction, is modulated by the emotion conveyed by others and associated physiological response. However, in modern societies with overcrowded and hyperstimulating environments, we can only surreptitiously glimpse the faces of others in order to quickly make behavioural adjustments. How this impacts social interactions is not yet well understood. In the present study, we investigated this issue by testing whether facial expressions that are difficult to identify modify the physiological response (Electrodermal Activity, EDA) and subsequent judgment of interpersonal comfort distance. We recorded participants' EDA while they provided comfort judgments to interpersonal distances with a Point-Light Walker (PLW). The PLW, with an emotionally neutral gait, moved towards and crossed participants at various distances after the latter were exposed to a negative (anger), positive (happiness) or neutral facial expression presented at the perceptual threshold. Bayesian analyses of the data revealed an increase vs decrease of interpersonal comfort distance with the PLW depending on the negative vs positive emotional valence of the facial expression. They also showed an increase in EDA when the approaching PLW violated interpersonal comfort distance after participants were exposed to an angry facial expression. These effects correlated with the subjective assessment of the arousal of facial expressions. Thus, previous exposure to barely visible facial expressions can alter the representation of social comfort space and the physiological response associated with a violation of interpersonal comfort distances, depending on the valence and arousal of the emotional social stimuli.

Keywords: Social interaction, interpersonal space, facial expression, electrodermal activity, physiological response, perceptual threshold, visual masking

1. Introduction

Among the numerous non-verbal signals in a social situation, facial expressions are considered as crucial indications for interpreting the current social context and identifying potential sources of hazards and threats. However, in our modern societies characterised by overcrowded and hyperstimulating environments, we can only surreptitiously glimpse the faces of others and quickly make behavioural adjustments almost without realizing it. How the emotional signals carried by others' faces, which can be difficult to identify because of their poor visibility (e.g. quickly glimpse, poor lightening, overcrowding…), transience and diversity, influence our social behaviour remains an open issue. A key component of social interactions is the adjustment of interpersonal distance both in animals (Hediger, 1968) and in humans (Hall, 1966; Hayduk, 1978). Selecting an appropriate interpersonal distance involves two constraints: the need to approach conspecifics to interact with them and the need to maintain a margin of safety with others to protect the body from external hazards (Dosey & Meisels, 1969; Hayduk, 1983; Siegman & Feldstein, 2014). As evidence for a protective spatial buffer around the body, a strong physiological response was reported when non-familiar conspecifics unexpectedly violated the margin of safety of others, producing in them an increase a) in electrodermal activity (EDA, Aiello, Derisi, Epstein, & Karlin, 1977; McBride, King, & James, 1965), b) in the activity of the neuro-emotional network including the amygdala (Kennedy, Gläscher, Tyszka, & Adolphs, 2009), and c) in the level of stress-related hormones such as cortisol (Evans & Wener, 2007).

Previous studies suggested that interpersonal comfort distance is related to how one represents the space where we can act on reachable objects with the body (i.e., the peripersonal space, Quesque et al., 2017, but see Patané, Farnè, & Frassinetti, 2017). As evidence, Quesque and collaborators revealed that using a tool, which is known to modify arm's length in the body schema, resulting in an increase in the peripersonal space, also alters preferred interpersonal distances (Quesque et al., 2017). Moreover, the fronto-parietal structures supporting peripersonal space representation were found to contribute also to interpersonal distance adjustments (Vieira, Pierzchajlo, & Mitchell, 2019). Interpersonal comfort distance is also modulated by a number of variables, including cultural habits (Hall, 1966), ethnicity (Leibman, 1970), gender and age (Iachini et al., 2016), prior information about people's morals (Iachini, Pagliaro, & Ruggiero, 2015) and psychopathological characteristics (Nandrino, Ducro, Iachini, & Coello, 2017). Accordingly, individuals suffering from social anxiety (Dosey & Meisels, 1969), claustrophobia (Lourenco, Longo, & Pathman, 2011), borderline personality disorder (Schienle, Wabnegger, Schöngassner, & Leutgeb, 2015) or autistic spectrum disorder (Candini et al., 2017; Perry, Levy-Gigi, Richter-Levin, & Shamay-Tsoory, 2015) usually prefer wider interpersonal distances, whereas those with high psychopathic traits usually prefer narrower interpersonal distances (Rimé, Bouvy, Leborgne, & Rouillon, 1978; Vieira & Marsh, 2014; Welsch, Hecht, & von Castell, 2018).

Non-verbal behaviour such as facial expressions also provides crucial clues in the adjustment of interpersonal distances (Cartaud, Ruggiero, Ott, Iachini, & Coello, 2018; Lockard, Mcvittie, & Isaac, 1977; Ruggiero et al., 2017; Vieira, Tavares, Marsh, & Mitchell, 2017). Previous studies suggested that facial expressions are processed quickly and automatically because they are an essential component of social interactions and are important for survival (Buck, Savin, Miller, & Caul, 1972; Darwin, 1872; Ekman & Friesen, 1971; Schrammel, Pannasch, Graupner, Mojzisch, & Velichkovsky, 2009). Therefore, perceiving positive facial expression (i.e., happiness) usually leads to a reduction in interpersonal comfort distance (Lockard et al., 1977; Ruggiero et al., 2017), while perceiving negative facial expression (e.g. anger) usually leads to an increase in interpersonal comfort distance (Cartaud et al., 2018). Furthermore, the physiological response to the violation of interpersonal comfort distance depends on the valence of the emotion carried by the intruder's face.

In particular, it was found that neural activity in the amygdala increases in the presence of an angry or fearful facial expression, but not in the presence of neutral or happy facial one (Whalen et al., 2001). Moreover, the neural response is positively correlated with the preferred distances selected with these facial expressions (Vieira et al., 2017). EDA used as a proxy of physiological response to emotional stimuli is also modulated by the valence and arousal of facial expressions (Buck et al., 1972; Lang, Greenwald, Bradley, & Hamm, 1993) and more significantly when the emotional stimuli are in the peripersonal space (Cartaud et al., 2018).

Although it is widely accepted that facial expressions modulate both the electrodermal activity and interpersonal distance, it is not yet known how barely visible facial expressions modulate physiological response and alter behavioural adjustment to subsequent interactions with neutral social stimuli, even though this situation occurs every day. To address this issue, we conducted an experiment in which the difficulty to identify a facial expression was controlled by presenting the visual stimuli at perceptual threshold using forward and backward visual masks (Breitmeyer, 2007; Deplancke, Madelain, & Coello, 2016; Lamme, Supèr, Landman, Roelfsema, & Spekreijse, 2000; Macknik & Martinez-Conde, 2009). After being exposed to a barely visible facial expression (anger, happiness, neutral), participants provided a comfort judgment of interpersonal distance with an approaching human-like point-light walker (PLW with a neutral gait) crossing them at different distances, and EDA was recorded. We expected an increase in EDA when participants were previously exposed to an angry facial expression presented at perceptual threshold, especially when the PLW violated the participants' interpersonal comfort distance. Moreover, we expected interpersonal comfort distance to increase or decrease when the approaching PLW was preceded by an angry or happy facial expression, respectively, compared to a neutral one. Finally, we expected the magnitude of these effects to be related to the level of subjective arousal associated with the facial expressions.

2. Method

2.1. Participants

Forty-five healthy right-handed participants with normal or corrected-to-normal vision participated in the experiment. Due to the poor quality of the electrodermal activity recording for six of them, only 39 (27 women, M_{age} = 19.69 years, SD_{age} = 1.10) were included in the data analysis. They all gave their written informed consent, and the protocol received approval by the local Institutional Ethics Committee (Reference No. 2018-279-S61) and conformed to the principles of the Declaration of Helsinki (World Medical Association, 2013).

2.2. Apparatus and stimuli

Participants stood 1 m from a 4 m x 2 m screen on which 3D visual stimuli were rear-projected with a spatial resolution of 4 K (3840 x 2060 px), using a stereoscopic video projector and Christie 3D active glasses (see Cartaud et al., 2018 for a detailed description). The stimuli consisted of 16 male and female faces selected from the NimStim set of facial expressions (Tottenham et al., 2009). Each face was associated with an angry, happy, or neutral facial expression (faces with an angry or happy expression had an open mouth but not neutral faces). The size of the face corresponded to that of an actual face presented 0.9 m from the participant. To display facial expressions at the perceptual threshold, the faces were displayed for 16.67 ms and were preceded and followed by a visual mask. The forward and backward visual masks [1]

[1] According to neurophysiological models of visual perception, the conscious processing of a visual stimulus depends on two neural activities: a first stimulus-dependent activity observed in the form of a transient feedforward sweep of activation (transient channel) and a second activity mediated via sustained re-entrant activations from higher cortical areas (sustained channel: Breitmeyer, 2007; Macknik & Martinez-Conde, 2007, 2009; Supèr & Lamme, 2007). Within this framework, backward visual masking has been shown to selectively suppress the second perceptual-dependent component of the neural response, whereas forward

corresponded to a distorted version of the face displayed and were presented with a duration randomly selected between 0.8 s to 1 s (see below for the procedure). They were computed online and consisted in randomly shifting vertically and horizontally each pixel composing the face, according to an [-100 px, +100 px] interval centred on the pixel's position. Then a random angle was applied (noise.spread plugin developed by Micheal Mure and implemented in Gimp (https://github.com/MichaelMure/gimp-plugins/blob/master/common/noise-spread.c). This masking procedure allowed the colour and light flow of the visual stimuli to be maintained while altering the visual features and visibility of the faces.

The facial expressions and their masks could be followed by the PLW (see procedure section) that consisted of 13 white dots presented on a black background which provided information about the movement of the head, left and right ankles, knees, hips, wrists, elbows, and shoulders (see Mouta, Santos, & Lopez-Moliner, 2012), without providing any about the body itself. When displayed, the PLW appeared congruently with the location of the face, the starting position of the PLW was ±30 deg in relation to the perpendicular gaze of the participants (minus sign for left locations). It remained still for 0.5 s, then walked towards the participants at a constant speed of 1.2 m/s (simulated looming velocity was constant, Mouta et al., 2012), and finally disappeared when reaching a distance of 1.5 m from them. The PLW approached the participants with a gender-dependent (depending on the face) but emotionally neutral gait kinematics. Its trajectory crossed the participants' fronto-parallel plane either on their left or right side. The inter-shoulder distance at the crossing point (i.e. distance between the participants' shoulder and the PLW's shoulder) could vary between -8 and 72 cm (by 8 cm increments, negative sign representing

visual masking is thought to suppress the first stimulus-dependent component of the neural response along with partial suppression of its later component (Breitmeyer, 2007; Deplancke, Madelain, & Coello, 2016; Lamme, Supèr, Landman, Roelfsema, & Spekreijse, 2000; Macknik & Livingstone, 1998; Macknik & Martinez-Conde, 2009).

collision with the participants). The 0 cm condition was specified for each participant and was calculated according to the distance separating the mid-sagittal body axis from the participants' shoulder). Participants physiological responses were registered by EDA through a BIOPAC MP36 physiological amplifier (BIOPAC Systems, Inc., Goleta, CA, United States). Two Ag-AgCl electrodes filled with GEL101 electrolytic mixture were tied on the distal phalanges of the index and major fingers of the non-dominant hand (Fowles et al., 1981). The room temperature during the experiment was maintained at 21°C for all participants, and the signal was recorded at a sample rate of 1000 Hz.

2.3.Procedure and measures

Before starting the experiment, participants were requested to complete a self-administered battery of questionnaires on LimeSurvey (version 2.63.1) in order to control for exclusion criteria (no drug and alcohol consumption or excessive stimulating beverage within the last 24 hours, no previous history of neurological or psychiatric disorders). The battery also included the Edinburgh Test and the State-Trait Anxiety Inventory STAI-YB (Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983; French version by Bruchon-Schweitzer & Paulhan, 1993) to check for laterality (M = 0.78, SD = 0.32, Oldfield, 1971) and atypical anxious symptoms (which was the case for none of the participants with an average anxiety-state score: 29.31 SD = 4.95 and anxiety trait: 43.36 SD = 8.16). Then, participants were placed in front of the vertical screen as described earlier and were given instructions. They started with the perceptual threshold determination task, followed by the comfort judgment of interpersonal distance task, and ended with the subjective assessment of arousal of facial expressions. The two sessions of comfort judgment of interpersonal distance were set up in order to analyse both the physiological (EDA, session 1) and behavioural (interpersonal comfort distance, session 2) responses, while limiting the habituation effect associated with repeated stimuli on the physiological responses. Accordingly, in session 1 the PLW crossed the participants' fronto-parallel plane at only three inter-shoulder distances (-8, 32, 72 cm) whereas in session 2, the participant encountered every condition (-8 to 72 cm by step of 8 cm) so that behavioural responses could be accurately analysed. All tasks were programmed using Psychtoolbox-3 (Kleiner et al., 2007).

2.3.1. *Perceptual threshold determination*

To determine psychophysically the perceptual threshold of facial expressions, participants had to identify the facial expressions in a set of four faces (two males and two females with three facial expressions). Each facial expression (angry, happy and neutral) was associated with a specific response key (1, 2 and 3 on the keypad) and a familiarization phase was included. Each face was displayed for 16.67 ms between a forward and a backward visual mask but the mean luminance of the face (and that of the masks) was modified in each trial by adjusting the values of the channels in the HSV colour space (Hue, Saturation, Value) to a given mean between 0 and 0.2 by step of 0.02 (0 and 1 corresponding respectively to no luminance and full luminance, see Fig. 1).

----- INSERT FIGURE 1 ABOUT HERE -----

Thus, two faces per gender were presented randomly with three facial expressions across 11 luminance ratios resulting in a total of 132 trials (method of constant stimuli). We thus determined the averaged perceptual threshold of the facial expressions. Despite the happiness and anger superiority effect in visual perception (Brosch, Sander, Pourtois, & Scherer, 2008; Hansen & Harsen, 1988), we decided to use the same perceptual threshold for every facial expression, including the neutral stimuli. Indeed, as the same individual luminance was used for the facial expression and for the forward and backward masks, using a different luminance threshold as a function of the facial expression would have provided anticipatory information about the forthcoming facial expression as soon as the forward mask appeared. The threshold (66.67% of the correct responses, each stimulus being associated with three possible responses, chance level corresponded to 1/3 of the correct responses) was determined using a maximum likelihood fit procedure based on a second-order derivative optimization method to obtain the logit regression model that best fitted the participants' correct vs wrong identification of the facial expressions using the equation:

$$y = \frac{1}{3} + (1 - \frac{1}{3}) * \frac{e^{(\alpha + \beta X)}}{1 + e^{(\alpha + \beta X)}} \quad (1)$$

where y is the participants' probability of giving a correct answer for each facial expression (from 1/3 to 1) at the luminance ratio X, and (-α/β) is the critical value of X corresponding to the transition between correct/non-correct responses expressing thus the perceptual threshold of facial expressions. For each participant, temporal and luminance parameters associated with individual perceptual thresholds were registered and then used in the subsequent comfort judgment of interpersonal distance task (session 1 and 2) for presenting facial expressions at the perceptual threshold. The mean luminance threshold was 0.12 with a 95% confidence interval between 0.11 and 0.13.

2.3.2. *Comfort judgment of interpersonal distance*

2.3.2.1. Session 1: Physiological responses

After having determined the individual perceptual threshold, the experimenter equipped participants with electrodes placed on the index and major fingers of the non-dominant hand and provided instructions before starting the comfort judgment of interpersonal distance task. Following a training session including six trials, the task began with a 30 s recording of the EDA while the participants were still and staring at a black screen (signal stabilization period after participants moved from sitting to standing position). Then, they were requested to judge whether the distance at which the approaching PLW crossed their fronto-parallel plane was comfortable or not (2-AFC paradigm). At the beginning of each trial, a facial expression at the individual perceptual threshold was displayed, then the PLW approached and disappeared when reaching the distance of 1.5 m from the participants. Once the PLW had disappeared, participants provided their comfort judgment with the index and major fingers of the dominant hand (counterbalanced across participants) by pressing the ENTER or PLUS keys of the keypad positioned on a table near their right hand. Participants thus had to represent the end of the trajectory mentally until they represented the PLW crossing their fronto-parallel plane. Irrespective of its starting location (±30°), the PLW walked 4.5 m and crossed the participants' fronto-parallel plane according to three possible inter-shoulder distances (-8, 32 or 72 cm) randomly selected. A new set of 12 faces (6 males and 6 females, not seen before) was used and each face was associated with only one facial expression (angry, happy or neutral), resulting thus in two faces per gender per facial expression. To limit the habituation effect leading to a decrease in the physiological response, each face was presented only once per crossing distance on either the left or right side (randomly selected). A black screen then appeared for a random duration of 4 to 5.5 s following the participants' response.

Participants performed 36 trials in a single block (2 genders x 3 facial expressions x 3 crossing distances x 2 starting locations). The schematic representation of a typical trial is displayed in Fig. 2.

----- INSERT FIGURE 2 ABOUT HERE -----

2.3.2.2.<u>Session 2: Behavioural responses</u>

This task was similar to the previous one, i.e. participants had to judge whether the distance at which the PLW crossed their fronto-parallel plane was comfortable or not. However, electrodermal activity was not recorded, and the latency separating the participants' response from the following trial was randomly selected between 0.5 and 0.7 s. Furthermore, for each starting location the PLW crossed the participants' fronto-parallel plane at one of the 11 possible inter-shoulder distances on the contralateral side (from -8 to 72 cm by step of 8 cm). A total of 264 trials was performed (2 faces x 2 genders x 3 facial expressions x 11 crossing distances x 2 starting locations) divided in three blocks with a resting period before each new block. This session allowed a precise evaluation of the boundary of interpersonal comfort distance of each participant.

2.3.3. Post experimental stimuli assessment

At the end of the experiment, participants were requested to provide a subjective evaluation of the emotional intensity (arousal) of the facial expressions (SEI, 0: low intensity; 10: high intensity). The facial expressions were presented at the perceptual threshold in the centre of the screen 0.9 m from the participants. When the face disappeared, a horizontal line with a cursor in the middle was displayed indicating “low intensity” on the left side and “high intensity” on the right side. The horizontal line remained on the screen until the response was provided by the participants with the computer mouse. This evaluation was used only as a control variable for the analysis of the physiological and behavioural responses. The mean SEI and its 95% confidence interval were 5.05 [4.63, 5.48] for angry facial expressions, 5.43 [5.01, 5.95] for happy ones and 2.42 [2.05, 2.78] for neutral facial expressions. Overall, the experiment lasted about two hours, including a debriefing of the experiment.

2.4.Data recording and analysis

Participants’ electrodermal activity was analysed using the LEDALAB toolbox (version 3.4.9, Benedek & Kaernbach, 2010). The physiological signal was first down-sampled at 20 Hz, then smoothed using a 50-sample gaussian window filter corresponding to a cut-off frequency of 0.42 Hz. We first decomposed the physiological signal into tonic and phasic components using continuous decomposition analysis. Then, we analysed the average of the phasic information in the signal (phasic driver, a proxy of sudomotor nerve response) over each epoch (CDA.SCR). The time window of interest was 0.5 to 5 s following stimulus onset. Five trials associated with unexpected actions from the participants were removed from the analysis (e.g. coughing, 0.36% of the trials). Comfort judgments were analysed from the (comfortable/not comfortable) responses provided by the participants depending on the inter-shoulder distance and the facial expression. Participants’ responses were pooled for the PLW starting from the right and left side (see Quesque et al., 2017 for details). The boundary of interpersonal comfort distance was determined from the participants’ responses at each distance using the equation:

$$y = \frac{e^{(\alpha + \beta X)}}{1 + e^{(\alpha + \beta X)}} \tag{2}$$

in which y is the participants' (comfortable/not comfortable) response, X is the crossing distance, and (-α/β) is the critical value of X corresponding to the transition between comfortable and uncomfortable stimuli, thus expressing the boundary of interpersonal comfort distance.

All statistical analyses were carried out by Bayesian linear mixed models regression with the brms package (brms 2.8.0 and RStan 2.18.2, Bürkner, 2017; Gelman, Lee, & Guo, 2015), using R (version 3.5.1) and R Studio software (version 1.1.463). This method made it possible to quantify the credible parameter values of the models through their posterior distribution, given the likelihood of the data and prior information about plausible values of the parameters. The brms package uses a formula syntax similar to the lme4 package for model specification so that generalized mixed effect models can easily be specified, and interfaces with RStan to sample draws from the posterior distribution. For all the models used, we took interindividual variability into account by adding the Subject level random effects. Mildly informative prior information was given on the fixed effects by specifying a normal distribution ($M = 0$, $SD = 1$) favouring no specific direction for the effects but constraining their magnitude to reasonable value. The default priors proposed by brms (a half student-t distribution and a lkj distribution) were used for the random effects when applicable. Posterior distribution was approximated by a total of 8000 Markov chain Monte Carlo (MCMC) samples obtained from four chains, after a warm-up of 2000 samples per chain. Convergence of the MCMC chains was validated by computing the Rhat statistic and through visual inspection. Contrasts between estimates of the parameters of the posterior distribution were judged as probable when their posterior 95% Credible Intervals (CI, between 2.5% and 97.5% of the posterior distribution) did not include 0 as a probable difference.

Accordingly, if the CI of a contrast includes 0, the null hypothesis cannot be rejected. Each model used for the data analysis is detailed in the following section. Data and statistical analysis are available on the OSF platform (https://osf.io/dkq3f/?view_only=d9d44db7b78a41a895f2c1129cbeb6e2).

3. Results

3.1. Comfort judgment of interpersonal distance

3.1.1. Session 1: Physiological response

A Bayesian mixed-effects regression model with a Hurdle Gamma response distribution was used to analyse the phasic driver (µS) as a function of Facial Expression (angry, happy, neutral), Crossing Distance (-8, 32, 72 cm), Subjective Emotional Intensity (0-10), Participant Gender (male, female) and Stimulus Gender (male, female), according to the model:

$$\begin{aligned} Phasic\ driver \sim & \text{ Facial Expression } * Crossing\ Distance\ * SEI \\ & + Participant\ Gender\ + Stimulus\ gender \\ & + (1 \mid Subject) \end{aligned} \tag{3}$$

As shown in Fig. 3, data analysis revealed an interaction between Facial Expression and Crossing Distance with an increased phasic driver of 17.25E-04 µS [0.7 E-04, 34.61 E-04] for angry faces in comparison to neutral faces at the -8 cm crossing distance. Data analysis also revealed an increase in 19.73E-04 µS [0.65E-04, 42.82E-04] and 19.19E-04 µS [0.72 E-04, 41.8 E-04] for neutral faces at the 32 cm crossing distance in comparison to -8 cm and 72 cm crossing distances, respectively. Finally, we observed an interaction effect between SEI and Crossing Distance and between SEI and Facial Expression on the EDA. A greater slope due to one-point increase in SEI evaluation was observed at the -8 cm compared to the 72 cm Crossing Distance

(+4.94E-04 μS [1.45E-04, 9.05E-04]), and was also observed for angry faces in comparison to neutral (+4.51E-04 μS [0.51E-04, 8.86E-04]) and happy faces (+3.79E-04 μS [0.45E-04, 7.68E-04]). No gender effect emerged for either the gender of the participants or the gender of the stimulus (+22.01 E-04 μS [-7.86, 59.59], -2.65 E-04 μS [-9.89, 4.27] respectively). The R-Squared of this fit was computed using the function bayes_R2 and revealed a coefficient of .23 [.18, .29]. Complementary data are available in appendix 1 (Table A).

----- INSERT FIGURE 3 ABOUT HERE -----

Even though we used only three distances, we analysed the percentage of comfortable responses for each distance. Considering comfort judgments in session 1, a Bayesian logistic mixed-effects regression model was used with a Bernoulli distribution likelihood to analyse the probability of responding 'comfortable' per condition as a function of Facial Expression (angry, happy, neutral), and Crossing Distance (-8, 32 and 72 cm, as a categorical variable), according to the model:

$$(Comfortable/Not\ comfortable\ response) \sim \text{Facial Expression} * Distance + (1 \mid Subject) \quad (4)$$

The main results are reported in Table 1 (averaged R-Squared of fit: R^2 = .56 [.54, .58]).

----- INSERT TABLE 1 ABOUT HERE -----

3.1.1.1.Session 2: Behavioural response

Concerning comfort judgement of interpersonal distance, a Bayesian logistic mixed-effects regression model with a Binomial distribution likelihood was used to analyse the variation in the proportion of ‘comfortable’ responses per condition as a function of Facial Expression (angry, happy, neutral), Crossing Distance (-8 to 72 cm, as a continuous variable), SEI, Participant Gender (male, female) and Stimulus Gender (male, female) according to the model:

$$(Number\ of\ \text{‘}Comfortable\text{’} \mid Number\ of\ trials) \sim \text{Facial Expression} * \text{SEI} * Crossing\ Distance * Participant\ Gender * Stimulus\ gender + (FE * FEI * Crossing\ Distance \mid Subject) \quad (5)$$

Once the model was fitted, the thresholds (mu threshold) and slopes (mu slope) of the logistic functions were computed at group and individual levels for Facial Expression and Facial Expression * SEI using equation (2), β being the sum of the parameters of the model interacting with the distance, and α the sum of those that do not. Posterior estimates of the boundary of interpersonal comfort distance and contrasts are reported in Table 2, and fitted functions are presented in Fig. 4 (averaged R-Squared of fit: R^2 = .78, [.78, .79]).

----- INSERT TABLE 2 ABOUT HERE -----

----- INSERT FIGURE 4 ABOUT HERE -----

3.2.Reliability of measures of interpersonal comfort distance

Finally, we conducted a post-hoc validation of the measures of interpersonal comfort distance obtained in session 2 by fitting the proportion of ‘comfortable’ responses for each participant (session 1) at 32 cm (i.e., close to the boundary of interpersonal comfort distance) with respect to the boundary of interpersonal comfort distance and standard deviation (session 2) using model (5), with respect to each facial expression. To obtain the proportion of ‘comfortable’ responses at 32 cm, we fitted model (4) again but applied only the data of the 32 cm crossing distance, and used the posterior distribution of the estimates obtained from the fit. We then used the individual boundary of interpersonal comfort distance and standard deviations according to each facial expression from the posterior distribution. We removed outliers in the dataset before fitting the model (i.e. boundary of interpersonal comfort distance below 0 cm or greater than 150 cm, or when the standard deviation was greater than 1 for a total of six responses, 5.13% of the data). Finally, we used a Bayesian mixed-effects regression model with a Gaussian distribution likelihood taking measurement errors of the predictor thresholds into account (using Brms me() predictor specification), also taking into account the standard deviation according to the model:

$$Proportion\ of\ 'Comfortable'\ Responses \sim me(Boundary, Boundary\ SD) + (1 \mid Subject) \tag{6}$$

As shown in Fig. 5, this analysis revealed a strong relation between the boundary of interpersonal comfort distance and the proportion of 'comfortable' responses at 32 cm with a decrease of 1.14% [0.82, 1.47] in the proportion of responding 'comfortable' per 1 cm gain in the interpersonal comfort boundary (averaged R-Squared of fit: R^2 = .44 [.31, .55]).

----- INSERT FIGURE 5 ABOUT HERE -----

4. Discussion

We investigated the influence of being exposed to facial expressions presented at the perceptual threshold on automatic physiological response (measured through EDA) and interpersonal comfort distance assessed with human-like neutral stimuli (PLW). To reach the perceptual threshold, facial expressions associated with forward and backward visual masks were presented very quickly (16.67 ms) and with a very weak luminance (12% on average). Despite the presentation of facial expressions at the perceptual threshold, the latter had an effect on the physiological response, as revealed by EDA changes, as well as on the comfort judgment of interpersonal distance.

As regard physiological responses, an increase in EDA was observed when participants were previously exposed to an angry face, but only in the condition where the approaching PLW violated participants' interpersonal comfort space. A similar effect was not obtained when either participants were exposed to a neutral or happy facial expression, or when the approaching PLW respected participants' interpersonal comfort space. These data confirm that facial expressions, which trigger an autonomic reaction, are particularly relevant for adjusting approach-avoidance behaviours, even when not consciously perceived (Brosch et al., 2008; Phelps, Ling, & Carrasco, 2006). They also extend previous findings that a non-familiar conspecific invading social comfort space triggers defensive responses and behaviours (Kennedy et al., 2009). In addition, they provide new insights by showing that the defensive responses from the autonomic nervous system (ANS) depend considerably on facial expression, since the increase in physiological response was observed only when an angry facial expression was displayed. In addition, the increase in EDA with an angry face was observed despite the presentation of facial expressions at the perceptual threshold, making them difficult to identify, and while participants adjusted their behaviour to a neutral human-like stimulus. The latter observation is of paramount importance as it indicates that negative emotional experience associated with the observation of others' behaviour can have a detrimental effect on future social interactions, even when related to emotionally neutral conspecifics. Interestingly, the magnitude of the effect was coherent with the subjective assessment of the arousal of facial expressions, despite the difficulty of identifying it. The more arousing the angry face, the stronger the EDA and the greater the interpersonal comfort distance. Furthermore, the concurrent increase in the arousal of facial expressions and EDA was also greater when the crossing distance was -8 cm in comparison to 72 cm. These results are in line with the literature on the emotional relevance of stimuli for the ANS response. They also confirm that the arousal of facial expressions can be assessed despite the difficulty of identifying the expression (LeDoux, 1996; Silvert, Delplanque, Bouwalerh, Verpoort, & Sequeira, 2004).

As expected, no increase in electrodermal responses was found when facial expressions were followed by a PLW crossing the participants' fronto-parallel plane at, or farther than, the boundary of interpersonal comfort distance. This was true except in the condition with a neutral facial expression and when the PLW crossed the participants' fronto-parallel plane at the boundary of interpersonal comfort distance (i.e. 32 cm). Considered together with the percentage of 'comfortable' responses provided at this distance (63.16%), this surprising increase in physiological response in this experimental condition might be due to the specific difficulty encountered in this particular condition. Indeed, a neutral facial expression could be conceived as a clueless expression related to the emotional state of others, rendering the comfort distance decision more difficult for stimuli presented at the boundary of interpersonal comfort distance. Thus, participants had to judge the comfort of the crossing distance based on the PLW trajectory without any influence of the facial expression. The increase in EDA was not observed at the boundary of interpersonal comfort distance when participants were exposed to a happy or angry facial expression, as the emotional valence possibly compensated for the ambiguity of the location of the PLW with respect to the boundary of interpersonal comfort distance. In support of this interpretation, it has been shown that the electrodermal response increases as the mental load required to perform the task also increases (Nourbakhsh, Wang, Chen, & Calvo, 2012).

As regards interpersonal comfort judgments, we found that they increased with the approaching PLW when participants were previously exposed to a negative facial expression, and decreased when they were previously exposed to a positive facial expression, in comparison to neutral ones. These findings are in agreement with the effect of the valence of facial expressions on interpersonal comfort distance (Cartaud et al., 2018; Ruggiero et al., 2017). They also go further by showing that exposure to facial expressions at the perceptual threshold is sufficient to alter interpersonal comfort distance, with respect to an emotionally neutral stimulus. Interpersonal comfort distance adjustments were also dependent on the gender of the stimulus but not of the participants. They were larger when the stimuli were male than female for all three facial expressions, as often observed in the literature on proxemics (Argyle & Dean, 1965; Iachini et al., 2016; Uzzell & Horne, 2006). We also found an influence of the subjective assessment of the arousal of facial expressions, suggesting a concurrent modulation of interpersonal comfort distance by the valence of facial expressions and their subjective arousal.

Finally, comparing the proportion of comfortable responses at 32 cm with the psychophysical boundary of interpersonal comfort distance revealed a strong congruency of the data according to the facial expression, as revealed by the linear regression between the two measures. Although this finding seems quite intuitive, this linear relation underlines the fact that aware assessment of the interpersonal comfort distance provides a robust measure of the spatial component of social interactions. It also gives more strength to previous studies that used the same method in order to assess the boundary of interpersonal comfort distance, and which found a similar outcome (Cartaud et al., 2018; Quesque et al., 2017).

Considered as a whole, the data in the present study show that facial expressions, even of poor visual quality, can trigger defensive-related physiological responses with a concurrent modification of interpersonal comfort distance, even when interacting with emotionally neutral human-like stimuli. They suggest that human beings in social situations adapt their social behaviour depending on the valence and arousal of the emotion identified in others, and that social adjustments occur with changes in physiological markers. This suggests that the presence of emotional social stimuli in overcrowded hyperstimulating modern societies can influence forthcoming social interactions with neutral conspecifics, despite their poor visual quality. Further studies should assess the effect of facial expressions presented in peripheral vision, as is often the case in overcrowded social settings. Indeed, facial expressions in the visual periphery have been found to involve the retino-tectal neural pathway specifically. This pathway is known to provide information on low spatial frequency/high contrast stimuli, thus facilitating identification of human faces (e.g., Nakano, Higashida, & Kitazawa, 2013) and facial expressions (e.g., de Gelder, Vroomen, Pourtois, & Weiskrantz, 1999).

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Author Notes

Author Contributions

AC, LO, JH, TI and YC conceived and planned the experiments and contributed to writing the manuscript and interpretation of the results. AC, LO and YC carried out the experiments and analysed the data. AC, LO, JH, TI and YC wrote the paper.

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Declaration of Interest statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Fig. 1. Illustration of facial expressions and masks used in experiment with different levels of luminance (top face and masks: maximum luminance, bottom face and masks: medium luminance).

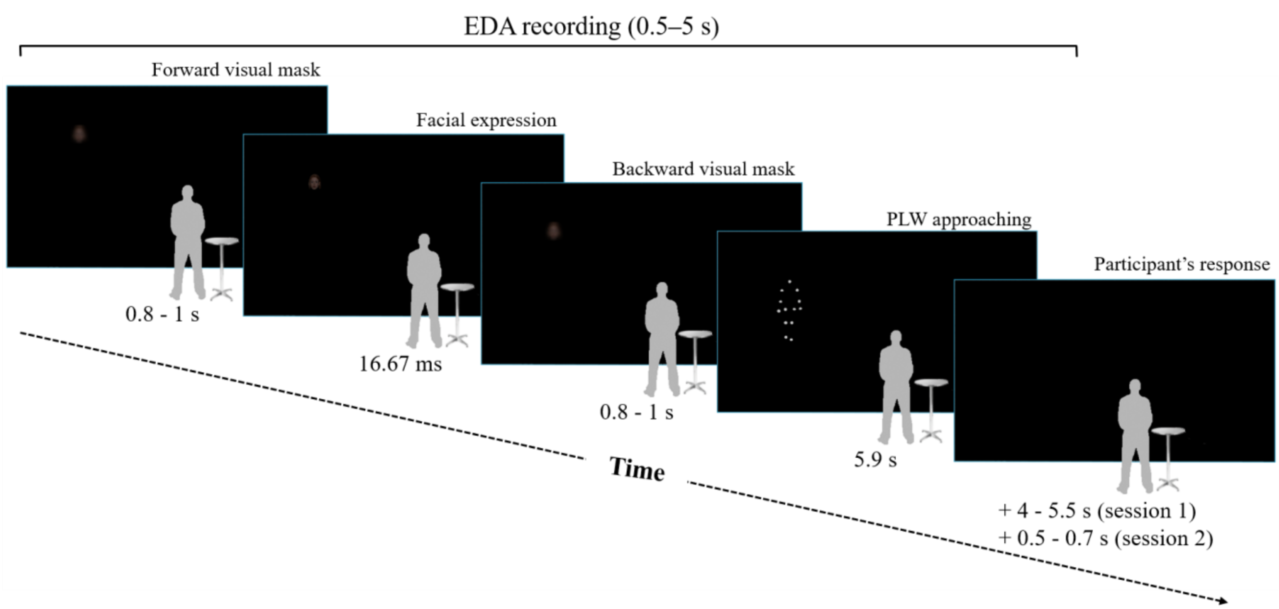

Fig. 2. Sequence of events in trial during comfort judgement of interpersonal distance task. Participants had to judge whether the PLW crossed their fronto-parallel plane at a comfortable inter-shoulder distance or not. Keypad placed on table near right hand of participants.

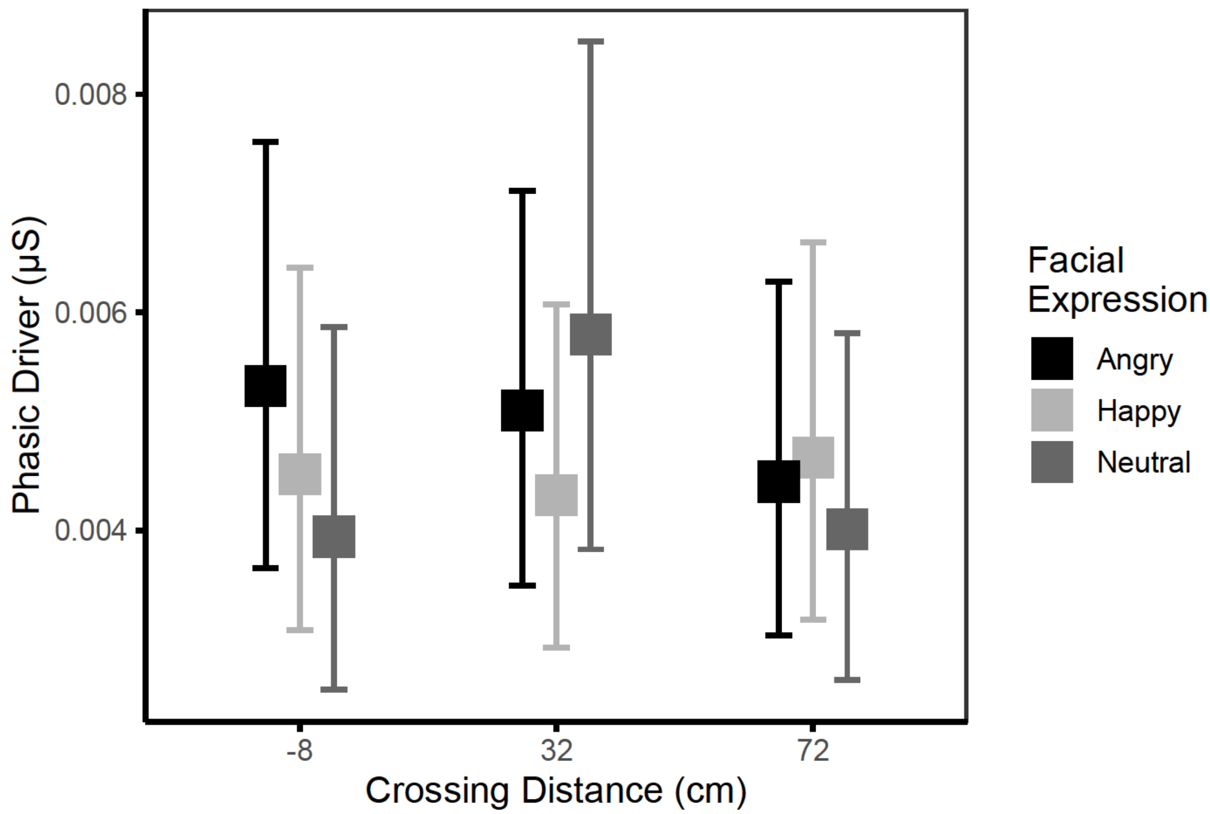

Fig. 3. Posterior mean Phasic Driver (μS) estimates and 95% CI as a function of facial expression and crossing distance for fixed mean SEI of 4.3.

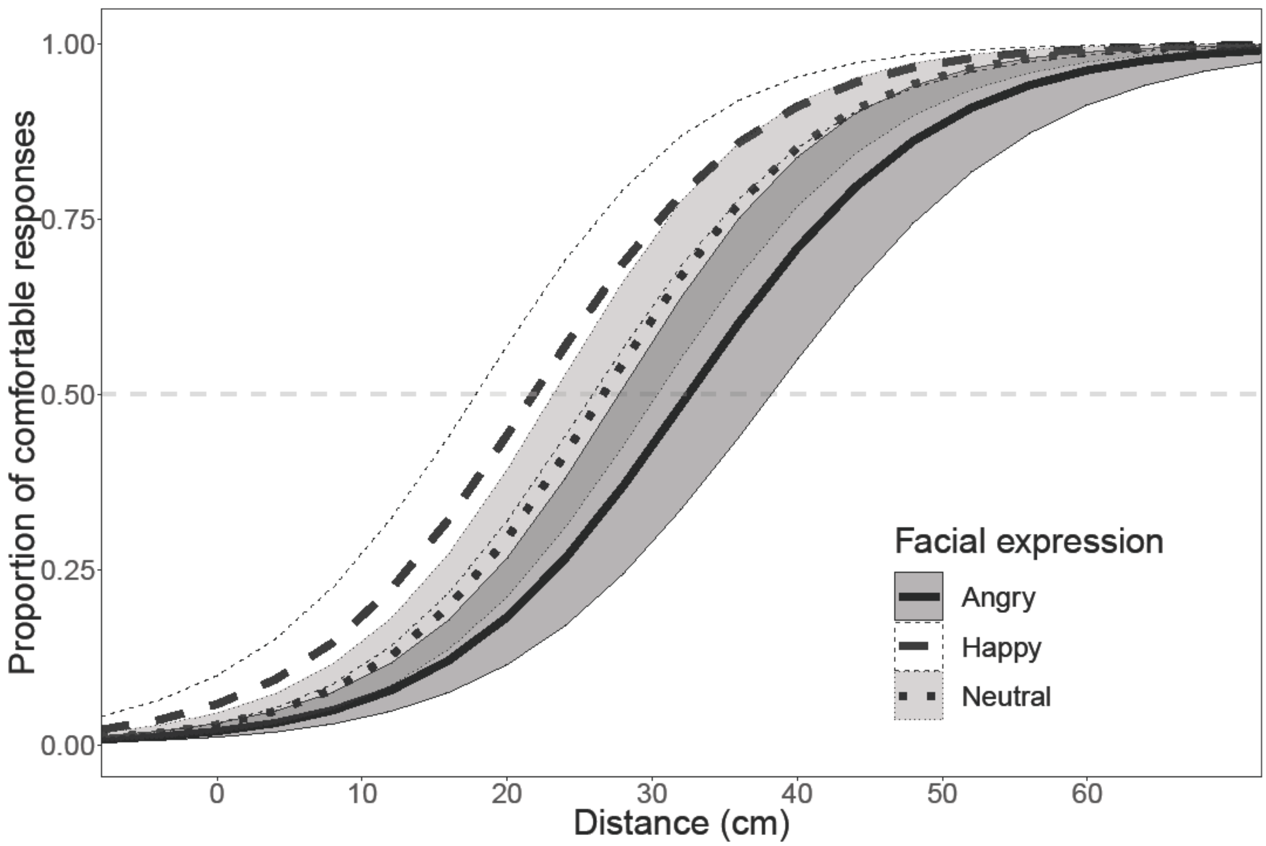

Fig. 4. Mean prediction and 95% CI of posterior distribution of proportion of "comfortable" responses per crossing distance and facial expression. Dashed grey horizontal line represents comfort distance boundary at 50%.

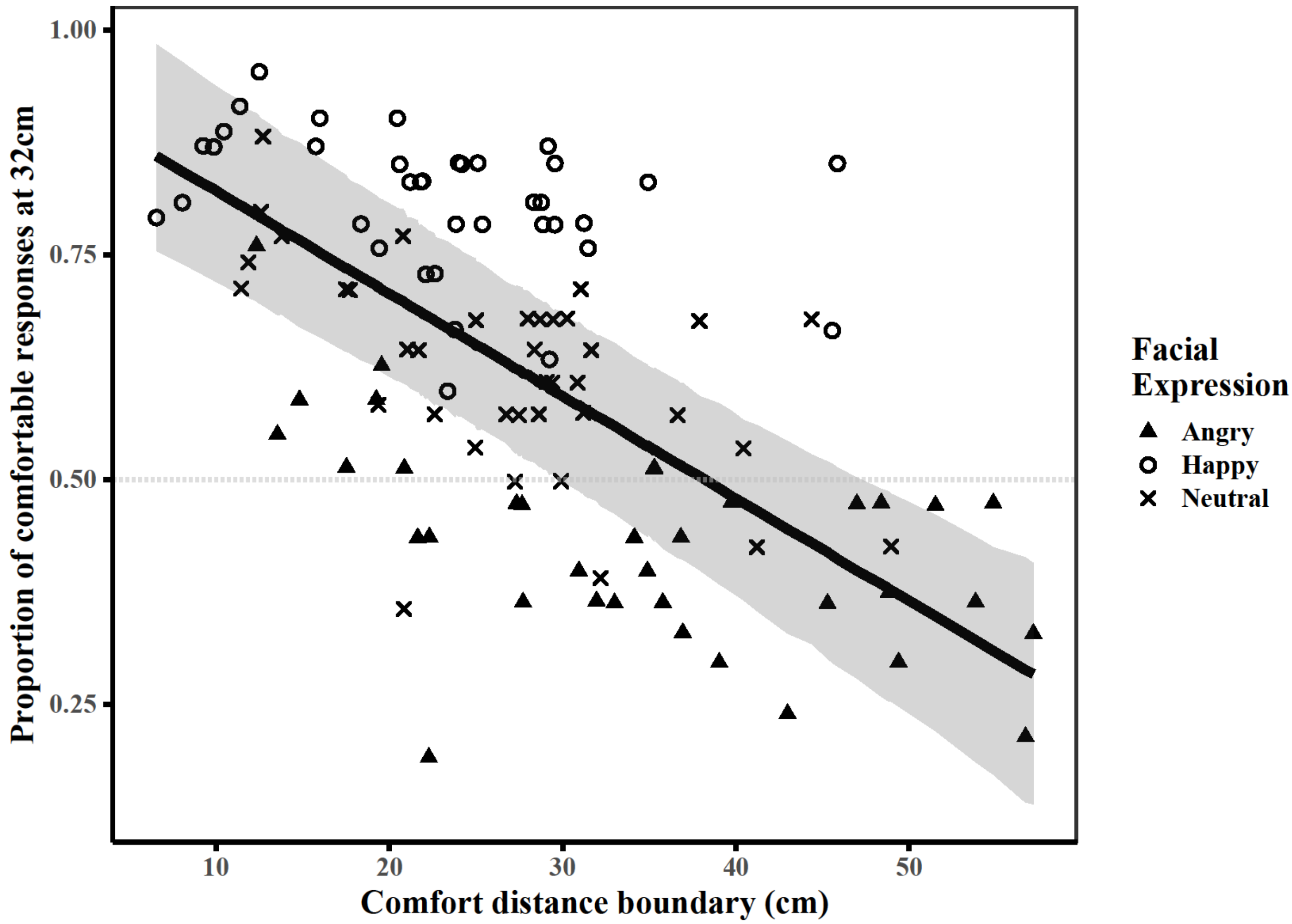

Fig. 5. Mean prediction and 95% CI of posterior distribution of proportion of 'comfortable' responses for crossing distance at 32 cm per comfort distance boundary (cm) and prior estimates of this fit. The 95% CI corresponds to boundary SD fixed to its mean (0.038). Dashed grey horizontal line represents proportion at 0.5 of 'comfortable' responses.

Table legend

Table 1. Estimated percentage of ‘comfortable’ response (%) and 95% CI as a function of facial expression and crossing distance

Estimate	Mean %	95 % CI
-8 cm	7.86	[5.36, 10.88]
32 cm	62.47	[56.09, 68.48]
72 cm	92.68	[89.83, 95.12]
Angry at 32 cm	41.54	[32.36, 51.18]
Happy at 32 cm	82.71	[75.33, 88.71]
Neutral at 32 cm	63.16	[53.73, 72.34]

Table 2. Comfort distance boundary (cm) as a function of facial expression and SEI

Estimate	Comfort distance boundary (cm)	95% CI
Angry	33.12	[27.97, 38.94]
Neutral	26.68	[23.14, 30.38]
Happy	21.93	[17.79, 26.06]
Contrast Angry - Happy	*11.19*	*[6.6, 16.48]*
Contrast Angry - Neutral	*6.44*	*[3.26, 10.11]*
Contrast Happy - Neutral	*-4.75*	*[-7.68, -2.06]*
Contrast Subject Male - Female	-0.66	[-7.49, 6.15]
Contrast Avatar Male - Female	*5.52*	*[4.21, 6.94]*
Avatar Male	30	[26.02, 34.39]
Avatar Female	24.48	[20.89, 28.35]
Contrast Angry Avatar Male - Female	*5.68*	*[3.4, 8.24]*
Contrast Neutral Avatar Male - Female	*5.84*	*[4.15, 7.64]*
Contrast Happy Avatar Male - Female	*5.05*	*[3.12, 7.07]*
Trend SEI	-0.02	[-0.56, 0.53]
Trend SEI Happy	-0.83	[-1.77, 0.03]
Trend SEI Angry	*0.84*	*[0.05, 1.75]*
Trend SEI Neutral	-0.02	[-0.66, 0.63]
Trend SEI Happy - Angry	*-1.67*	*[-2.97, -0.49]*
Trend SEI Happy - Neutral	-0.81	[-1.84, 0.15]
Trend SEI Neutral - Angry	-0.86	[-1.84, 0.05]

Note: Italics represent contrasts with CI that do not overlap with zero (i.e. robust estimate with 95% CI).

Table A.1. Estimate Phasic Driver (E-04 µS) and 95% CI as a function of Facial Expression, Crossing Distance and IEF. Italics represent contrasts with CI that do not overlap with zero (i.e. robust estimate with 95% CI).

Contrast	**Estimate Phasic Driver (E-04 µS)**	**95% CI**
Angry - Neutral	4.65	[-5.98, 14.77]
Happy - Neutral	-1.28	[-12.22, 9.02]
Angry - Happy	5.93	[-2.73, 15.31]
Subject Male - Female	22.01	[-7.86, 59.59]
Stimulus Male - Female	-2.65	[-9.89, 4.27]
-8 - 32	-0.85	[-10.21, 8.54]
32 - 72	7.01	[-1.24, 16.14]
-8 - 72	6.16	[-2.23, 15.23]
Trend SEI	0.36	[-1.58, 2.36]
Angry - Neutral -8	*17.25*	*[0.7, 34.61]*
Happy - Neutral -8	5.62	[-10.66, 20.95]
Angry - Happy -8	11.63	[-3.56, 28.01]
Angry - Neutral 32	-7.44	[-29.73, 11.61]
Happy - Neutral 32	-16.71	[-40.23, 1.84]
Angry - Happy 32	9.27	[-5.46, 25.04]
Angry - Neutral 72	4.15	[-10.56, 19.11]
Happy - Neutral 72	7.29	[-8.99, 24.1]
Angry - Happy 72	-3.14	[-19.16, 11.25]
Angry -8 - 32	4.97	[-10.76, 21.2]
Happy -8 - 32	2.61	[-11.51, 17.03]
Neutral -8 - 32	*-19.73*	*[-42.82, -0.65]*
Angry -8 - 72	12.57	[-2.44, 28.87]
Happy -8 - 72	-2.2	[-18.42, 12.82]
Neutral -8 - 72	-0.53	[-15.61, 15.38]
Angry 32 - 72	7.61	[-6.71, 22.58]
Happy 32 - 72	-4.81	[-20.46, 9.97]

Neutral 32 - 72	*19.19*	*[0.72, 41.8]*
Trend SEI Happy	-0.7	[-3.35, 1.77]
Trend SEI Angry	*3.1*	*[0.26, 6.56]*
Trend SEI Neutral	-1.42	[-4.07, 1.7]
Trend SEI Angry - Happy	*3.79*	*[0.45, 7.68]*
Trend SEI Angry - Neutral	*4.51*	*[0.59, 8.86]*
Trend SEI Happy - Neutral	0.72	[-3.01, 4.08]
Trend SEI 72	-2.26	[-4.81, 0.13]
Trend SEI -8	2.68	[-0.21, 6.07]
Trend SEI 32	0.65	[-2.29, 3.79]
Trend SEI -8 - 72	*4.94*	*[1.45, 9.05]*
Trend SEI -8 - 32	2.03	[-1.74, 6.08]
Trend SEI 72 - 32	-2.91	[-6.63, 0.39]

Note: Italics represents contrasts with CI that doesn't overlap with zero (i.e. robust estimate with 95% CI).