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Haptic coordination: Squeezing a vibrating stress ball decreases anxiety and arousal

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Title: Haptic coordination: squeezing a vibrating stress ball decreases anxiety and arousal

Running head: Haptic coordination and anxiety

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footnotes: 0, Number of appendices 1

GraphPad Prism 7 and Affinity Photo were used to produce the graphics.

Highlights:

- Users were pleased to interact with our new haptic robot
- Squeezing a vibrating robotic ball decreases anxiety and modulates arousal
- The detuning between the frequency of hand squeezing and of ball vibrations affects arousal
- When the detuning is large, the level of stress affects the stability of haptic coordination

Objectives

- Evaluate the effect of a vibrating robotic ball on anxiety
- Assess how the dynamics of haptic coordination between the squeezing and ball vibration modulate emotional state
- Evaluate the detuning between the frequency of ball vibration and the frequency of squeezing and arousal

Methods



N = 28

- Participants looked at a stressful or calming picture and then repeatedly squeezed a vibrating stress ball
- To evaluate anxiety, electrodermal activity (EDA) was measured and anxiety questionnaire was administered



Vibrating robotic ball

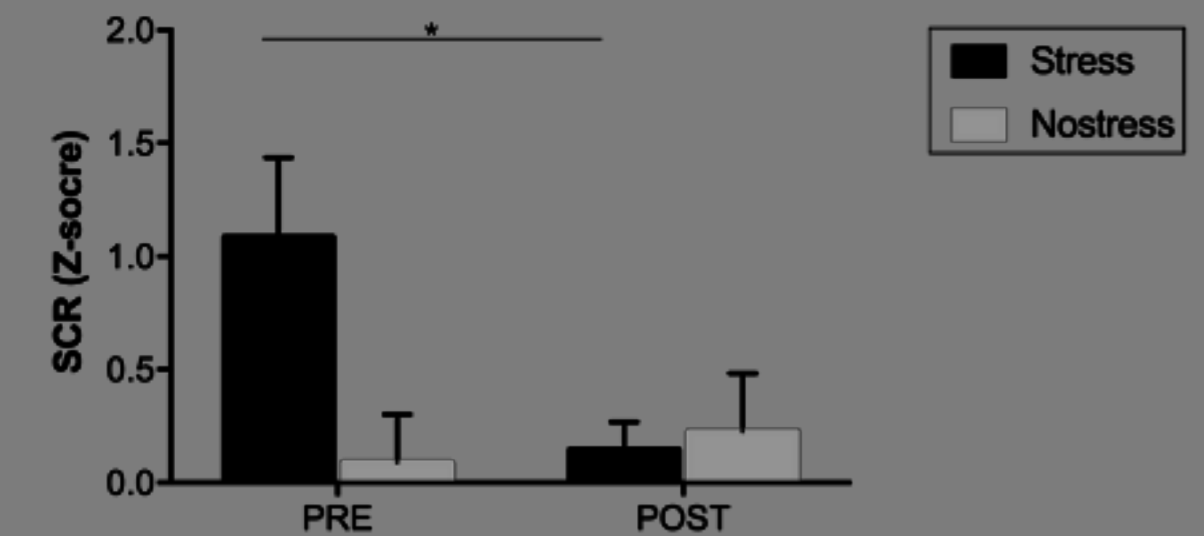


Electrodermal activity

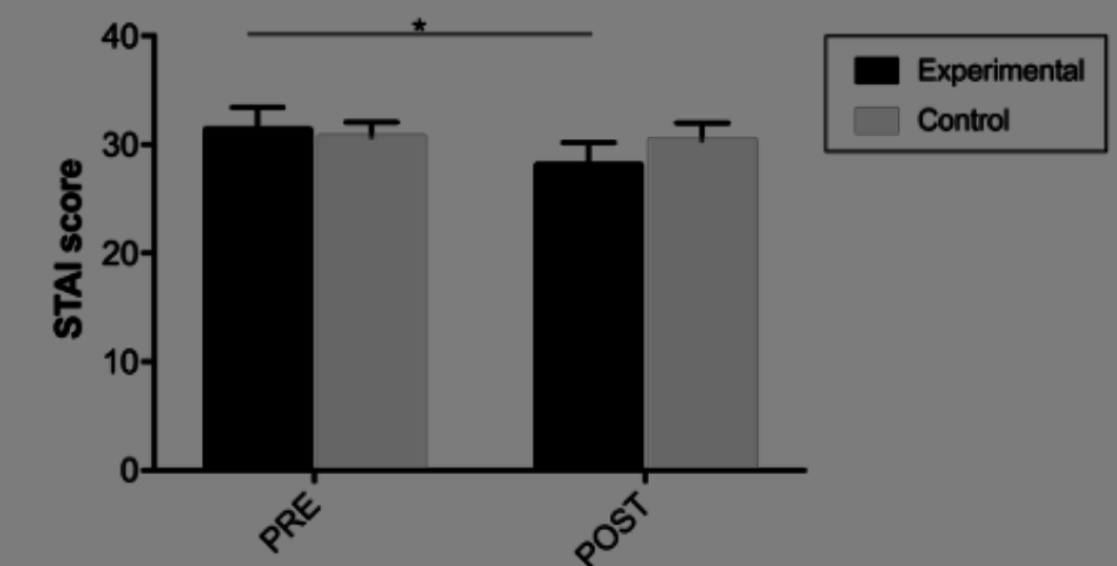


Outcomes

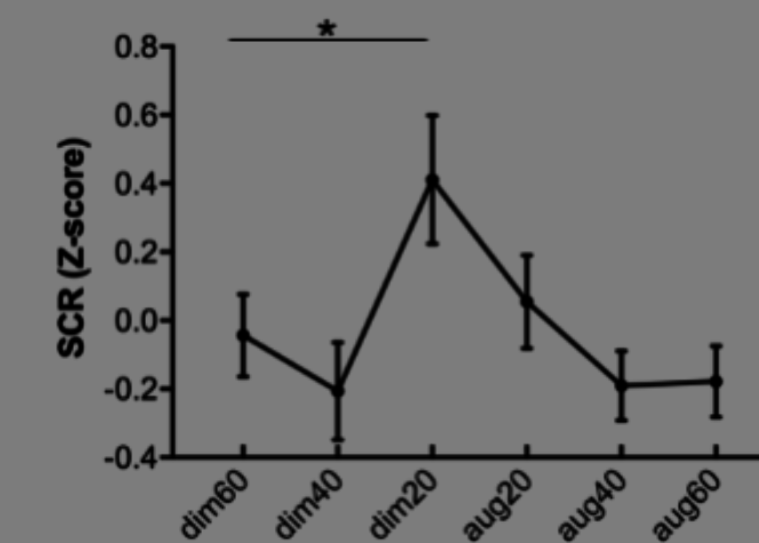
- Squeezing the vibrating ball lowers arousal



- Squeezing the vibrating ball lowers anxiety



- Arousal is modulated by the detuning



Conclusion

The vibrating ball acted as a stress reliever : EDA and anxiety decreased after the haptic interaction

1 **Abstract**

2 We evaluated the effect of haptic coordination on anxiety and arousal. Participants looked at a stressful
3 or calming picture and then repeatedly squeezed a vibrating stress ball for 20 s. Using a pre-post
4 paradigm with a control group, we showed that squeezing the vibrating ball reduced anxiety and arousal,
5 as assessed by the State-Trait Anxiety Inventory and electrodermal activity, respectively. The stability
6 of haptic coordination was manipulated by varying the detuning between the preferred squeezing
7 frequency and the intrinsic frequency of ball vibration. Coordination stability affected arousal and stress
8 affected stability. The data were discussed in the light of Kahneman's attentional resource sharing model.

9

10 **Keywords:** Haptic coordination, anxiety, robotic, electrodermal activity, perception-action

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24 **1. Introduction**

25 More than one in three adults (35-39%) worldwide experience stress or worries each day (GALLUP,
26 2020). Among the evidence-based methods of coping with unpleasant overarousal is *self-generated*
27 *touch*: petting animals (Pendry & Vandagriff, 2019), knitting (Riley et al., 2013), self-brushing (Matiz
28 et al., 2020), facial self-touch (Mueller et al., 2019) or self-squeezing in ‘hug machine’ (Edelson et al.,
29 1999). Tennis players who dynamically squeeze their racket best resist the pressure of sports competition
30 (Beckmann et al., 2021)(Beckmann et al., 2013). Self-generated touch is thought to activate mechanisms
31 of emotional regulation: brain research suggested that repeated hand squeezing triggers inhibitory bouts
32 of alpha rhythms protecting the nervous system against overarousal (Cross-Villasana et al.,
33 2015)(Jensen & Mazaheri, 2010). We decided thus to develop a small, inexpensive, portable robotic toy,
34 a *vibrating stress ball* to be squeezed, hoping that it may act as a stress reducer. Fully aware of the
35 immaturity of our prototype, we present here the very first blueprint of this project, undertaken under
36 the theoretical umbrella of Coordination Dynamics (Kelso, 1995), and of the circumplex model of
37 emotion (Russell, 1980).

38 *1.1 Affective haptics in robotics*

39 Having acknowledged that touch is a powerful vector of calming (Heirtenstein, 2006; Smith and
40 Maclean, 2007; Eid and Al Osman, 2016), social robotics has begun to add tactile qualities to
41 automatons to transform them into stress relievers (Paredes & Chan, 2011; Kelling et al., 2016). The
42 fur-covered robot Paro, (Wada and Shibata, 2006) or the purring ‘haptic creature’ (Sefidgar, 2016) are
43 typical achievements of this endeavor. In this field, special attention has been given to interfaces
44 producing vibrotactile stimulation (Azevedo et al., 2017, see also Zhou et al., 2020). Experimental
45 studies examined the link between the affective impact of vibrations (e.g., pleasantness, arousal) and
46 their engineering parameters (e.g., frequency, amplitude, waveform). Authors developed vibration
47 libraries (eg. VibViz) linking vibrotactile patterns to affects (Seifi et al., 2015).

48 In these experimental procedures, however, participants were asked to assess the affective impact of
49 vibrotactile interfaces while holding their hand motionless in contact with vibration generator. These
50 procedures lack ecological validity: haptic robots are meant to be squeezed, stroked, patted, rubbed, etc.

51 (Yohanan & MacLean, 2012). Human-robot interaction engages so-called Active touch (Gibson, 1962).
52 In Active-touch situations, mechanoreceptors do not passively collect tactile inputs: they actively gather,
53 pattern, and modulate the tactile sensation (Blakemore et al., 1998; Gibson, 1962; Lederman & Taylor,
54 1972; Prescott et al., 2011; Turvey, 1996). We need thus to consider the dynamics of human movement
55 to verify if it affects the user's vibrotactile experience. In the present work, we intend to assess whether
56 and how the dynamics of hand squeezing modulates the affective impact of the vibrating stress ball.

57 *1.2 Measuring affects*

58 To evaluate the affective impact of vibrotactile interfaces, social robotics often adopt the circumplex
59 model (Russell, 1980). In this model, all affects are placed inside a circle divided into four quadrants by
60 two axes: the axis of arousal (high-low) and the axis of valence (positive-negative). Emotions such as
61 stress and anxiety appear inside the quadrant of high arousal and negative valence, whereas calm and
62 serenity are considered as its opposite. In experimental settings, arousal is objectively assessed by
63 electrodermal activity (EDA), and valence by standardized psychometric scales. We expect that
64 squeezing the vibrating ball reduces arousal and anxiety, evaluated by the two complementary methods.

65 EDA is measured by applying a constant voltage (U) between two electrodes placed on the skin. The
66 intensity (I) of the electric current flowing between the electrodes depends on the resistive skin
67 properties. The main modulator of skin resistance (R) is the sweat secreted by the sweat glands. If the
68 participant is aroused, his/her sweat glands open, the conductive sweat fills the sweat ducts, and the
69 resistance of the skin drops. As a result, the more the individual is excited, the lower the skin resistance
70 (R in $K\Omega$), and the skin conductance (SCR in μS) is higher, in accordance with Ohm's law ($I = U/R$;
71 Boucsein, 2012a).

72 In a typical paradigm dedicated to assessing emotion-related variations of the EDA, participants are
73 first instructed to relax for the SCR to reach baseline. Then, they are asked to watch emotion-inducing
74 stimuli (Bernat et al., 2006). One to three seconds after the onset of an emotion-inducing stimulus, SCR
75 exhibits an event-related (ie. phasic) rise peaking 0.2 to 1 μS above its baseline and then it returns to the
76 resting level (Dawson et al. 2007). To meet these timeframes, we displayed emotion-inducing pictures
77 for 6 seconds, followed by a 20-second inter-stimulus interval, where participants rested staring at a

78 black screen. Each trial thus made it possible to observe the rising and the return of SCR towards its
79 baseline. *We expect SC to increase more when a stressful picture, rather than a calming image is*
80 *displayed (Hypothesis 1). We also expect that after interacting with the vibrating ball, SC will decrease*
81 *(Hypothesis 2).*

82 To evaluate anxiety and arousal we used the State-Trait Anxiety Inventory (STAI-Y-1), a self-rating
83 scale of high reliability and validity, capturing anxious thoughts ('I feel frightened', 'I am tense') at the
84 very moment of assessment (Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983). It is the most
85 commonly used test of the state of anxiety in applied research (Grös et al., 2007). We complemented
86 this measure with the Pleasure, Arousal, Dominance (PAD) scale, developed to explore user experience
87 in environmental psychology and marketing research (Mehrabian and Russell, 1974). *We expect that*
88 *anxiety decreases after interacting with the robotic ball (Hypothesis 3) and that users enjoy playing with*
89 *the object (Hypothesis 4).*

90 *1.3 Haptic coordination and affect*

91 When squeezing a ball, the compression forces produced by the fingers generate reaction forces at
92 the point of contact with the object (Wu et al., 2018). This creates a perception-action loop, where the
93 squeezing hand produces force feedback captured by mechanoreceptors. To analyze what happens inside
94 this perceptual-motor loop, it is useful to consider the repetitively squeezing hand as a palm-finger
95 oscillator unilaterally coupled by force feedback to the ball. Under such an umbrella, our robotic stress
96 ball is seen as another oscillator, vibrating thanks to inserted actuators. Through the lens of Coordination
97 Dynamics (Kelso, 1995), the two oscillators form a haptic coordination system, supposed to exhibit the
98 well-known dynamic of coupled nonlinear oscillators (Kay et al., 1991; Kugler et al., 1980).

99 Nonlinear coupling between two oscillators leads their oscillations to a 1:1 phase locking, most often
100 resulting in a synchronous, in-phase coordination pattern (Haken et al., 1985). The most popular variable
101 capturing this coordination is *relative phase (RP)*: the spatiotemporal lag between the oscillations
102 produced by the oscillators in each movement cycle (Schöner & Kelso, 1988). If RP variability is weak
103 the coordination is *stable*. Coordination stability mainly depends on the difference between the intrinsic

104 frequencies of coupled oscillators ($\omega_1 - \omega_2$), called *detuning* ($\Delta\omega$): As the detuning grows, stability drops
105 almost linearly (Amazeen et al., 1995; Mitra et al., 1997; Schmidt et al., 1998).

106 Previous work on person-to-person coordination, *via* bilateral visual coupling, showed that stable
107 coordination patterns are associated to positive affect (Tschacher et al., 2014), positive evaluation of the
108 partner (Cheng et al., 2020; Hove & Risen, 2009; Launay et al., 2014), pleasure (Varni et al., 2010) and
109 empathy (Rennung & Göritz, 2016). Children who were cradled synchronously (stable coordination
110 pattern) or asynchronously (less stable coordination pattern) with a teddy bear then preferred to play
111 with the teddy bear that was used in the synchronous condition (Tunçgenç et al., 2015).

112 Recently, Zhang et al. (2016) showed that the stability of coordination is associated with arousal. We
113 tried here to generalize this effect, documented in person-to-person coordination, to non-social
114 interactions. The question is whether the stability of the haptic coordination between the palm-finger
115 oscillator and the vibrating ball affects the arousal generated by the observation of stressful pictures. To
116 vary coordination stability, we used the detuning paradigm (Amazeen et al., 1995; Mitra et al., 1997;
117 Schmidt et al., 1998). The frequency of the vibrating ball was increased and decreased in steps above
118 and below the preferred frequency of squeezing of the participant. *We expect that the stability of haptic*
119 *coordination drops as detuning rises* (Hypothesis 5). *We also expect that there is a relationship between*
120 *detuning and SC, evaluating the affective experience of the user* (Hypothesis 6).

121

122 **2. Methods**

123 *2.1. Participants*

124 A total of 28 volunteers took part in this study. The experimental group was composed of 14
125 participants between the ages of 23-38 (9 males, 1 left-handed, mean age = 29.57, sd = 4.95) and the
126 control group consisted of 14 participants between the ages of 24-35 (7 Males, all right-handed, mean
127 age = 27.35, sd = 3.22). All were naïve as to the purpose of the experiment and were not paid for their
128 participation. They had normal or corrected to normal vision. None reported tactile impairments or
129 neurological, psychological, or psychiatric disorders. All participants provided written informed consent

130 to participate in this study, which was approved by the Research Ethics Committee of the Federal
131 University of Toulouse (No. 2020-278), and conformed to the principles expressed in the Declaration
132 of Helsinki. We excluded data from three participants in the electrodermal analysis: two persons due to
133 motion corrupted finger data and one person probably hypo-responsive.

134 2.2. Material

135 2.2.1. Vibrating stress ball

136 The prototype of the vibrating ball was designed as a stress ball of 300 g and 7cm in diameter, covered
137 with velvet and filled with wadding and polystyrene beads. We wired together and inserted inside the
138 ball a circuit composed of four pressure sensors (*Interlink model 402 FSR*), four actuators generating
139 vibrations (*Vibrating Mini Motor Disc*), a resistance of 10 K-ohms, and an Arduino Uno microcontroller
140 (ATMEGA328P MCU). The program controlling actuators were written in C++, implemented on
141 Arduino IDE, and loaded on the microcontroller. The pressure-dependent decrease of resistance
142 recorded by sensors (in Ohms) were sent to the microcontroller at the rate of 9600 baud. The
143 microcontroller also generated vibrations, governed by a mathematical model loaded on the device (see
144 below). The whole circuit was inserted into an 8.5 cm × 5 cm plastic support.

145 2.2.2. Hopf model

146 To generate vibrations in our ball, we used the easy-to-control nonlinear Hopf oscillator, often
147 exploited in gait simulations (Ahmadi et al., 2009; Buchli et al., 2006; Righetti et al., 2009). Its dynamics
148 are governed by the following set of ordinary differential equations:

$$149 \quad \dot{x} = (\mu - r^2)x - \omega y + \epsilon F \quad \text{Equation 1}$$

$$150 \quad \dot{y} = (\mu - r^2)y - \omega x$$

$$151 \quad r = \sqrt{x^2 + y^2}$$

152 where x and y are the states of the system, μ controls the amplitude, $A = \sqrt{\mu}$, ω the intrinsic frequency
153 of oscillations; F the driving force and ϵ refers to the amount of perturbations. After a series of pilot
154 attempts, we decided to set μ to 2 and ϵ to zero. The oscillator exhibits thus a limited cycle attractor,
155 with radius $\sqrt{\mu}$ and a stable intrinsic frequency ω . During the experiment, the state variables were

156 updated by the Euler method, whereas x , ranging between -2 and 2, was used to control vibrations of
157 the motor disc and stored for further analysis. To manipulate the intrinsic frequency of the model, six
158 detuning conditions were created regarding the intrinsic frequency of each participant: three conditions
159 where the ball vibrated above (aug60, aug40, aug20) and three where the ball vibrated below (dim20,
160 dim40, dim60) the preferred frequency of squeezing of participant. The labels 'dim20' and 'aug20'
161 means that the preferred frequency of the participant was lowered by 20%.

162 2.2.3. *Electrodermal activity sensor*

163 The EDA BITalino sensor is equipped with UC-E6 connectors that allow it to be connected to two
164 Ag/AgCl electrodes and to the Arduino with a connector composed of 3 cables, one connected to 3.3V,
165 another to the ground (GND) and the last one to an analog input of the Arduino. To guarantee safe use of
166 the EDA sensor, the Arduino was powered with eight batteries of 1.5 V *via* a jack. Each electrode has a
167 contact diameter of 24mm, 1mm thickness, and is filled with a conductive and adhesive hydrogel. The
168 electrodes, positioned on the inner side of the middle phalanges of the index and middle fingers of the
169 participant's non-dominant hand, applied to the skin a current of 0.132V. The analog signal was sent to
170 Arduino Uno, digitalized at 33Hz by Analog to Digital Converter (ADC), and converted skin resistance
171 (ohm, Ω) to conductivity (microSiemens, μS), ranging from 2 to 25 μS , at the resolution of 10 bits.

172 2.2.4. *Visual stimuli*

173 Forty-eight pictures from the *Open Affective Standardized Image Set* (OASIS), an open-access library,
174 have been chosen to trigger the desired levels of arousal and valence (Kurdi et al., 2017). In line with the
175 Russel model (Russel, 1980), each of these images is associated with its valence and its degree of arousal,
176 quantified from self-reported subjective ratings on a 1-7 Likert scale. These levels ranged from 'very
177 negative' (1) to 'very positive' (7) for valence, and from 'very low' (1) to 'very high' (7) for arousal. We
178 selected 24 images of high valence-low arousal corresponding to calm and 24 images of low valence-high
179 arousal corresponding to stress. In this picture set, images selected to elicit calm were associated with
180 the levels of arousal lower than 3 and to levels of valence extending from 4.5 to 5.5. Images selected as

181 triggering stress were linked to levels of arousal greater than 4.5 and of valence less than 3. These
182 pictures were displayed at the center of a black screen (see Figure. 1, left).

183 INSERT, PLEASE, FIGURE 1 ABOUT HERE

184

185 *2.2.5. Preference test*

186 A preference test was created to determine the most calming vibration frequency of the ball. For each
187 frequency, the ball was programmed to vibrate for 10 seconds to create the tactile sensation. Then five
188 emoji were presented in a horizontal line, associated to five preference assessments ranging from very
189 stressful (1) to very relaxing (5) on a Likert scale. The participant selected an assessment by sliding the
190 cursor.

191 *2.2.6. Experimental setup*

192 All instructions were displayed in white on a black screen. Each picture appeared for 6s on full
193 screen, followed by a black screen for the 20s. The flow of the experimental procedure and the
194 preference test were controlled by a custom program written in Python (3.8) and the pygame library.
195 The program also controlled the robot and stored the data sent by the microcontroller, sampled at 33 Hz,
196 to the computer (13-inch Macbook Pro) for further analysis.

197 *2.2.7. Psychology tests*

198 The STAI-Y-1 questionnaire, composed of 20 items (eg. “I am worried”; “I feel calm”) was used to
199 evaluate the anxiety state. Each item is rated on a 4-point scale ranging from “not at all” to “very much
200 so” (Gauthier & Bouchard, 1993); high scores reflect high anxiety levels. The French translation of
201 STAI-Y-1, validated by Gauthier and Bouchard (1993), was applied. To evaluate the emotional state of
202 participants, we used the Mehrabian’s Pleasure, Arousal, Dominance (PAD) scale (Mehrabian and
203 Russell, 1974), validated in French by Detandt (2017). The instrument contains 18 items assessing
204 participant’s reactions to an environmental object along three dimensions: pleasure *vs.* displeasure,
205 arousal *vs.* non-arousal, and dominance *vs.* submissiveness. Each item corresponds to a pair of

206 anonymous adjectives (eg. pleased-annoyed) to be rated on a nine-point Likert scale, ranging from -4
207 to +4.

208 We developed a sensory analysis questionnaire of vibrotactile sensation based on an Osgood
209 differential scale and pre-existing questionnaires (Muramatsu et al., 2013; Muramatsu & Niitsuma,
210 2013; Okamoto et al., 2013; Strohmeier & Hornbæk, 2017) (Gunther & OModhrain, 2003; Hasegawa
211 et al., 2019; Picard et al., 2003). Participants were instructed to describe their hedonic and sensory
212 experience with the ball using 23 pairs of opposing descriptor words (eg familiar - unfamiliar). The
213 rating scale, therefore, ranges from -4 to +4, 0 representing the central segment of the scale. For
214 example, for the "pleasant-unpleasant" pair, if the participant rated the vibrotactile experience with the
215 haptic robot as extremely pleasant, then they should circle the number 4 on the left. The questionnaire
216 appears in Appendix 1.

217 2.3. Procedure

218 Once the proper functioning of the device and its communication with Arduino had been verified, the
219 participant was asked to complete the STAI-Y-1 questionnaire. Then he had to sit in front of a computer
220 screen, take the robot in his dominant hand, find a comfortable position, and familiarize himself with this
221 ball by squeezing it several times. After the familiarization, the experimenter attached electrodes to the
222 palmar side of the phalanges of the middle and index fingers of his non-dominant hand, in line with
223 conventional guidelines (Braithwaite et al., 2015), and the experiment began.

224 The experimental procedure involved 5 steps (Figure 2): (1) spontaneous frequency test, (2) baseline,
225 (3) pre-test, (4) interaction with robot, and (5) post-test. In the end, all questionnaires, including STAI-
226 Y-1, were administered. EDA was recorded during these steps 2- to 5 in both groups.

227

228 INSERT, PLEASE, FIGURE 2 ABOUT HERE

229

230 On the spontaneous frequency test, participants were asked to squeeze the haptic robot at their own pace
231 for 20 seconds, then stop. This condition, repeated 4 times, allowed the experimenter to determine the
232 spontaneous frequency of each participant and to introduce the frequency parameter (ω) into the model.

233 Then, during the baseline, participants were instructed to rest with their eyes fixed on the middle of the
234 screen for 3 minutes, with no stimuli presented.

235 Immediately after, the experiment continued according to the pre-post procedure. In each of the pre-
236 test and post-test trials, a randomly drawn picture was displayed on the screen for 6 seconds, then
237 removed for 20 seconds, the participant being merely instructed to look at the screen. After the pre-test,
238 participants from the experimental group interacted with the robot according to similar procedure: a
239 picture was displayed for 6 seconds, then removed, and the subjects were asked to repetitively press the
240 ball for 20 seconds, then to rest motionless looking at the black screen for the next 20 seconds to recover
241 from previous stimulus (See Figure 2). Participants from the control group were submitted to the same
242 procedure, except that they did not interact with the robot, that is, they simply looked at the black screen
243 for 20sec.

244 There was 12 pre-test and 12 post-test trials. Each test involved six stressful and six calming pictures,
245 presented at random. Between the pre-test and post-test occurred four blocks of six interaction trials.
246 Each block involved six vibration frequencies ranging from aug60 to dim60 or from dim60 to aug60, 3
247 stressful and 3 calming pictures. Frequencies and pictures were selected at random provided that for
248 each frequency, there were 2 stressful and 2 calming pictures. After the post-test, the EDA sensors were
249 removed, and participants completed the preference test and all the psychological tests. The whole
250 experimental procedure lasted nearly 1 hour.

251 2.4. Data analysis

252 2.4.1. Electrodermal activity

253 The values acquired by the sensor were transformed in conductivity according to the transfer
254 function:

$$255 \quad EDA (\mu S) = \frac{ADC}{2^n} \times \frac{VCC}{0.12} \quad \text{Equation 2}$$

256 Then, the EDA raw signals were analyzed with Matlab (R2018a, Mathworks, Natick, MA, USA) using
257 Ledalab v3.4.7 software (<http://ledalab.de>). First, the data were downsampled to 11 Hz, cleaned of
258 artifacts using a fitting spline, and filtered with an adaptative smoothing. Next, the rapid, event-related
259 phasic components SCR were extracted from the slower, tonic component (SCL) using Continuous

260 Deconvolution Analysis (CDA) introduced by (Benedek & Kaernbach, 2010). To neutralize individual
261 differences in conductance changes and to allow for meaningful intra-subject comparisons, we
262 computed z-scores (Ben-Shakhar, 1985) using means and standard deviations of the participant's
263 conductance changes within each condition (pre-test, interaction trials, post-test). According to the
264 convention, SCRs occurring within the five-second response window starting 1 second after the onset of
265 the stimulus and ending 6 seconds after the start of the stimulus and rising above the minimum amplitude
266 criterion of 0.05 μ S were considered as having been triggered by the stimulus (Dawson et al., 2007;
267 Levinson and Edelberg, 1985). After this signal processing, we analyzed three indexes of EDA: 'SCR'
268 which correspond to the average phasic activity, 'AmpSum' and to the Sum of SCR-amplitudes of
269 significant SCRs within the response window and 'PhasicMax' which is the maximum value of phasic
270 activity within the response window.

271 2.4.2 Robot-human coordination

272 The signals collected by the force-sensitive resistor were mean-centered, detrended, and low-pass
273 filtered using a second-order dual-pass Butterworth filter with a cutoff frequency of 20 Hz. We evaluated
274 then the *instantaneous frequency* of pressures produced by the participant, using the Matlab unbuild
275 function (instfreq). Coordination between the human pressures and the ball vibrations was assessed by
276 *continuous relative phase* using the Hilbert transform (Rosenblum et al., 2001). To avoid transients, the
277 first two and last two seconds of the time series were removed from the analysis. For each trial, the
278 variance of RPs was calculated using circular statistics (Batschelet, 1981). Low variability illustrates a
279 stable coordination pattern. When humans and robot were not phase-locked, phase wrapping appears.
280 To account for this effect, we calculated the range, that is the difference between the lowest and the
281 highest value, of unwrapped RP: larger the Unwrap_RP larger the phase wrapping.

282 2.4.3. Psychological tests

283 For each participant, we calculated the average STAI-Y-1 score before and after the interaction with
284 the haptic robot. We also collected the scores for each pair of adjectives from the PAD scale and from the
285 sensory analysis questionnaire. Finally, we analyzed the preference test by averaging responses obtained
286 for each frequency of vibrations.

287 *2.4.4. Statistical analysis*

288 To ensure that our ‘stressful’ images raised EDA, we performed a 2 (Images= {Stressful, Calming})
289 ANOVA on the z-scores of SCR, AmpSum and PhasicMax. Then, we evaluated the effect of the ball on
290 arousal. In the first step, we calculated the difference between pre-test and post-test on the z-scores in SCR,
291 AmpSum and PhasicMax. In the second step, a 2 (Images) X 2 (Group = {Control, Experimental})
292 ANOVA on all the EDA indexes was carried out. We finally checked the effect of the ball on anxiety using
293 2 (Conditions = {pre-test, post-test}) X 2 (Group) ANOVA on the average STAI-Y-1 score. If appropriate,
294 we followed the analysis by post-hocs tests with Holm adjustment for multiple comparisons.

295 We focused on the user experience with the robot. For each pair of adjectives in PAD scale, we tested
296 whether PAD scores differed from zero using one-sample t-test and adjusting p-values with the Benjamini-
297 Hochberg (BH) adjustment for multiple comparisons. The same analysis was undertaken for the sensory
298 questionnaire. Finally, we evaluated the effect of the frequency of vibration using a 6 (Frequencies)
299 ANOVA on the preference test. This analysis was followed by post-hoc tests with Holm's correction for
300 multiple comparisons.

301 We analyzed the haptic coordination in the experimental group. A 6 (Frequencies) X 2 (Images)
302 ANOVA was performed on instantaneous frequency to test whether the frequency of ball vibrations or the
303 stress affected the frequency of hand pressures. Then, the same ANOVA was carried out on the SD of the
304 relative phase and on the range of unwrapped RP to check whether the stability of haptic coordination
305 was affected by the detuning and the stress-inducing images. This analysis was followed by polynomial
306 quadratic contrasts for frequencies to test the change of the stability in RP as a function of detuning. We
307 finally performed six customized contrasts, using a pair of +1 and -1 coefficients, to compare RP stability
308 when participant looked at stressful and at calming images.

309 To end the whole analysis, we focused on the EDA collected during the interaction with the robot in
310 the experimental group. We carried out a 6 (Frequencies) X 2 (Images) ANOVA on SCR to test whether
311 the frequency of vibrations modulates EDA.

312 Before all these analyses, we ensured that all variables were normally distributed, using Shapiro-
313 Wilk test ($p < 0.05$). Given that all factors with repeated measures have two levels, the sphericity

314 assumption was always fulfilled. For all ANOVAs, Images, Conditions and Frequencies corresponded
315 to repeated measures factors. For all results, only significant effects at $p < 0.05$ are reported.

316

317 **3. Results**

318 *3.1. EDA increases for stressful pictures*

319 An individual trial exemplifying the variation of SCR in response to calming and stressful images is
320 displayed on the Figure 1 (B). The 2 (Images) ANOVA performed on SCR revealed a main effect of
321 Images ($F(1,49) = 16.30, p < 0.01$), Phasicmax ($F(1,49) = 13.143, p < 0.001$) and Ampsum ($F(1,49) =$
322 $16.382, p < 0.001$): the three EDA indices were higher for stressful than for calming pictures.

323 *3.2. Interacting with the ball lowers SCR*

324 Figure 3 (top panels) illustrate SCR as a function of Images and Group in the pre-test and post-test
325 condition. The 2 (Images) X 2 (Group) ANOVA carried out on the pre-post difference in SCR evidenced
326 a main effect of Images ($F(1,23) = 4.582, p < 0.05$) and an Images x Group interaction ($F(1,23) = 4.948,$
327 $p < 0.05$). Subsequent post-hoc analyses using Holm correction revealed that in the experimental group,
328 the pre-post difference was lower for stressful than for calming images ($p < 0.003$, Figure 3A). As for the
329 control group, SCR did not change significantly between pre-test and post-test (Figure 3B).

330

331 INSERT, PLEASE, FIGURE 3 ABOUT HERE

332

333 *3.3. Interacting with the ball lowers Phasicmax*

334 Figure 3 (bottom panels) illustrate Phasicmax as a function of Conditions and Images. The same
335 ANOVA realized on the pre-post difference highlighted a main effect for Images ($F(1,23) = 5.947, p <$
336 0.001) and an Images x Group interaction ($F(1,23) = 4.320, p < 0.05$). Further post-hoc analysis with
337 Holm correction of the latter interaction showed that, in the experimental group, Phasicmax was lower in
338 the post-test than in the pre-test condition ($p < 0.01$, Figure 3C). Phasicmax did not change between pre-

339 test and post-test in the control group (Figure 3D). Finally, the same ANOVA performed on Ampsum
340 index only exhibited a main effect for Images only ($F(1,23) = 4.972, p < 0.05$).

341 *3.4. Interacting with robot lowers anxiety*

342 STAI-Y-1 scores as a function of Group and Conditions are depicted on Figure 4. First, the 2
343 (Conditions) X 2 (Group) ANOVA evidenced a main effect of Conditions ($F(1,26) = 8.373, p < 0.01$)
344 and a Conditions x Group interaction ($F(1,26) = 6.165, p < 0.03$) on STAI-Y-1 score. Post-hoc analysis
345 with Holm adjustment revealed that STAI score was lower after the interaction with the ball in the
346 experimental group only ($p < 0.004$).

347

348 INSERT, PLEASE, FIGURE 4 ABOUT HERE

349

350 *3.5. Users enjoyed playing with the ball*

351 One-sample t-tests evidenced that PAD scores felt below zero for pairs of adjectives on the pleasure
352 and arousal subscales ($p < 0.05$). Participants reported they felt ‘pleased’, ‘amused’, ‘satisfied’,
353 ‘hopeful’, ‘content’, ‘happy’ (Figure 5A), “wide awake”, “calm” and “animated” (Figure 5B). The same
354 analysis carried out on the sensory questionnaire revealed five significant judgements: participants
355 described their vibrotactile experience as ‘pleasant’, ‘comfortable’, ‘attractive’, ‘affective’, ‘soothing’
356 (Figure 5C), ‘undulating’, ‘soft’, ‘energetic’, and ‘elastic’ ($p < 0.05$).

357

358 INSERT, PLEASE, FIGURE 5 ABOUT HERE

359

360 *3.6. Slow frequencies are preferred*

361 The 6 (Frequencies) ANOVA on preference scores exhibited a significant effect of Frequencies (F
362 $(5,40) = 12.00, p < 0.001$). Holm's post-hoc analysis showed that slower frequencies (-20%, -40%, -60%)
363 were rated as more relaxing ($p < 0.005$) comparing to faster ones (+ 20%; + 40%, + 60%), (Figure 5D).

364 *3.7. Instantaneous frequency was unchanged*

365 The 6 (Frequencies) X 2 (Images) ANOVA carried out on the instantaneous frequency displayed no
366 significant effects, meaning that participants do not tend to coordinate with the robot. Spontaneous
367 frequencies of the participants were quite variable, ranging from 0.27 to 1.48 Hz with standard deviation
368 of 0.33.

369 *3.8. Detuning and stress modulate RP variability*

370 Figure 6A pictures the effect of Frequencies and Images on RP variability. The 6 (Frequencies) X 2
371 (Images) ANOVA carried out on the SD of RP evidenced a main effect of Frequencies ($F(5,65) = 4.302$,
372 $p < 0.002$) and a Frequencies x Images interaction ($F(5,65) = 2.390$, $p < 0.05$). Polynomial contrast on
373 Frequencies revealed a significant quadratic trend ($t(65) = 3.919$, $p < 0.001$). Customized contrast
374 exhibited a significant difference between stressful and calming pictures at aug40 ($t(69,201) = -2.286$,
375 $p < 0.025$).

376 The same ANOVA performed on the range of unwrapped RP (Figure 6B) exhibited a main effect of
377 Frequencies ($F(5,65) = 2.754$, $p < 0.03$), and a Frequencies x Stimulus interaction ($F(5,65) = 2.847$, p
378 < 0.03). Polynomial contrast on Frequencies revealed a significant quadratic trend, ($t(65) = 2.209$, $p <$
379 0.031). Customized contrast highlighted a significant difference between stressful and calming images
380 at aug60 ($t(36,965) = -2.588$, $p < 0.014$).

381 INSERT, PLEASE, FIGURE 6 ABOUT HERE

382

383 *3.9. Detuning modulate SCR*

384 Figure 7 illustrates the effect of Frequencies and Images on SCR. The 6 (Frequencies) X 2 (Images)
385 ANOVA performed on the SCR only evidenced a main effect of Frequencies ($F(5,50) = 2.733$, $p < 0.03$).
386 Simple contrast on Frequencies revealed a significant effect on the comparison dim60-dim20 ($t(50) =$
387 2.244 , $p < 0.03$). It is noteworthy that a tendency toward statistical significance was also observed for
388 the Frequencies x Images interaction ($p = 0.054$).

389

390

391 **4. Discussion**

392 Using a pre-post paradigm with a control group, we assessed the effect of squeezing a vibrating ball
393 on anxiety and arousal. Participants were exposed to calming or stressful images, which modulated their
394 arousal (cf. Hypothesis 1). In the stress-inducing condition, arousal decreased when the vibrating ball
395 was squeezed (cf., hypothesis 2). The haptic interaction also reduced anxiety (cf., Hypothesis 3).
396 Overall, users enjoyed the interaction (cf. Hypothesis 4), preferring slow ball vibration, however. There
397 was also a relationship between arousal and coordination stability, modulated by the detuning between
398 hand squeezing and ball vibration (hypotheses 5-6).

399 *4.1. Stress balls as stress relievers*

400 Our data showed that participants preferred the ball to vibrate at frequencies lower than their
401 spontaneous frequency. Moreover, the variability between the spontaneous frequencies of participants
402 was quite large. This implies that future anti-stress robots should record and adapt their vibrations to
403 human movements. Fortunately, Hopf's model can be easily extended in this direction: Righetti et al.,
404 (2009) developed an adaptive Hopf oscillator that locks in phase with the frequency of the input.

405 If stress balls are intended for use in clinical populations, they should produce rapid, noticeable, and
406 systematic anxiety decreases. Simple, non-vibrating balls have been showed to reduce stress during
407 hemodialysis (Kasar et al., 2020), but failed to do so during dental treatment (Torres-Gomez et al., 2021)
408 and skin surgery (Yanes et al., 2018). Linking the subjective experience to physical parameters is tricky:
409 what works for a particular individual depends on that person's preferences. In (Torres-Gomez et al.,
410 2021) study, participants commented that the stress ball used was either too firm, too big, or too small,
411 which could have prevented them from benefiting from its use. Our data suggest that trying to relate the
412 user's vibrotactile experience to engineering parameters, the participants' preferred frequencies should
413 be taken into account.

414

415 *4.2. Arousal and stability*

416 Arousal, movement, and anxiety were already linked in the literature (Pendry & Vandagriff, 2019;
417 Riley et al., 2013), (Matiz et al., 2020)(Edelson et al., 1999). We add to this evidence by sketching a
418 linkage between arousal and coordination stability. Our data showed that when the haptic coordination
419 between hand squeezing and vibrating ball was most stable, arousal was greater. Likewise, when arousal
420 was raised by watching stressful pictures, the stability of coordination increased.

421 Such a relationship between stability and arousal was also reported by Zhang et al., (2016). In
422 Zhang's study, participants oscillated their index while watching a virtual partner do the same. In the
423 bilateral visual coordination, for stable coordination patterns, arousal was greater. Our data flesh out this
424 picture by sketching a bidirectional link between stability and stress/arousal: not only does stability
425 affect arousal but in turn, stress affects stability.

426 This experimental evidence is part of a bigger picture illustrating the interplay between neuro-
427 muscular and 'mental' processes in coordination. For stable coordination patterns attentional cost is low
428 (Temprado et al., 1999) (Kostrubiec et al., 2013), metabolic energy expenditure reduced (Lay et al.,
429 2005), and, as it appears now, arousal heightened. To further explain our data, we may thus refer to the
430 well-known (Kahneman, 1973) model of attention.

431 Let's imagine the 20-second period following the image removal as a dual-task period, where the
432 participant must divide his\her attentional resources between maintaining the image in short-term
433 memory and squeezing the ball. When the frequency of the ball is low, the haptic coordination is stable
434 and produced at a low attentional cost: attention is free to maintain the memory of the picture so that
435 arousal remains height. Now, when the frequency of movements is high and coordination stability low,
436 attentional resources are exceeded. Participant must choose between focusing attention on the movement
437 or on the memory of the picture. Possibly, s\he is more likely to devote his\her attention to stabilizing
438 coordination after viewing stressful images.

439 *4.3. Ambitions, limits, and future directions*

440 At the beginning of this project, we decided to develop a prototype of a vibrating stress ball, instead
441 of studying haptic processes in a laboratory context. The risk was to build just an immature proof of

442 concept, the gain lay in the possibility a rich range of meaningful issues might be revealed that would
443 have otherwise remained hidden.

444 While our study focuses on the frequency of ball vibrations, many other parameters deserve to be
445 studied: not only the vibrotactile parameters, such as the amplitude or the waveform of vibration, but
446 also the tactile properties of the materials composing the ball: the roughness of its cover, the
447 viscoelasticity, granularity and deformability of its padding, etc. (Cavdan et al., 2019; Muramatsu et al.,
448 2013) Because the sensory and hedonic analyses of stress balls are lacking, we were inspired by studies
449 of Seo and Aravidan (2015, Iii et al., 2009; Yohanan and MacLean, 2012), and performed numerous
450 trials and errors, to select presumably most pleasant materials for our robot. All in all, although
451 participants rated our robotic ball as 'undulating', 'soft', 'energetic', 'elastic', and overall pleasant, further
452 studies should be developed to select the best materials to be used for stress balls.

453 This is of paramount importance given that the vibrating ball was developed with the idea of offering
454 it as a stress reliever for people with autism spectrum disorder (ASD), displaying unusual sensory and
455 hedonic preferences (Bogdashina, 2010). One of the diagnostic features of ASD are motor stereotypies,
456 called 'stims': hand-flapping, body rocking, etc. (DSM-V, 2013). Long suppressed by therapists, they
457 start to be envisioned as stress regulators in the population often suffering from anxiety and overarousal
458 (Keller et al., 2021). However, because the stims may stigmatize persons with ASD in social situations,
459 clinicians seek to give them a socially acceptable form. Squeezing the vibrating balls may be a helpful
460 alternative, provided the ball is perfectly safe and resistant to perforation. Further studies should involve
461 not only larger sample sizes, but also persons displaying motor stereotypies and the disorders of anxiety
462 and arousal.

463 The greatest challenge lies in the manipulation of anxiety levels. We noted that the lower increase in
464 EDA could be due to the repeated presentation of stressful stimuli. Even though all the images are
465 different, the participant could grow accustomed to the affective impact of the stimuli and therefore the
466 first image will not have the same emotional impact as the last. Future studies should take place in more
467 ecological, anxiety-provoking contexts.

468

469 **5. Conclusion**

470 We evaluated the effect of squeezing a vibrating stress ball on anxiety and arousal. Participants
471 watched stressful or calming pictures and then squeezed the ball for 20 s. As predicted, the ball acted as
472 a stress reliever: EDA and anxiety decreased after this haptic interaction. Interestingly, the stability of
473 haptic coordination affected arousal: when coordination was most stable, EDA was greatest. Overall,
474 participants enjoyed interacting with the vibrating ball, giving preference to vibrations below their
475 preferred movement frequency.

476

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483 **Authors' Contributions.**

484 CB: conceptualization, methodology, software, investigation, data curation, formal analysis,
485 resources, writing - original draft, visualization

486 JCB: conceptualization, software, resources, supervision, writing – review and editing

487 JK: conceptualization, supervision, writing – review and editing

488 VK: funding acquisition, conceptualization, supervision, writing – review and editing, project
489 administration

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491

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493 **References**

- 494 Ahmadi, A., Mangieri, E., Maharatna, K., & Zwolinski, M. (2009). Physical realizable circuit structure
495 for adaptive frequency Hopf oscillator. *2009 Joint IEEE North-East Workshop on Circuits and*
496 *Systems and TAISA Conference*, 1- 4. <https://doi.org/10.1109/NEWCAS.2009.5290482>
- 497 Amazeen, P. G., Schmidt, R. C., & Turvey, M. T. (1995). Frequency detuning of the phase entrainment
498 dynamics of visually coupled rhythmic movements. *Biological Cybernetics*, 72(6), 511- 518.
499 <https://doi.org/10.1007/BF00199893>
- 500 Batschelet, E. (1981). *Circular statistics in biology*. Academic Press.
- 501 Beckmann, J., Fimpel, L., & Wergin, V. V. (2021). Preventing a loss of accuracy of the tennis serve
502 under pressure. *PLOS ONE*, 16(7), e0255060. <https://doi.org/10.1371/journal.pone.0255060>
- 503 Beckmann, J., Gröpel, P., & Ehrlenspiel, F. (2013). Preventing motor skill failure through hemisphere-
504 specific priming : Cases from choking under pressure. *Journal of Experimental Psychology:*
505 *General*, 142(3), 679- 691. <https://doi.org/10.1037/a0029852>
- 506 Benedek, M., & Kaernbach, C. (2010). A continuous measure of phasic electrodermal activity. *Journal*
507 *of Neuroscience Methods*, 190(1), 80- 91. <https://doi.org/10.1016/j.jneumeth.2010.04.028>
- 508 Bernat, E., Patrick, C. J., Benning, S. D., & Tellegen, A. (2006). Effects of picture content and intensity
509 on affective physiological response. *Psychophysiology*, 43(1), 93- 103.
510 <https://doi.org/10.1111/j.1469-8986.2006.00380.x>
- 511 Blakemore, S. J., Wolpert, D. M., & Frith, C. D. (1998). Central cancellation of self-produced tickle
512 sensation. *Nature Neuroscience*, 1(7), 635- 640. <https://doi.org/10.1038/2870>
- 513 Bogdashina, O. (2010). *Autism and the edges of the known world : Sensitivities, language, and*
514 *constructed reality*. Jessica Kingsley.
- 515 Boucsein, W. (2012). *Electrodermal Activity*. Springer US. <https://doi.org/10.1007/978-1-4614-1126-0>
- 516 Braithwaite, J. J., Watson, D. G., Jones, R., & Rowe, M. (2015). *A Guide for Analysing Electrodermal*
517 *Activity (EDA) & Skin Conductance Responses (SCRs) for Psychological Experiments*.
518 <https://doi.org/10.1007/s10948-012-1909-2>
- 519 Buchli, J., Righetti, L., & Ijspeert, A. J. (2006). Engineering entrainment and adaptation in limit cycle
520 systems : From biological inspiration to applications in robotics. *Biological Cybernetics*, 95(6),
521 645- 664. <https://doi.org/10.1007/s00422-006-0128-y>
- 522 Cavdan, M., Doerschner, K., & Drewing, K. (2019). The many dimensions underlying perceived
523 softness : How exploratory procedures are influenced by material and the perceptual task. *2019*
524 *IEEE World Haptics Conference (WHC)*, 437- 442.
525 <https://doi.org/10.1109/WHC.2019.8816088>
- 526 Cheng, M., Kato, M., Saunders, J. A., & Tseng, C. (2020). Paired walkers with better first impression
527 synchronize better. *PLOS ONE*, 15(2), e0227880. <https://doi.org/10.1371/journal.pone.0227880>

528 DSM-V. (2013). American Psychiatric Association Diagnostic and Statistical Manual of Mental
529 Disorders. In *SpringerReference*. Springer-Verlag.
530 http://www.springerreference.com/index/doi/10.1007/SpringerReference_179660

531 Edelson, S. M., Edelson, M. G., Kerr, D. C. R., & Grandin, T. (1999). Behavioral and Physiological
532 Effects of Deep Pressure on Children With Autism : A Pilot Study Evaluating the Efficacy of
533 Grandin’s Hug Machine. *The American Journal of Occupational Therapy*, 53(2), 145- 152.
534 <https://doi.org/10.5014/ajot.53.2.145>

535 GALLUP. (2020). *Global Emotions Report*. www.gallup.com

536 Grös, D. F., Antony, M. M., Simms, L. J., & McCabe, R. E. (2007). Psychometric properties of the
537 State-Trait Inventory for Cognitive and Somatic Anxiety (STICSA) : Comparison to the State-
538 Trait Anxiety Inventory (STAI). *Psychological Assessment*, 19(4), 369- 381.
539 <https://doi.org/10.1037/1040-3590.19.4.369>

540 Haken, H., Kelso, J. A., & Bunz, H. (1985). A theoretical model of phase transitions in human hand
541 movements. *Biological Cybernetics*, 51(5), 347- 356.

542 Hove, M. J., & Risen, J. L. (2009). It’s All in the Timing : Interpersonal Synchrony Increases Affiliation.
543 *Social Cognition*, 27(6), 949- 960. <https://doi.org/10.1521/soco.2009.27.6.949>

544 Jensen, O., & Mazaheri, A. (2010). Shaping Functional Architecture by Oscillatory Alpha Activity :
545 Gating by Inhibition. *Frontiers in Human Neuroscience*, 4.
546 <https://doi.org/10.3389/fnhum.2010.00186>

547 Kahneman, D. (1973). *Attention and Effort* (Prentice-Hall).

548 Kasar, K. S., Erzincanli, S., & Akbas, N. T. (2020). The effect of a stress ball on stress, vital signs and
549 patient comfort in hemodialysis patients : A randomized controlled trial. *Complementary*
550 *Therapies in Clinical Practice*, 41, 101243. <https://doi.org/10.1016/j.ctcp.2020.101243>

551 Keller, R., Costa, T., Imperiale, D., Bianco, A., Rondini, E., Hassiotis, A., & Bertelli, M. O. (2021).
552 Stereotypies in the Autism Spectrum Disorder : Can We Rely on an Ethological Model? *Brain*
553 *Sciences*, 11(6), 762. <https://doi.org/10.3390/brainsci11060762>

554 Kelso, J. A. S. (1995). *Dynamic patterns : The self-organization of brain and behavior*. MIT Press.

555 Kostrubiec, V., Danna, J., & Zanone, P.-G. (2013). Co-variation between graphic pattern stability and
556 attentional cost : A clue for the difficulty to produce handwritten traces. *Human Movement*
557 *Science*, 32(5), 1010- 1025. <https://doi.org/10.1016/j.humov.2012.12.005>

558 Kurdi, B., Lozano, S., & Banaji, M. R. (2017). Introducing the Open Affective Standardized Image Set
559 (OASIS). *Behavior Research Methods*, 49(2), 457- 470. [https://doi.org/10.3758/s13428-016-](https://doi.org/10.3758/s13428-016-0715-3)
560 [0715-3](https://doi.org/10.3758/s13428-016-0715-3)

561 Launay, J., Dean, R. T., & Bailes, F. (2014). Synchronising movements with the sounds of a virtual
562 partner enhances partner likeability. *Cognitive Processing*, 15(4), 491- 501.
563 <https://doi.org/10.1007/s10339-014-0618-0>

- 564 Lay, B. S., Sparrow, W. A., & O'Dwyer, N. J. (2005). The metabolic and cognitive energy costs of
565 stabilising a high-energy interlimb coordination task. *Human Movement Science*, 24(5- 6),
566 833- 848. <https://doi.org/10.1016/j.humov.2005.10.009>
- 567 Matiz, A., Guzzon, D., Crescentini, C., Paschetto, A., & Fabbro, F. (2020). The role of self body
568 brushing vs mindfulness meditation on interoceptive awareness : A non-randomized pilot study
569 on healthy participants with possible implications for body image disturbances. *European*
570 *Journal of Integrative Medicine*, 37, 101168. <https://doi.org/10.1016/j.eujim.2020.101168>
- 571 Mueller, S. M., Martin, S., & Grunwald, M. (2019). Self-touch : Contact durations and point of touch of
572 spontaneous facial self-touches differ depending on cognitive and emotional load. *PLOS ONE*,
573 14(3), e0213677. <https://doi.org/10.1371/journal.pone.0213677>
- 574 Muramatsu, Y., Niitsuma, M., & Thomessen, T. (2013). Building a cognitive model of tactile sensations
575 based on vibrotactile stimuli. *2013 IEEE 4th International Conference on Cognitive*
576 *Infocommunications (CogInfoCom)*, 149- 154.
577 <https://doi.org/10.1109/CogInfoCom.2013.6719231>
- 578 Pendry, P., & Vandagriff, J. L. (2019). Animal Visitation Program (AVP) Reduces Cortisol Levels of
579 University Students : A Randomized Controlled Trial. *AERA Open*, 5(2), 233285841985259.
580 <https://doi.org/10.1177/2332858419852592>
- 581 Rennung, M., & Göritz, A. S. (2016). Prosocial Consequences of Interpersonal Synchrony : A Meta-
582 Analysis. *Zeitschrift Für Psychologie*, 224(3), 168- 189. [https://doi.org/10.1027/2151-](https://doi.org/10.1027/2151-2604/a000252)
583 [2604/a000252](https://doi.org/10.1027/2151-2604/a000252)
- 584 Righetti, L., Buchli, J., & Ijspeert, A. J. (2009). Adaptive Frequency Oscillators and Applications. *The*
585 *Open Cybernetics & Systemics Journal*, 3(2), 64- 69.
586 <https://doi.org/10.2174/1874110X00903020064>
- 587 Riley, J., Corkhill, B., & Morris, C. (2013). The Benefits of Knitting for Personal and Social Wellbeing
588 in Adulthood : Findings from an International Survey. *British Journal of Occupational Therapy*,
589 76(2), 50- 57. <https://doi.org/10.4276/030802213X13603244419077>
- 590 Rosenblum, M., Pikovsky, A., Kurths, J., Schäfer, C., & Tass, P. (2001). Phase synchronisation : From
591 theory to data analysis. In *Handbook of biological physics* (F. Moss&S. Gielen, p. 279- 321).
592 Elsevier.
- 593 Russell, J. A. (1980). A circumplex model of affect. *Journal of Personality and Social Psychology*,
594 39(6), 1161- 1178. <https://doi.org/10.1037/h0077714>
- 595 Schmidt, R. C., Bienvu, M., Fitzpatrick, P. A., & Amazeen, P. G. (1998). A comparison of intra- and
596 interpersonal interlimb coordination : Coordination breakdowns and coupling strength. *Journal*
597 *of Experimental Psychology: Human Perception and Performance*, 24(3), 884- 900.
598 <https://doi.org/10.1037/0096-1523.24.3.884>

- 599 Schöner, G., & Kelso, J. A. S. (1988). A synergetic theory of environmentally-specified and learned
600 patterns of movement coordination : I. Relative phase dynamics. *Biological Cybernetics*, 58(2),
601 71- 80. <https://doi.org/10.1007/BF00364153>
- 602 Seifi, H., Zhang, K., & MacLean, K. E. (2015). VibViz : Organizing, visualizing and navigating
603 vibration libraries. *2015 IEEE World Haptics Conference (WHC)*, 254- 259.
604 <https://doi.org/10.1109/WHC.2015.7177722>
- 605 Temprado, J.-J., Zanone, P.-G., Monno, A., & Laurent, M. (1999). Attentional load associated with
606 performing and stabilizing preferred bimanual patterns. *Journal of Experimental Psychology:*
607 *Human Perception and Performance*, 25(6), 1579- 1594. <https://doi.org/10.1037/0096->
608 1523.25.6.1579
- 609 Torres-Gomez, J., Arnason, Sc., Hoopes, Wl., & Vandewalle, Ks. (2021). Management of dental anxiety
610 via distraction technique. *Journal of Clinical and Experimental Dentistry*, e350- e356.
611 <https://doi.org/10.4317/jced.57660>
- 612 Tschacher, W., Rees, G. M., & Ramseyer, F. (2014). Nonverbal synchrony and affect in dyadic
613 interactions. *Frontiers in Psychology*, 5. <https://doi.org/10.3389/fpsyg.2014.01323>
- 614 Varni, G., Volpe, G., & Camurri, A. (2010). A System for Real-Time Multimodal Analysis of Nonverbal
615 Affective Social Interaction in User-Centric Media. *IEEE Transactions on Multimedia*, 12(6),
616 576- 590. <https://doi.org/10.1109/TMM.2010.2052592>
- 617 Wu, J. Z., Sinsel, E. W., Warren, C. M., & Welcome, D. E. (2018). An evaluation of the contact forces
618 on the fingers when squeezing a spherical rehabilitation ball. *Bio-Medical Materials and*
619 *Engineering*, 29(5), 629- 639. <https://doi.org/10.3233/BME-181013>
- 620 Yanes, A. F., Weil, A., Furlan, K. C., Poon, E., & Alam, M. (2018). Effect of Stress Ball Use or Hand-
621 holding on Anxiety During Skin Cancer Excision : A Randomized Clinical Trial. *JAMA*
622 *Dermatology*, 154(9), 1045. <https://doi.org/10.1001/jamadermatol.2018.1783>
- 623 Yohanan, S., & MacLean, K. E. (2012). The Role of Affective Touch in Human-Robot Interaction :
624 Human Intent and Expectations in Touching the Haptic Creature. *International Journal of*
625 *Social Robotics*, 4(2), 163- 180. <https://doi.org/10.1007/s12369-011-0126-7>
- 626 Zhang, M., Dumas, G., Kelso, J. A. S., & Tognoli, E. (2016). Enhanced emotional responses during
627 social coordination with a virtual partner. *International Journal of Psychophysiology*, 104,
628 33- 43. <https://doi.org/10.1016/j.ijpsycho.2016.04.001>

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Appendix: Sensory analysis of vibro-tactile sensation

634

Instructions: Please describe your vibro-tactile (touch) experience with the ball. To this end, for each

635

pair of antagonistic descriptor words (e.g. “pleasant-unpleasant”) tick or circle a single number to

636

indicate how the closest descriptor word (pointed to by the icon) illustrates your experience. For

637



example, for the “pleasant-unpleasant” pair, if you consider the vibro-actile experience with the ball as

638

enormously pleasant, circle the number 4 on the left. There are no right and wrong answers. Please try

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to answer as best you can.

										
pleasant (agréable)	4	3	2	1	0	1	2	3	4	unpleasant (désagréable)
familiar (familière)	4	3	2	1	0	1	2	3	4	unfamiliar, strange (non familière, étrange)
natural (naturelle)	4	3	2	1	0	1	2	3	4	artificial (artificielle)
comfortable (confortable)	4	3	2	1	0	1	2	3	4	not comfortable (non confortable)
attractive (attractive)	4	3	2	1	0	1	2	3	4	repellent (répulsive)
affective (affective)	4	3	2	1	0	1	2	3	4	not affective (non affective)
useful, adding value (utile)	4	3	2	1	0	1	2	3	4	useless, superfluous (inutile, superflue)
brief, short, (brève, courte,)	4	3	2	1	0	1	2	3	4	continuous, long, (continue, longue, soutenue)
undulating, round (ondulante, ronde)	4	3	2	1	0	1	2	3	4	tingling, sharp (picotante, pointue)
strong (forte)	4	3	2	1	0	1	2	3	4	weak (faible)
hard (dure)	4	3	2	1	0	1	2	3	4	gentle (douce)
regular (régulière)	4	3	2	1	0	1	2	3	4	irregular (irrégulière)
smooth (lisse)	4	3	2	1	0	1	2	3	4	rough, textured (rugueuse, texturée)
featureless (sans relief)	4	3	2	1	0	1	2	3	4	with relief (avec relief)
slippery (glissante)	4	3	2	1	0	1	2	3	4	sticky, adhesive (collante, adhésive)
energetic (énergique)	4	3	2	1	0	1	2	3	4	sluggish (atone)

elastic, bendable (élastique, pliable)	4	3	2	1	0	1	2	3	4	inelastic, rigid (non élastique, rigide)
cold (froide)	4	3	2	1	0	1	2	3	4	hot (chaude)
dried (sèche)	4	3	2	1	0	1	2	3	4	wet (humide)
heavy (lourde)	4	3	2	1	0	1	2	3	4	light (légère)
large, large, voluminous (large, grand, volumineux)	4	3	2	1	0	1	2	3	4	small, narrow (petit, étroit)
thin (mince)	4	3	2	1	0	1	2	3	4	thick (épais)

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FIGURES CAPTIONS

Fig. 1. A. Experimental setup (left). **B.** Skin conductance variation to stressful or calming images during pre-test condition. Black vertical bar depicts the onset of stimulus (1: stressful, 2: calming).

Fig. 2. Timeline of the experimental procedure.

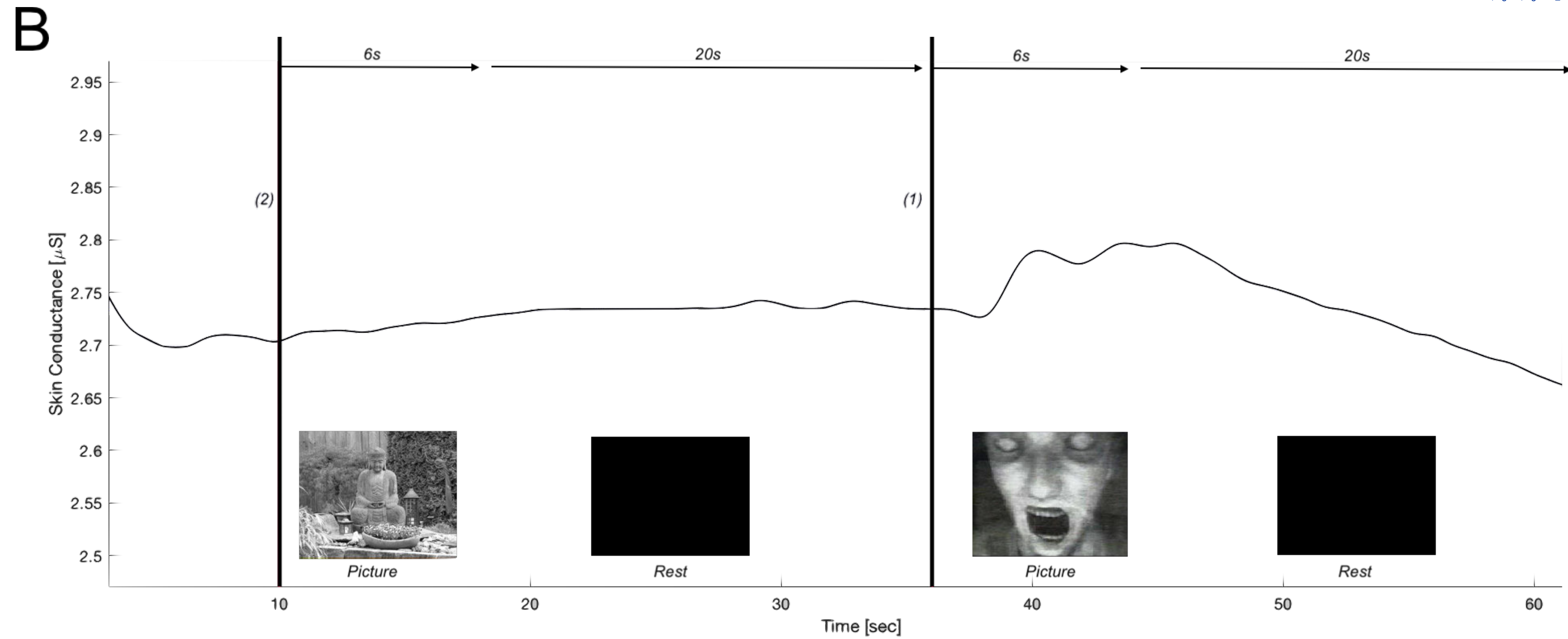
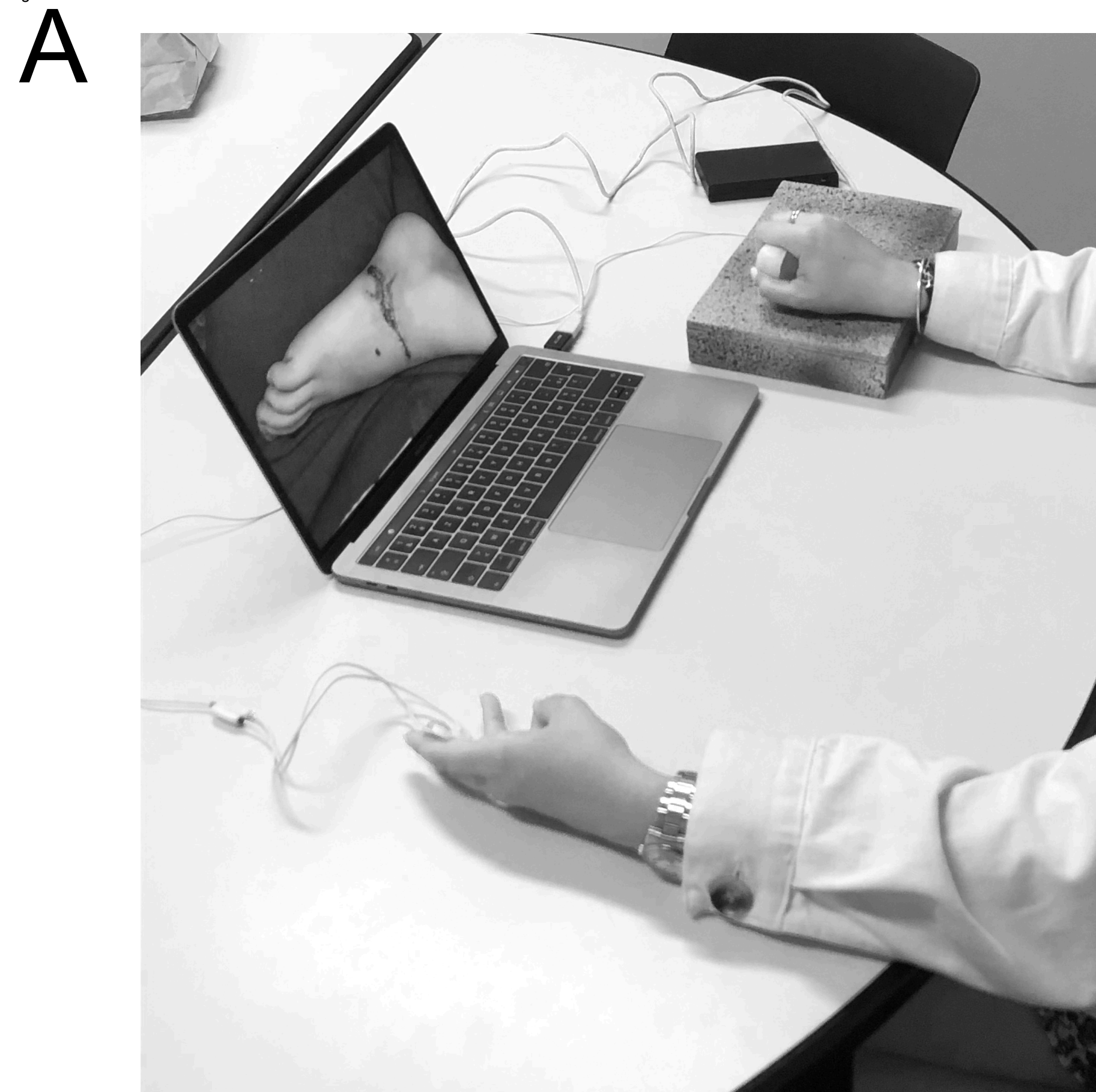
Fig. 3. A. Skin conductance response within response window (SCR, Z-score) recorded before and after interacting with the haptic robot. **B.** Skin conductance response within response window (SCR, Z-score) recorded before and after but without interaction with the haptic robot. **C.** Maximum of phasic activity within response window (Phasicmax, Z-score) recorded before and after interacting with the haptic robot. **D.** Maximum of phasic activity within response window (SCR, Z-score) recorded before and after but without interaction with the haptic robot. Vertical bars depict the standard error of the mean (SEM), asterisks indicate statistical significance levels (* for 0.05).

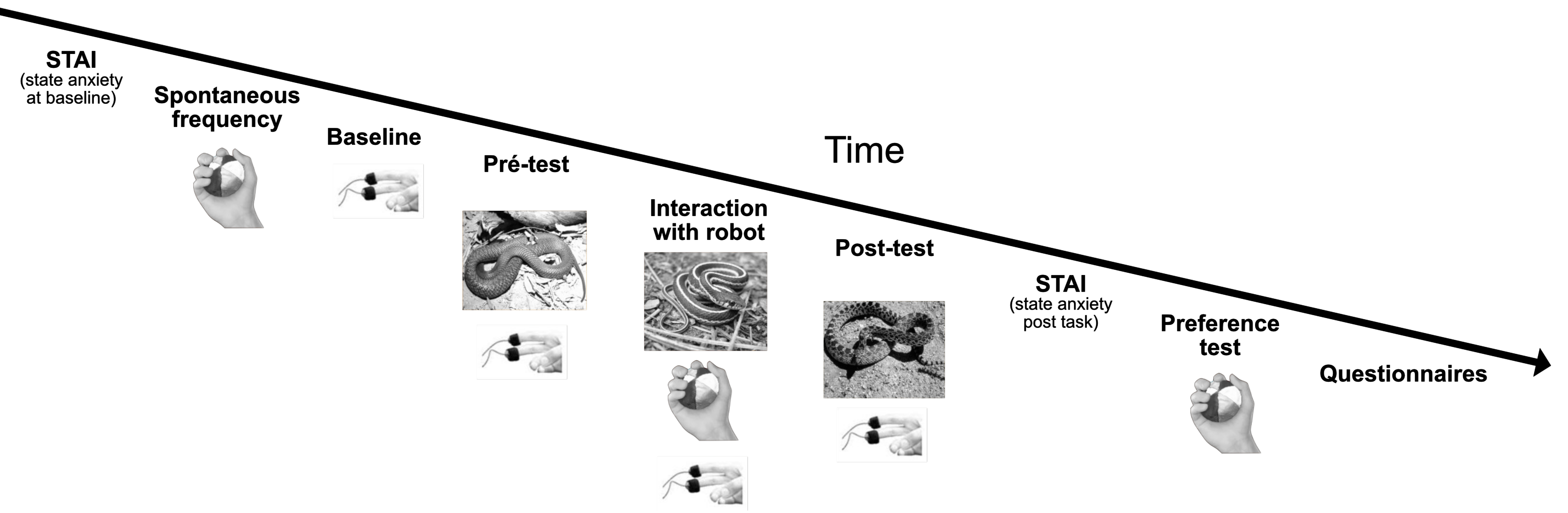
Fig. 4. STAI-Y-1 score between pre-test and post-test condition in both groups. Vertical bars depict standard error of the mean (SEM), asterisks indicate the statistical significance levels (* for 0.05).

Fig. 5. A. Pleasure subscale (PAD). **B.** Arousal subscale (PAD). **C.** Adjectives used to describe the vibrotactile sensation produced by the haptic robot. **D.** Emotional state according to different vibration frequencies. Vertical bars depict standard error of the mean (SEM), asterisks indicate statistical significance levels (* for 0.05).

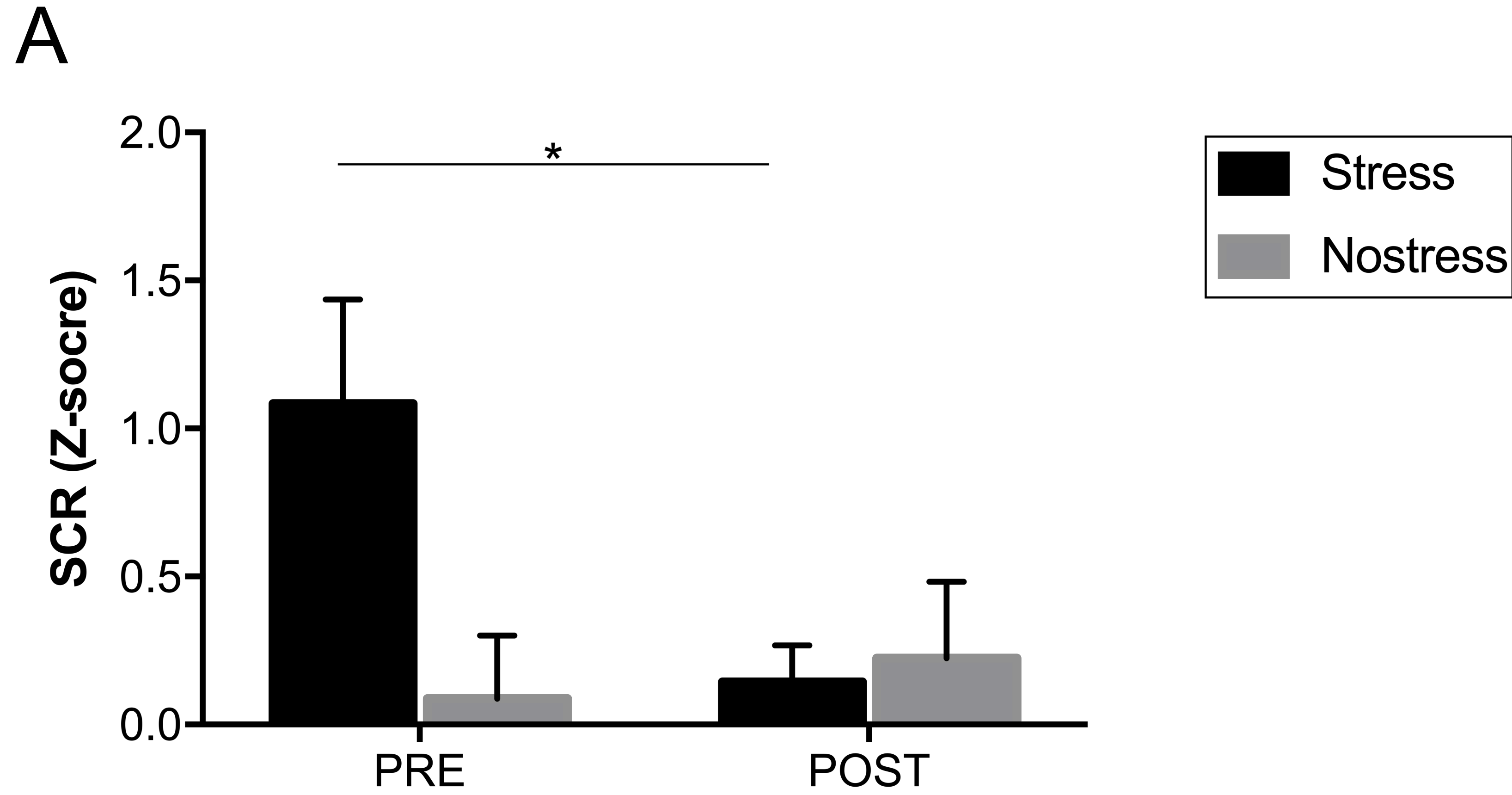
Fig. 6. A. Variability of relative phase (SD of RP) **B.** Unwrap of relative phase. Vertical bars depict standard error of the mean (SEM), asterisks indicate statistical significance levels (* for 0.05).

Fig. 7. Variation of skin conductance response (Z-score) to different robot vibrations. Vertical bars depict standard error of the mean (SEM), asterisks indicate statistical significance levels (* for 0.05).

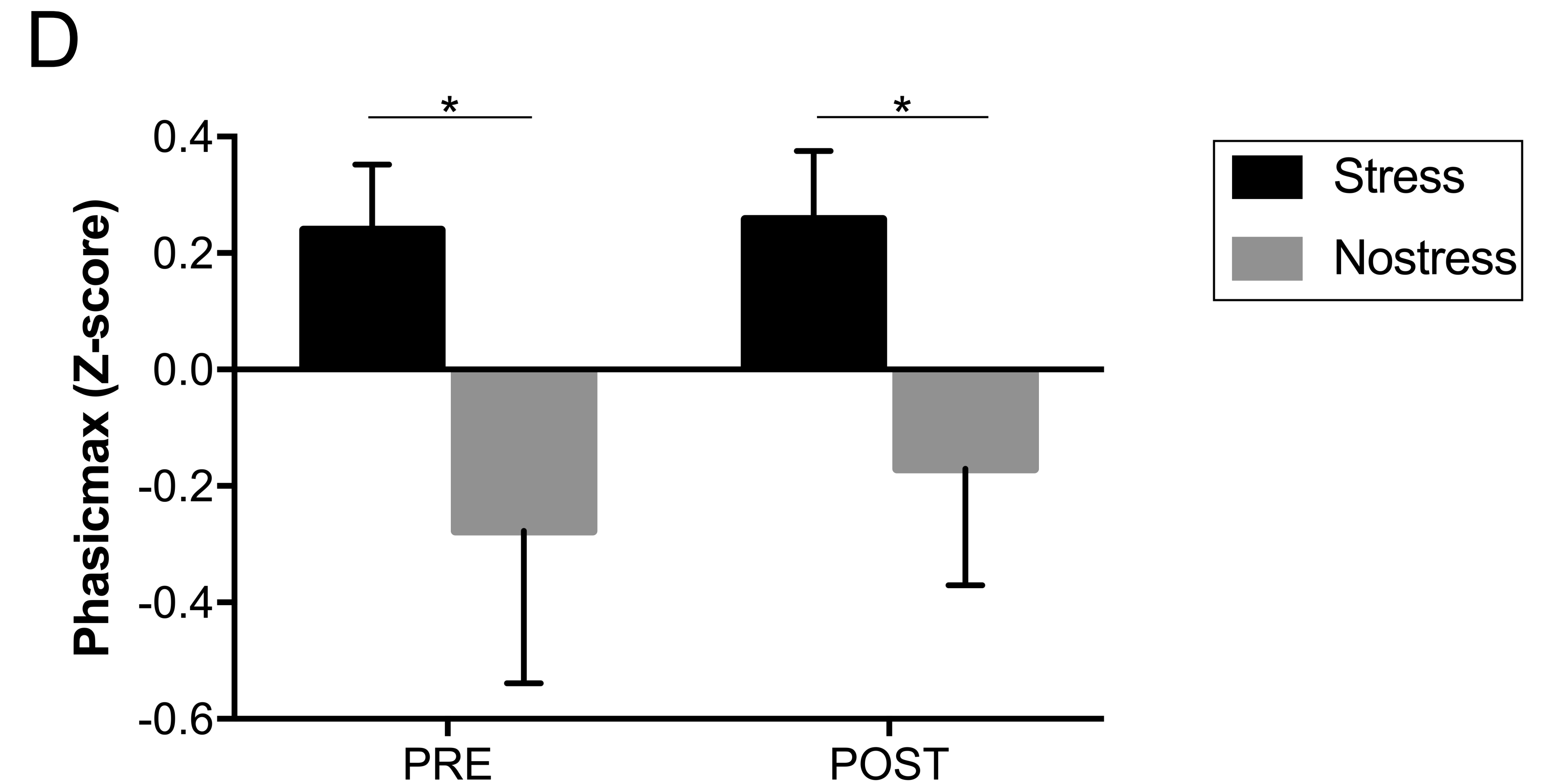
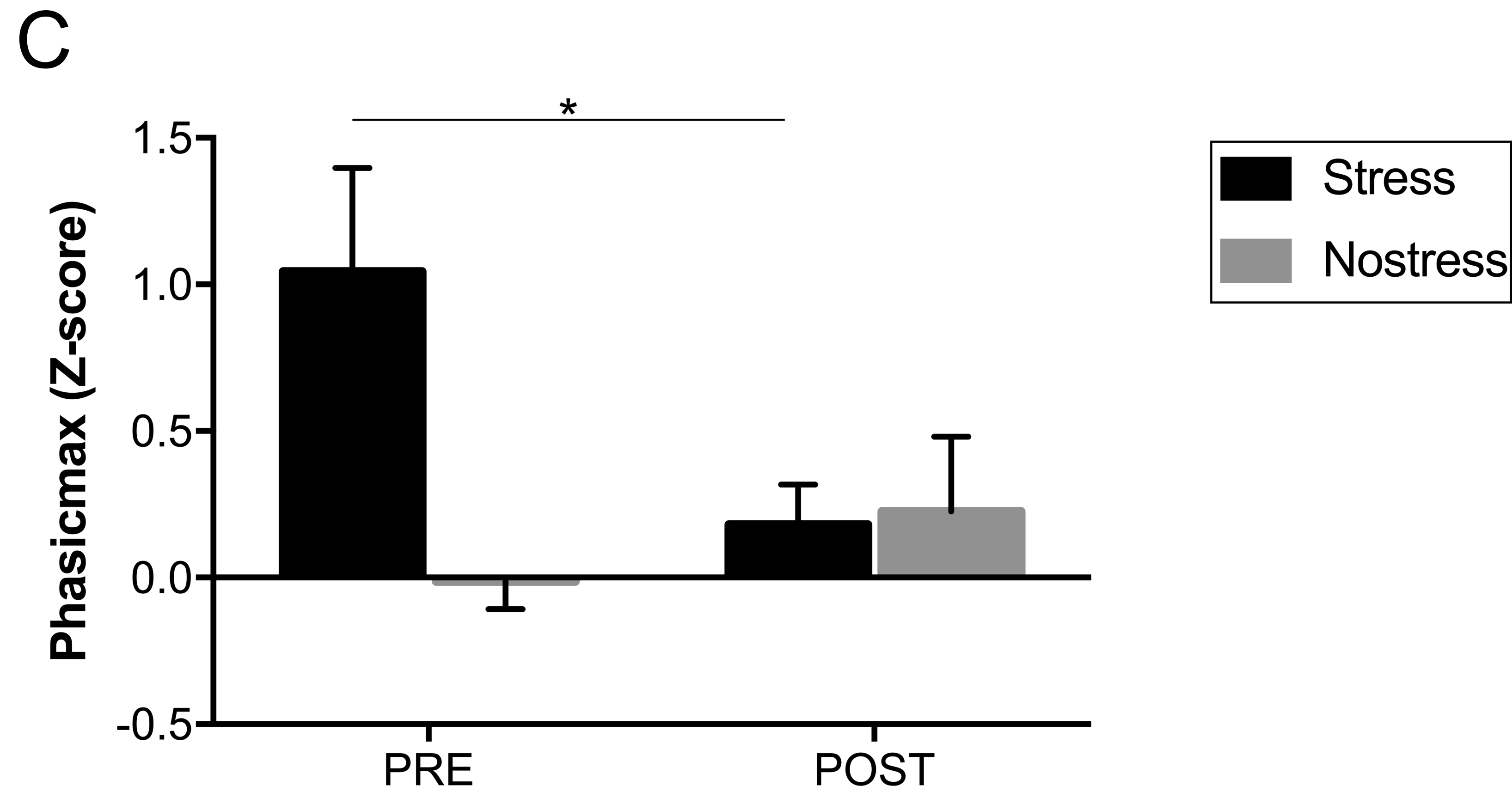
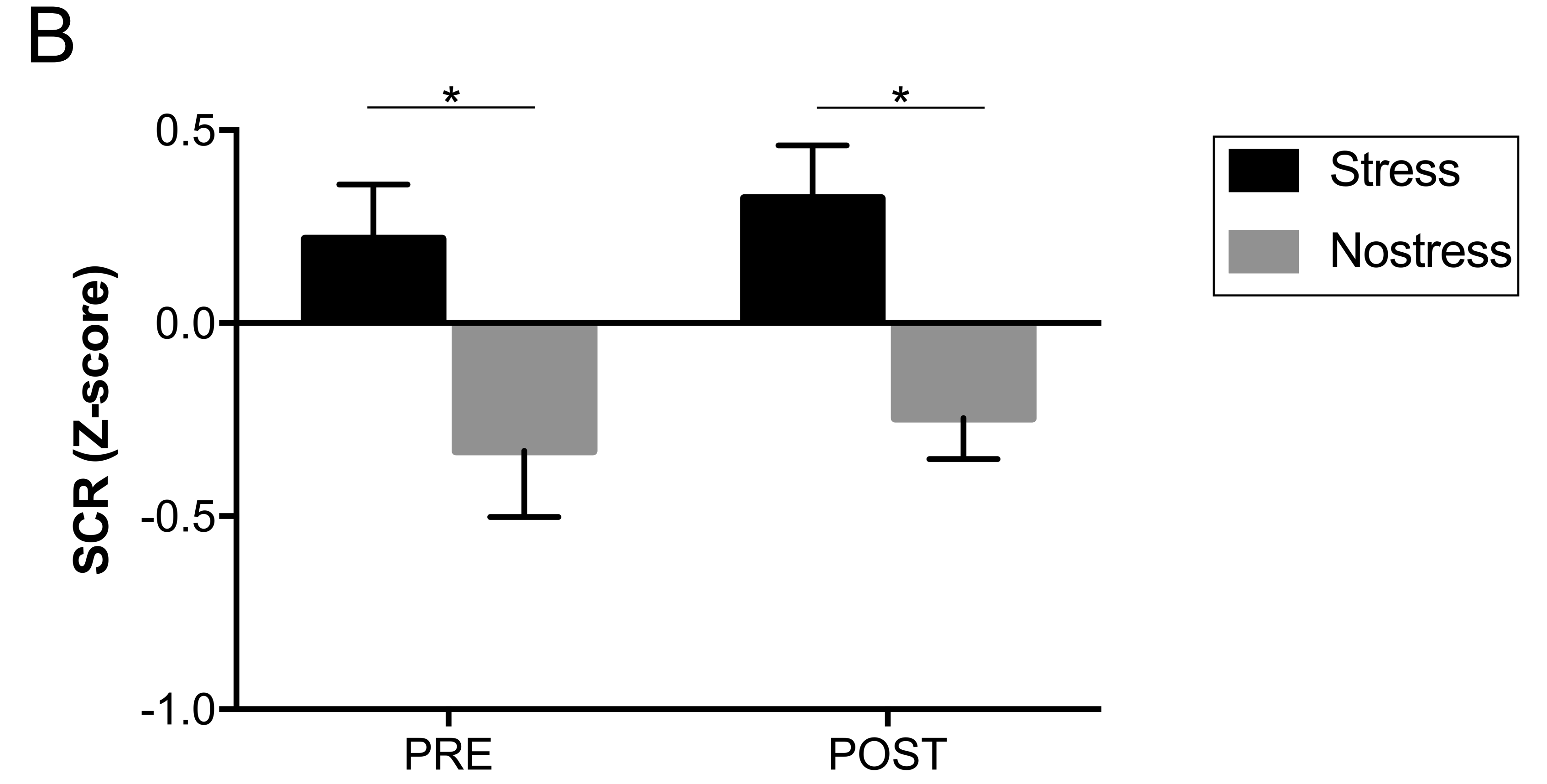


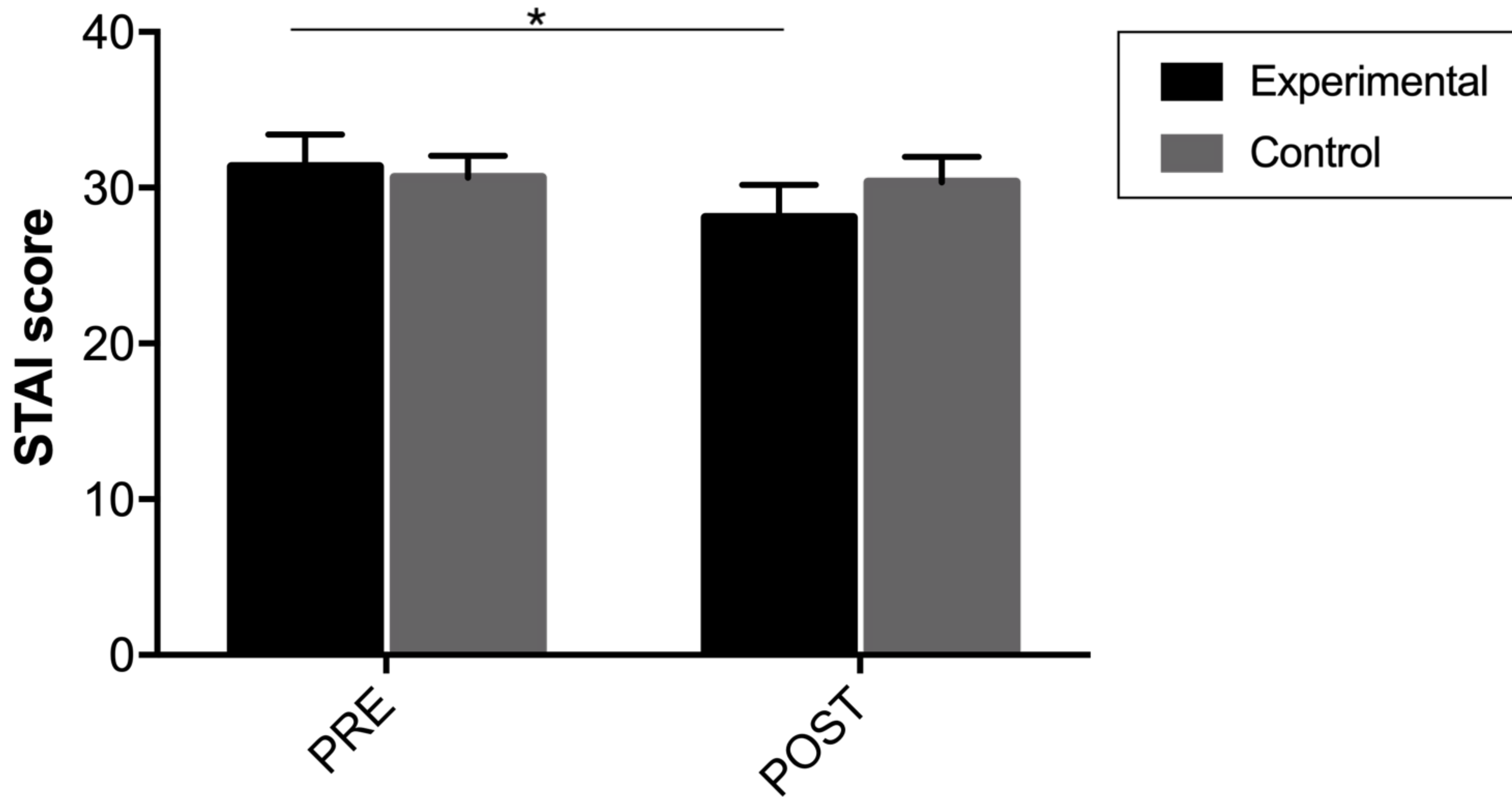


Experimental group

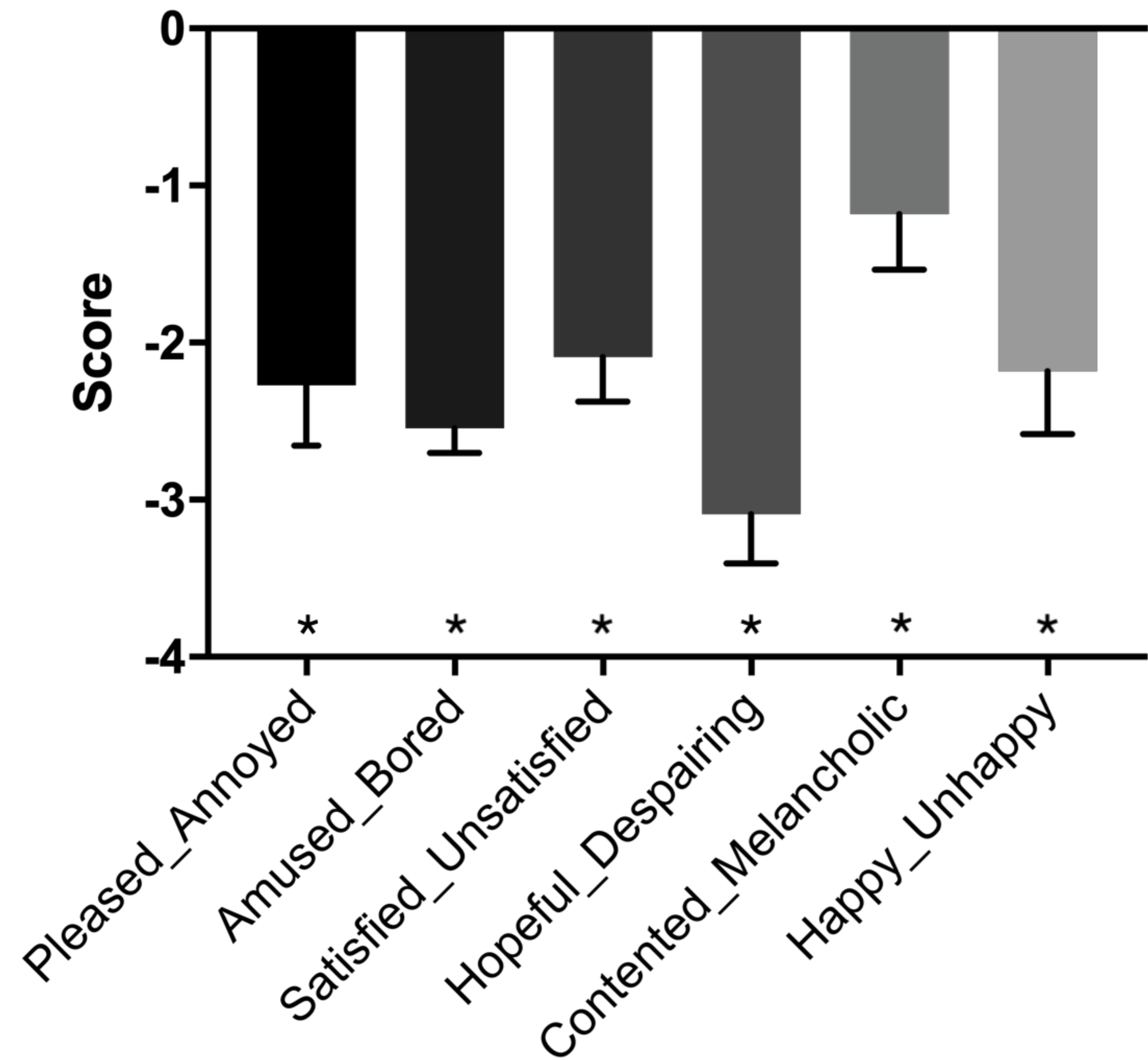


Control group

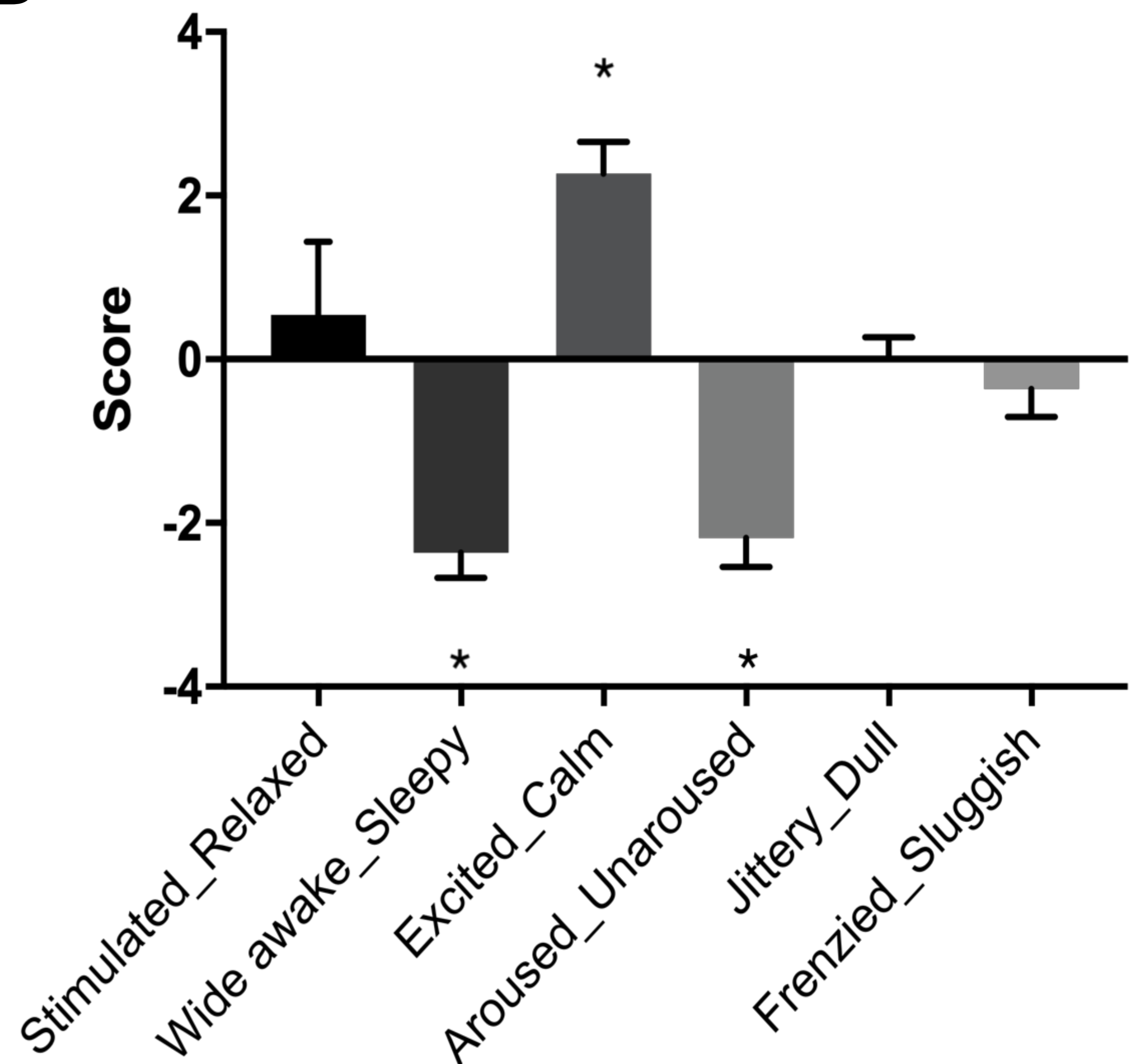




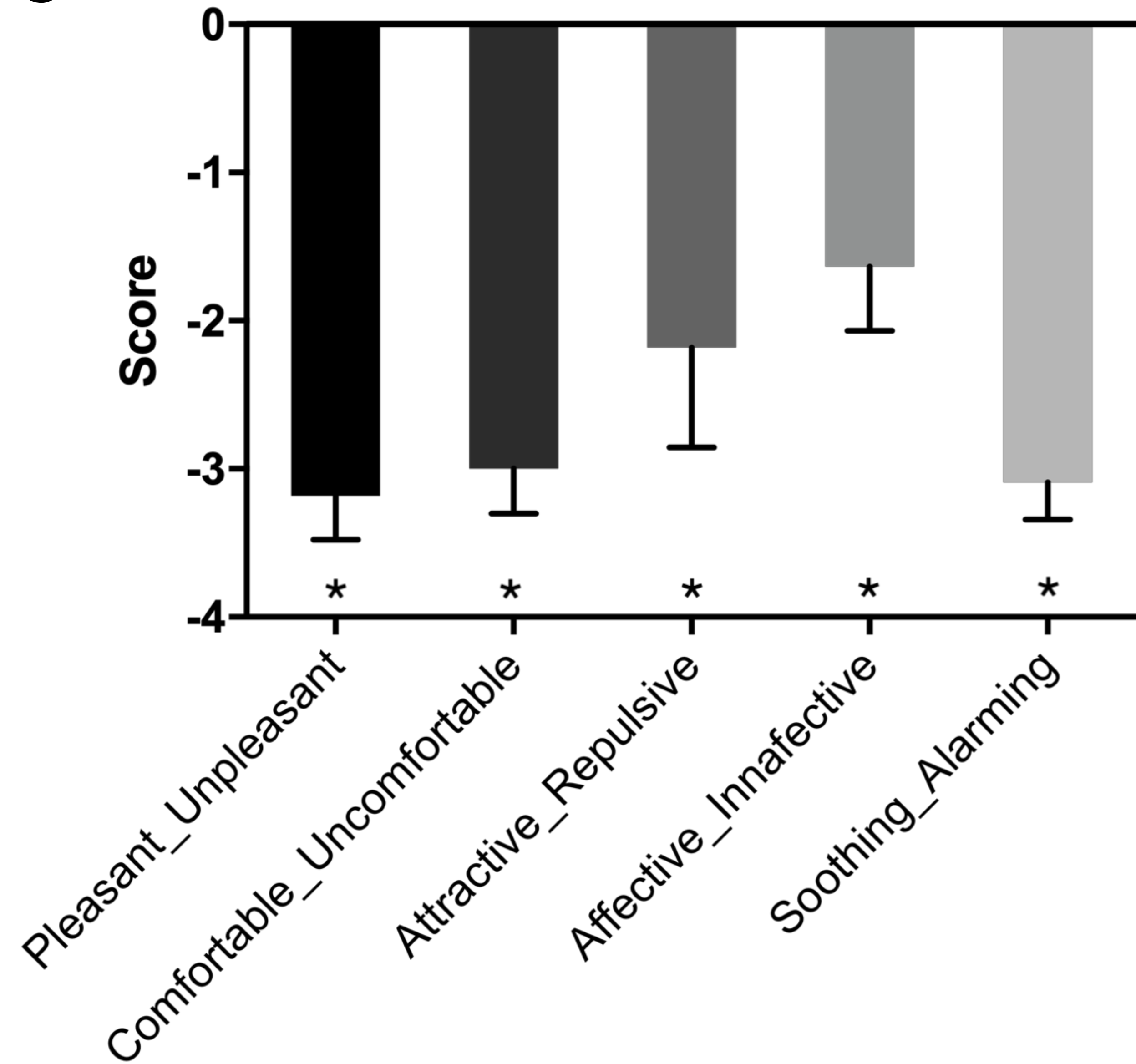
A



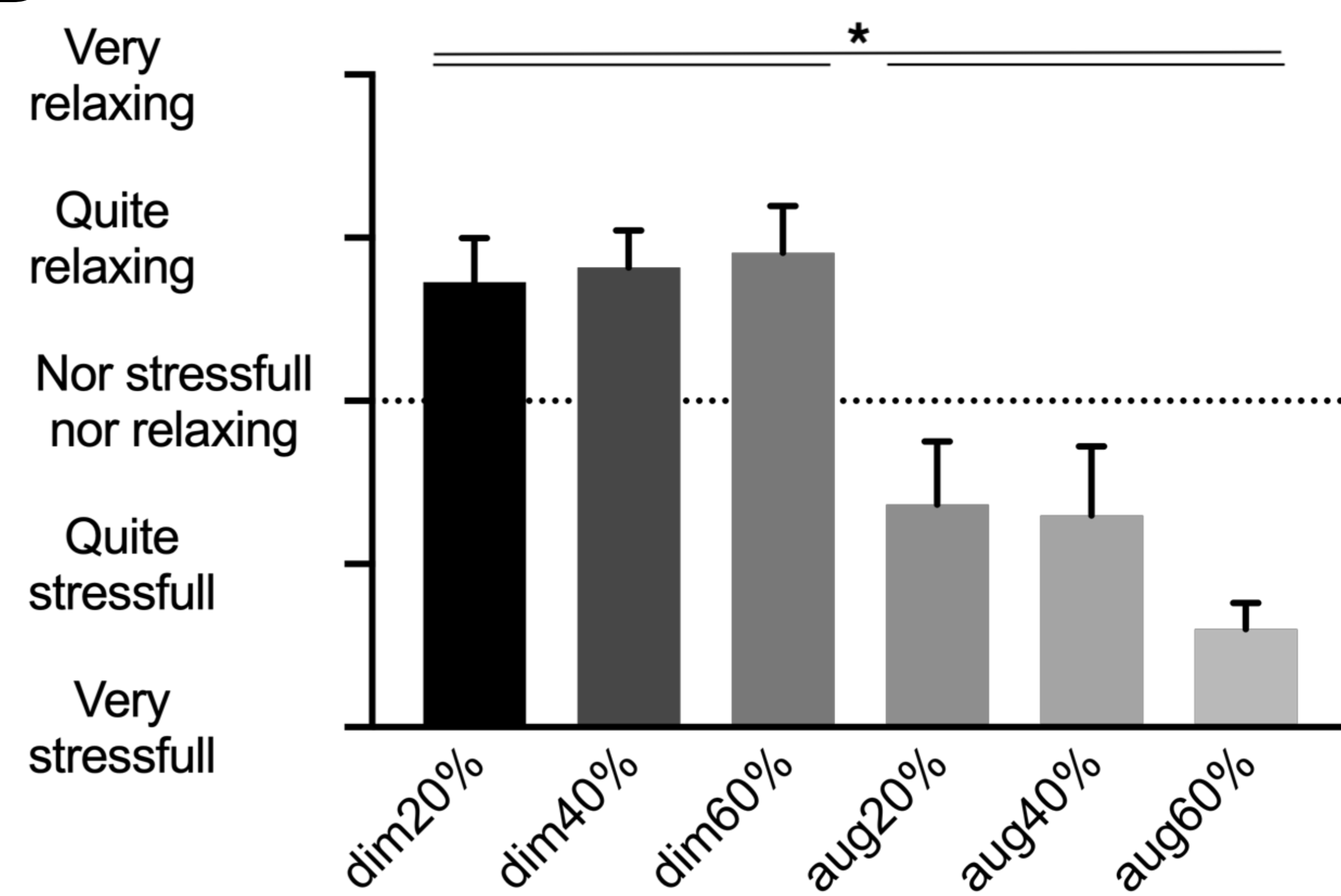
B



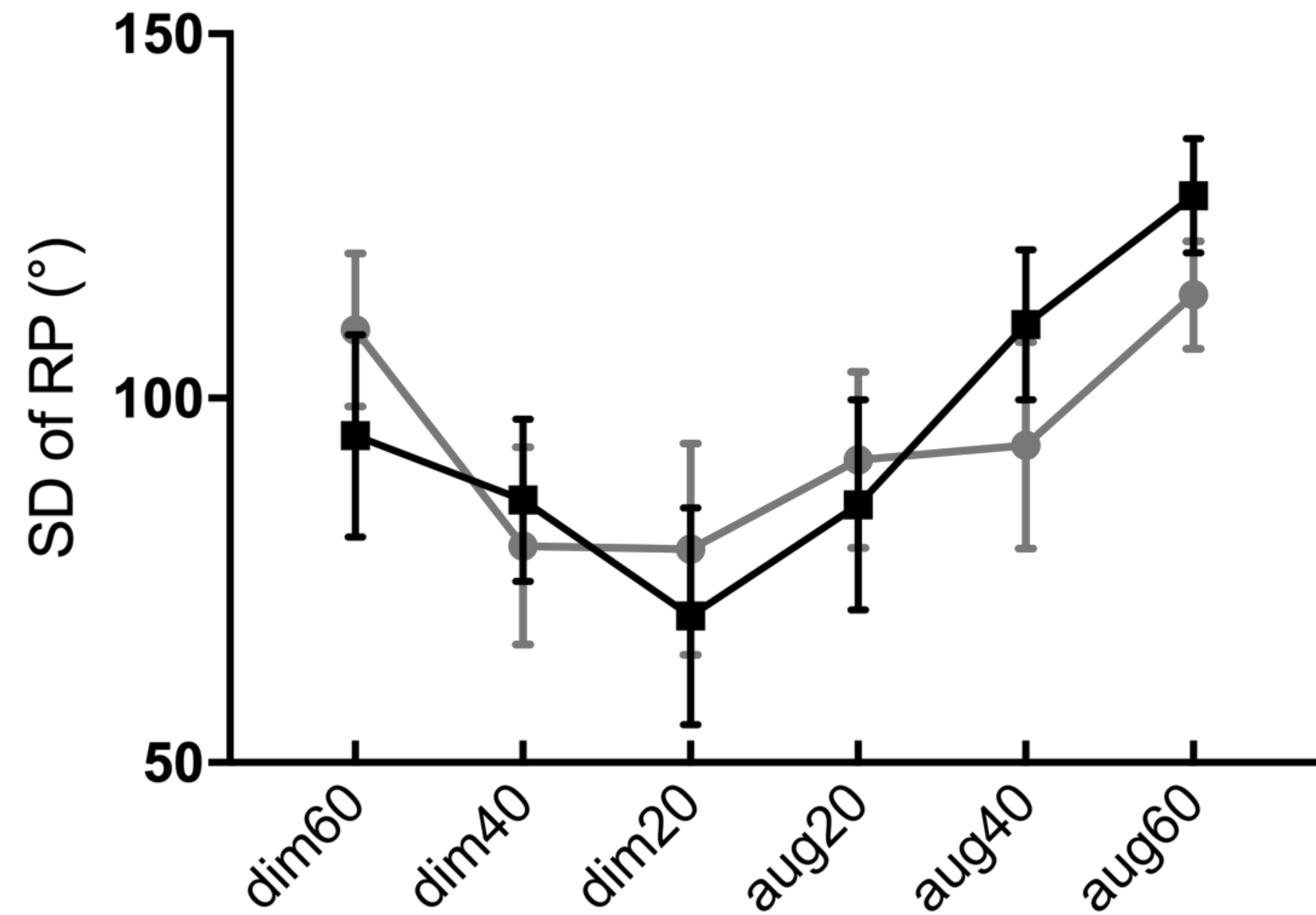
C



D



A



B

