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

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Number of figures: 7; Number of tables: 0, Number of equations 2, Number of 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

Graphical Abstract

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

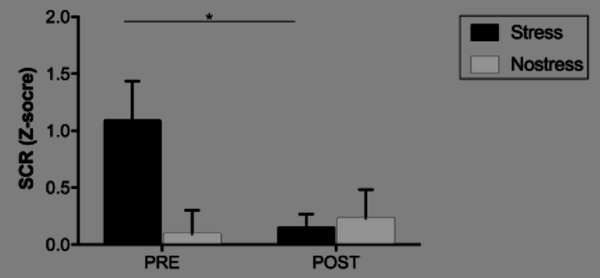
- Participants looked at a stressful or calming picture and then repeatedly squeezed a vibrating stress ball
- To evaluate anxiety, electrodermal activity (EDA) was measured and anxiety questionaire was administered

Vibrating robotic ball

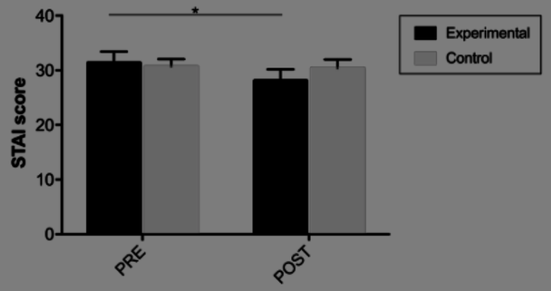
Electrodermal activity

Outcomes

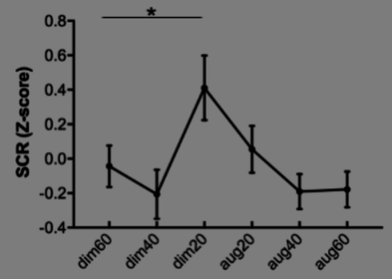
- Squeezing the vibrating ball lowers arousal



- Squeezing the vibrating ball lowers anxiety



- Arousal is modulated by the detuning



Conclusion

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

Abstract

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

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

1. Introduction

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

1.1 Affective haptics in robotics

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

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

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

1.2 Measuring affects

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

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

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

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

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

1.3 Haptic coordination and affect

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

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

frequencies of coupled oscillators (ω_1 - ω_2), called *detuning* ($\Delta\omega$): As the detuning grows, stability drops almost linearly (Amazeen et al., 1995; Mitra et al., 1997; Schmidt et al., 1998).

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

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

2. Methods

2.1. Participants

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

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

2.2. Material

2.2.1. Vibrating stress ball

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

2.2.2. Hopf model

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

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

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

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

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

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

2.2.3. Electrodermal activity sensor

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

2.2.4. Visual stimuli

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

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

INSERT, PLEASE, FIGURE 1 ABOUT HERE

2.2.5. Preference test

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

2.2.6. Experimental setup

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

2.2.7. Psychology tests

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

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

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

2.3. Procedure

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

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

INSERT, PLEASE, FIGURE 2 ABOUT HERE

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

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

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

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

2.4. Data analysis

2.4.1. Electrodermal activity

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

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

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

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

2.4.2 Robot-human coordination

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

2.4.3. Psychological tests

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

2.4.4. Statistical analysis

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

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

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

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

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

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

3. Results

3.1. EDA increases for stressful pictures

An individual trial exemplifying the variation of SCR in response to calming and stressful images is displayed on the Figure 1 (B). The 2 (Images) ANOVA performed on SCR revealed a main effect of Images ($F(1.49) = 16.30$, $p < 0.01$), Phasicmax ($F(1.49) = 13.143$, $p < 0.001$) and Ampsum ($F(1.49) = 16.382$, $p < 0.001$): the three EDA indices were higher for stressful than for calming pictures.

3.2. Interacting with the ball lowers SCR

Figure 3 (top panels) illustrate SCR as a function of Images and Group in the pre-test and post-test condition. The 2 (Images) X 2 (Group) ANOVA carried out on the pre-post difference in SCR evidenced a main effect of Images ($F(1.23) = 4.582$, $p < 0.05$) and an Images x Group interaction ($F(1.23) = 4.948$, $p < 0.05$). Subsequent post-hoc analyses using Holm correction revealed that in the experimental group, the pre-post difference was lower for stressful than for calming images ($p<0.003$, Figure 3A). As for the control group, SCR did not change significantly between pre-test and post-test (Figure 3B).

INSERT, PLEASE, FIGURE 3 ABOUT HERE

3.3. Interacting with the ball lowers Phasicmax

Figure 3 (bottom panels) illustrate Phasicmax as a function of Conditions and Images. The same ANOVA realized on the pre-post difference highlighted a main effect for Images ($F(1.23) = 5.947$, $p < 0.001$) and an Images x Group interaction ($F(1.23) = 4.320$, $p < 0.05$). Further post-hoc analysis with Holm correction of the latter interaction showed that, in the experimental group, Phasicmax was lower in the post-test than in the pre-test condition ($p < 0.01$, Figure 3C). Phasimax did not change between pre-

test and post-test in the control group (Figure 3D). Finally, the same ANOVA performed on Ampsum index only exhibited a main effect for Images only ($F(1.23) = 4.972$, $p < 0.05$).

3.4. Interacting with robot lowers anxiety

STAI-Y-1 scores as a function of Group and Conditions are depicted on Figure 4. First, the 2 (Conditions) X 2 (Group) ANOVA evidenced a main effect of Conditions ($F(1.26) = 8.373$, $p < 0.01$) and a Conditions x Group interaction ($F(1.26) = 6.165$, $p < 0.03$) on STAI-Y-1 score. Post-hoc analysis with Holm adjustment revealed that STAI score was lower after the interaction with the ball in the experimental group only ($p < 0.004$).

INSERT, PLEASE, FIGURE 4 ABOUT HERE

3.5. Users enjoyed playing with the ball

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

INSERT, PLEASE, FIGURE 5 ABOUT HERE

3.6. Slow frequencies are preferred

The 6 (Frequencies) ANOVA on preference scores exhibited a significant effect of Frequencies ($F(5.40) = 12.00$, $p < 0.001$). Holm's post-hoc analysis showed that slower frequencies (-20%, -40%, -60%) were rated as more relaxing ($p < 0.005$) comparing to faster ones (+ 20%; + 40%, + 60%), (Figure 5D).

3.7. Instantaneous frequency was unchanged

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

3.8. Detuning and stress modulate RP variability

Figure 6A pictures the effect of Frequencies and Images on RP variability. The 6 (Frequencies) X 2 (Images) ANOVA carried out on the SD of RP evidenced a main effect of Frequencies ($F(5.65) = 4.302$, $p < 0.002$) and a Frequencies x Images interaction ($F(5.65) = 2.390$, $p < 0.05$). Polynomial contrast on Frequencies revealed a significant quadratic trend ($t(65) = 3.919$, $p < 0.001$). Customized contrast exhibited a significant difference between stressful and calming pictures at aug40 ($t(69.201) = -2.286$, $p < 0.025$).

The same ANOVA performed on the range of unwrapped RP (Figure 6B) exhibited a main effect of Frequencies ($F(5.65) = 2.754$, $p < 0.03$), and a Frequencies x Stimulus interaction ($F(5.65) = 2.847$, $p < 0.03$). Polynomial contrast on Frequencies revealed a significant quadratic trend, ($t(65) = 2.209$, $p < 0.031$). Customized contrast highlighted a significant difference between stressful and calming images at aug60 ($t(36.965) = -2.588$, $p < 0.014$).

INSERT, PLEASE, FIGURE 6 ABOUT HERE

3.9. Detuning modulate SCR

Figure 7 illustrates the effect of Frequencies and Images on SCR. The 6 (Frequencies) X 2 (Images) ANOVA performed on the SCR only evidenced a main effect of Frequencies ($F(5.50) = 2.733$, $p < 0.03$). Simple contrast on Frequencies revealed a significant effect on the comparison dim60-dim20 ($t(50) = 2.244$, $p < 0.03$). It is noteworthy that a tendency toward statistical significance was also observed for the Frequencies x Images interaction ($p = 0.054$).

INSERT, PLEASE, FIGURE 7 ABOUT HERE

4. Discussion

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

4.1. Stress balls as stress relievers

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

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

4.2. Arousal and stability

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

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

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

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

4.3. Ambitions, limits, and future directions

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

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

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

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

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

5. Conclusion

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

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Authors' Contributions.

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

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

JK: conceptualization, supervision, writing – review and editing

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

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Appendix: Sensory analysis of vibro-tactile sensation

Instructions: Please describe your vibro-tactile (touch) experience with the ball. To this end, for each pair of antagonistic descriptor words (e.g. "pleasant-unpleasant") tick or circle a single number to indicate how the closest descriptor word (pointed to by the icon) illustrates your experience. For example, for the "pleasant-unpleasant" pair, if you consider the vibro-actile experience with the ball as enormously pleasant, circle the number 4 on the left. There are no right and wrong answers. Please try 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)

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).

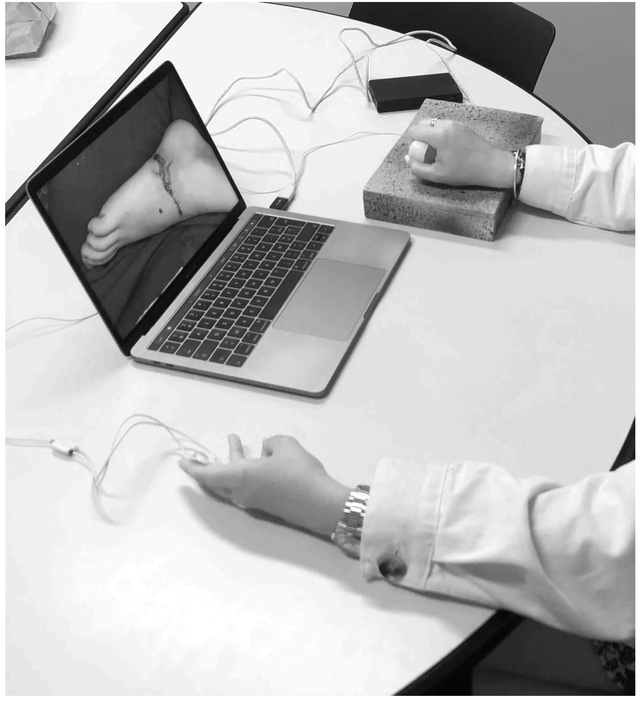
Fig. 4. STAI-Y-1 score between pre-test and post-test condition in both groups. Vertical bars depict standard error of the mean (SEM), asterisks indicate the statistical significance levels (* for 0.05).

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).

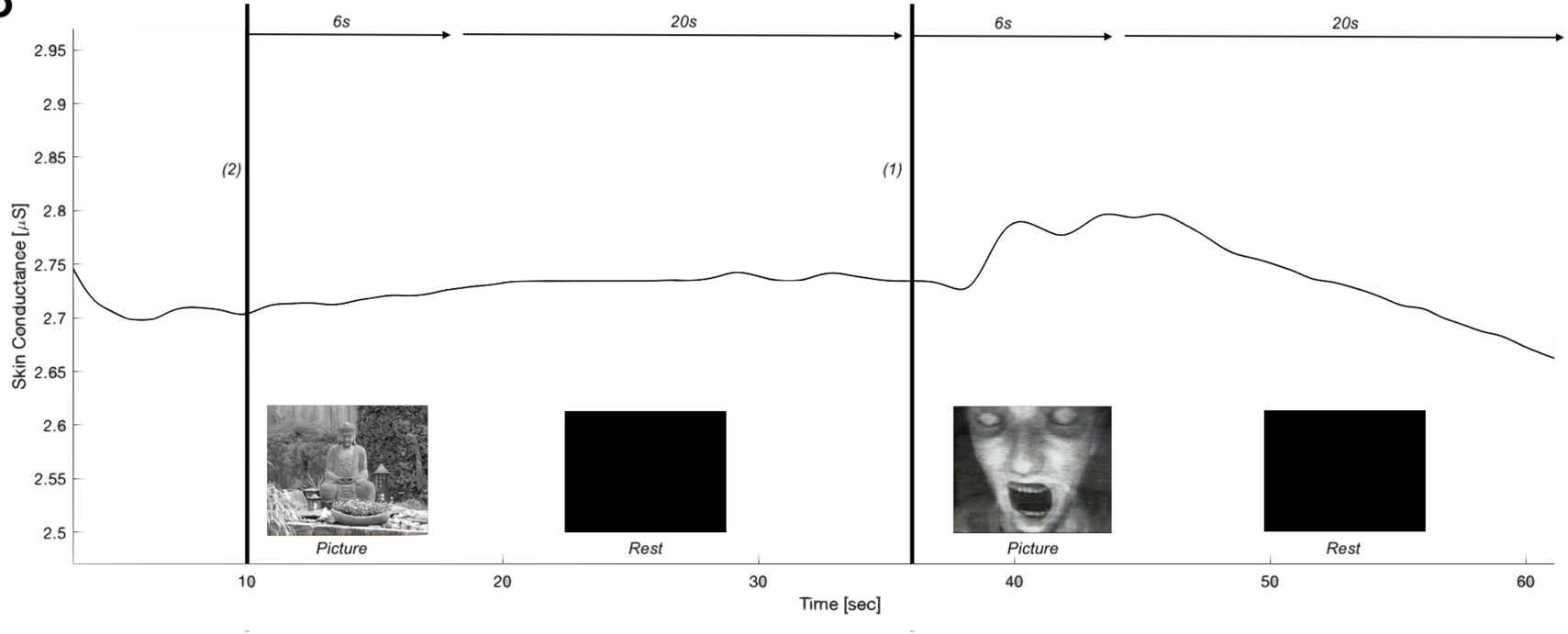
Fig. 6. A. Variability of relative phase (SD of RP) **B**. Unwrap of relative phase. Vertical bars depict standard error of the mean (SEM), asterisks indicate statistical significance levels (* for 0.05).

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).

A



B



STAI
(state anxiety
at baseline)

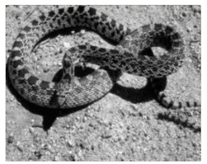
Spontaneous frequency

Baseline

Pré-test

Interaction with robot

Post-test



STAI
(state anxiety
post task)

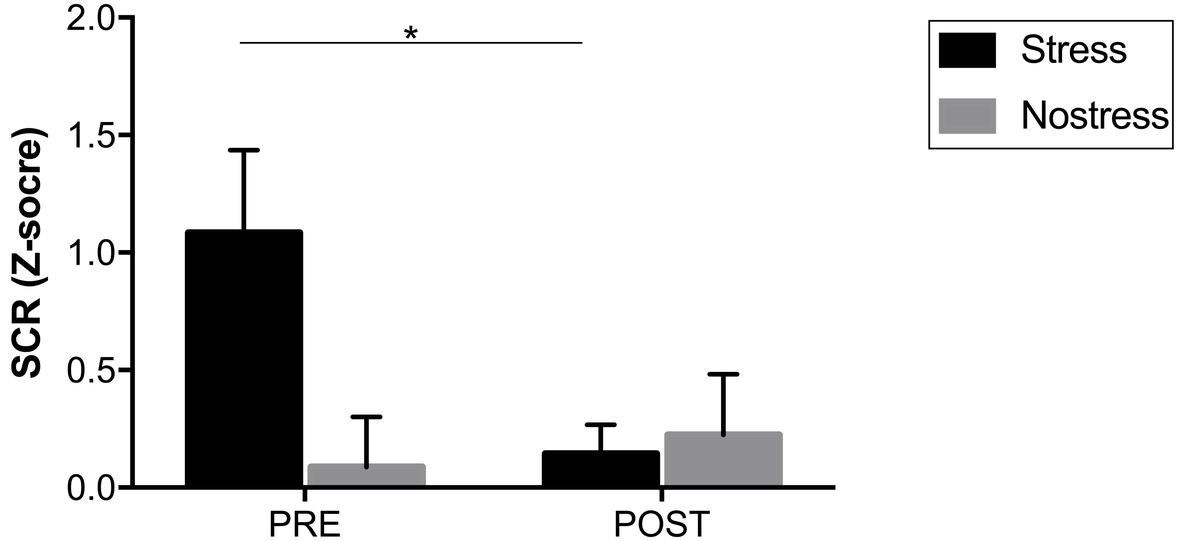
Preference test

Questionnaires

Time

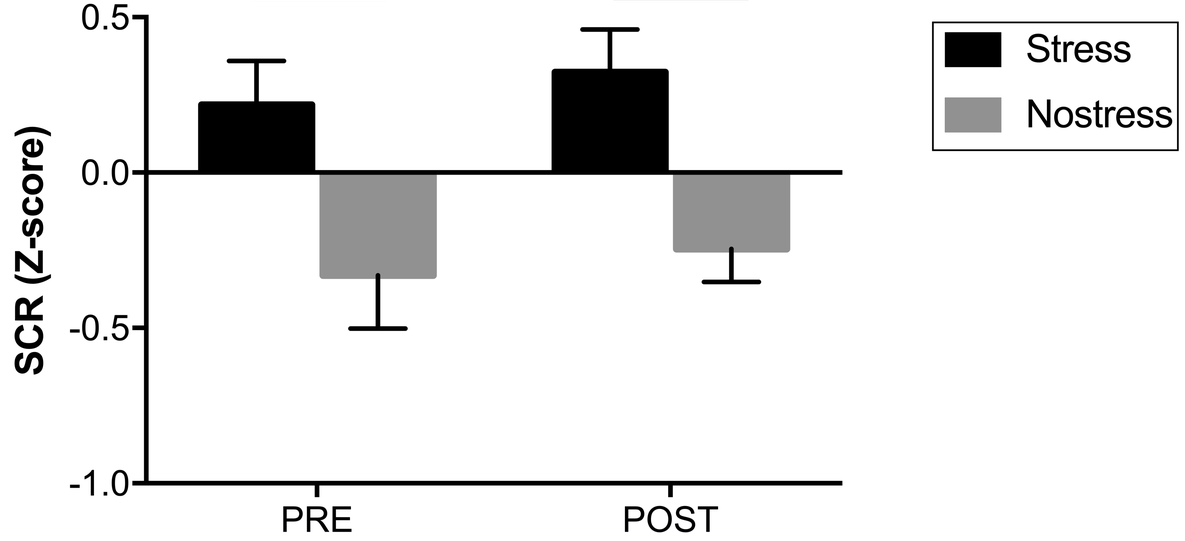
Experimental group

A

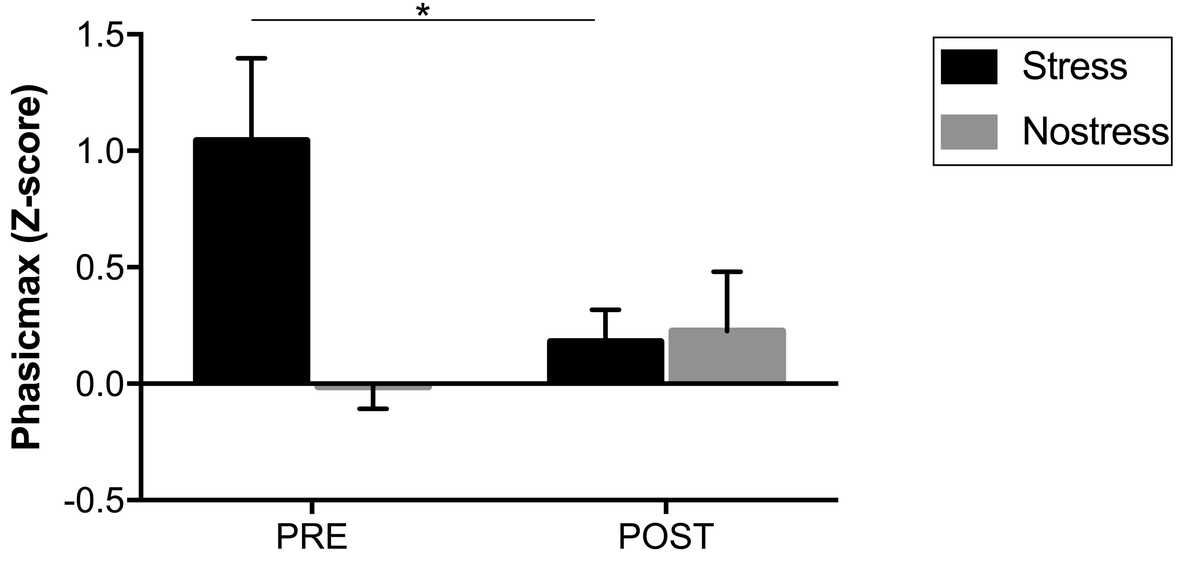


Control group

B



C



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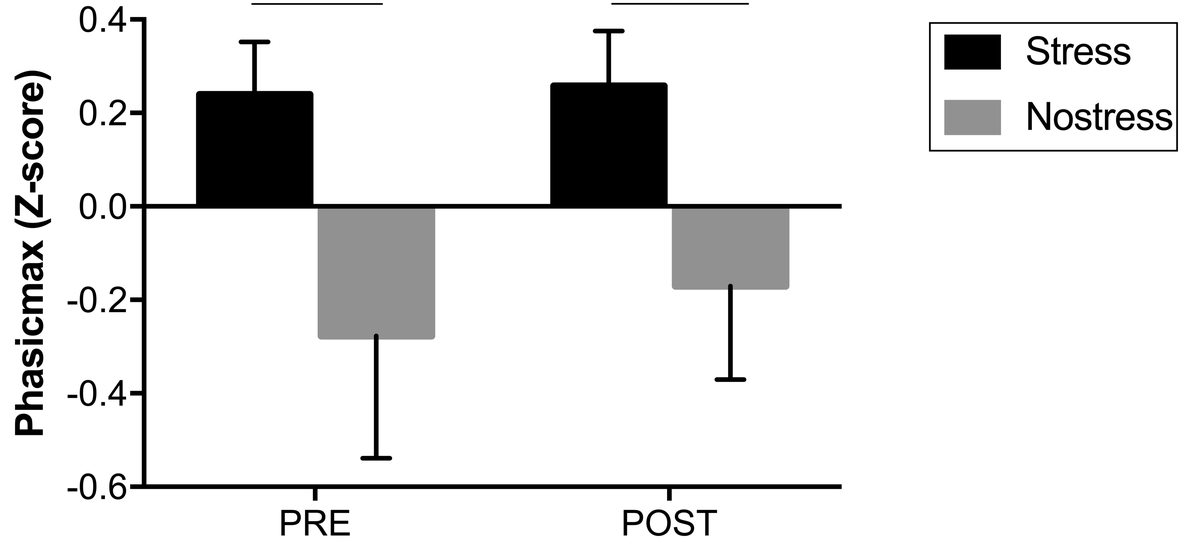

Figure4

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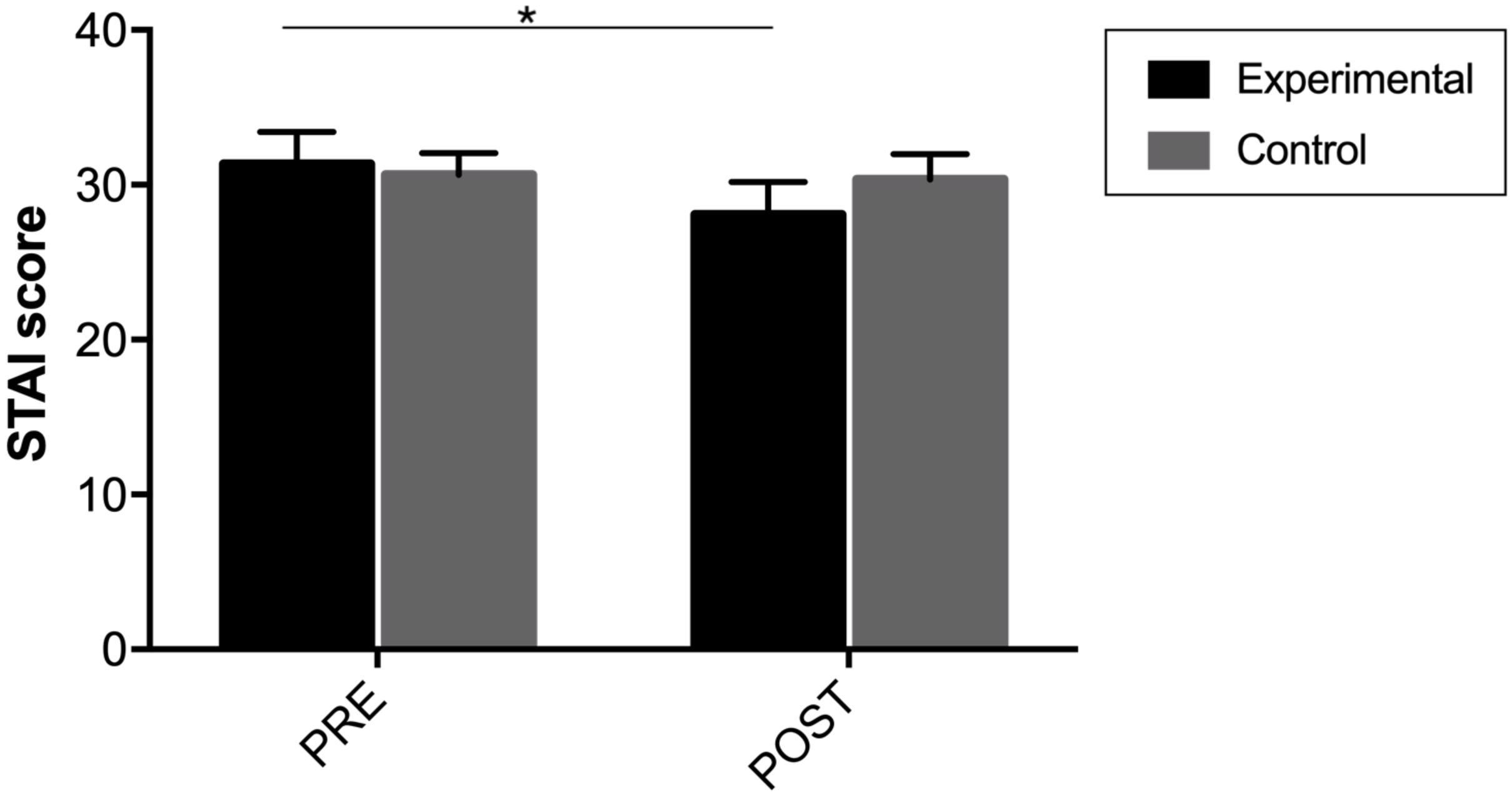

Figure5

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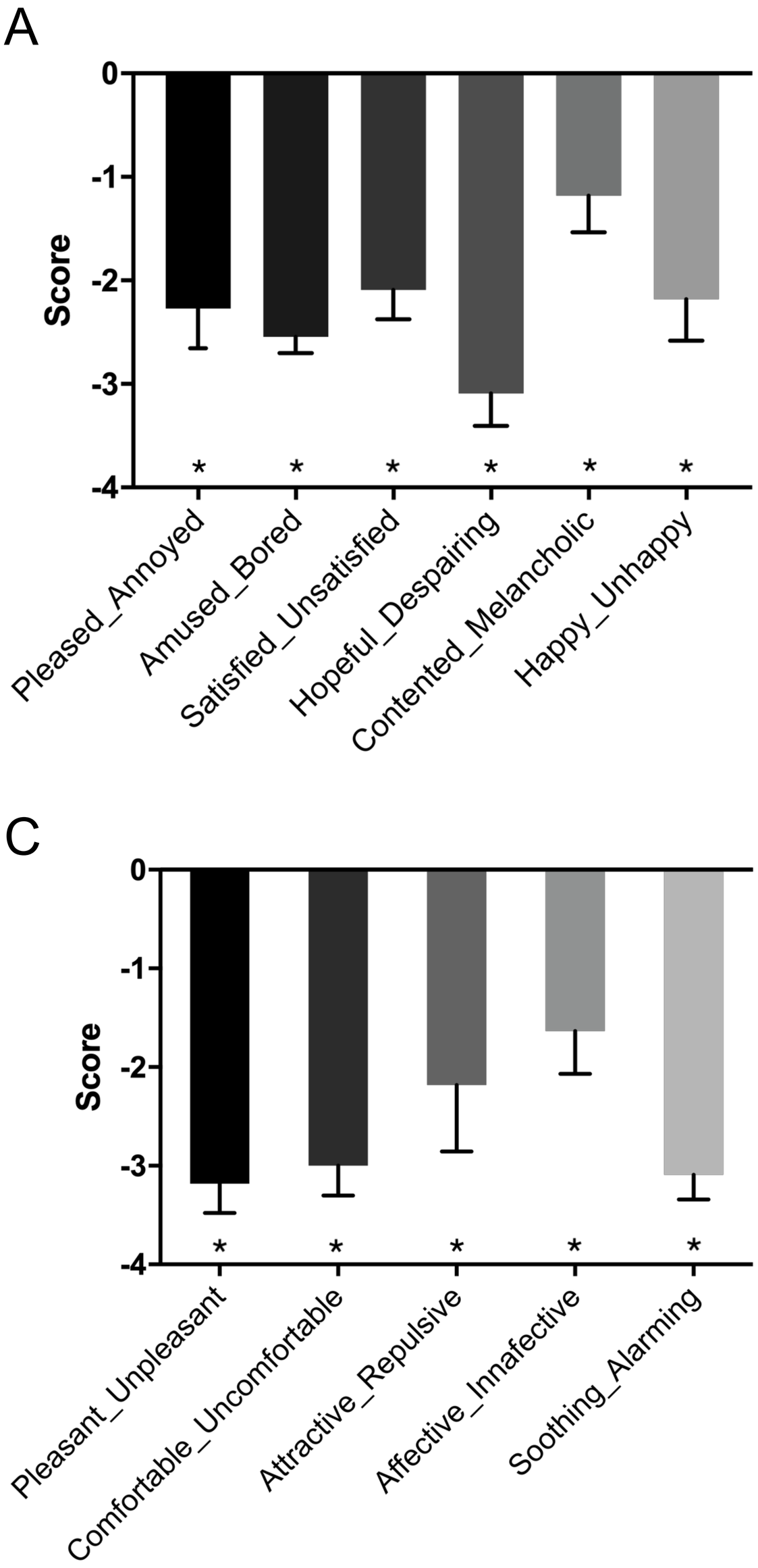

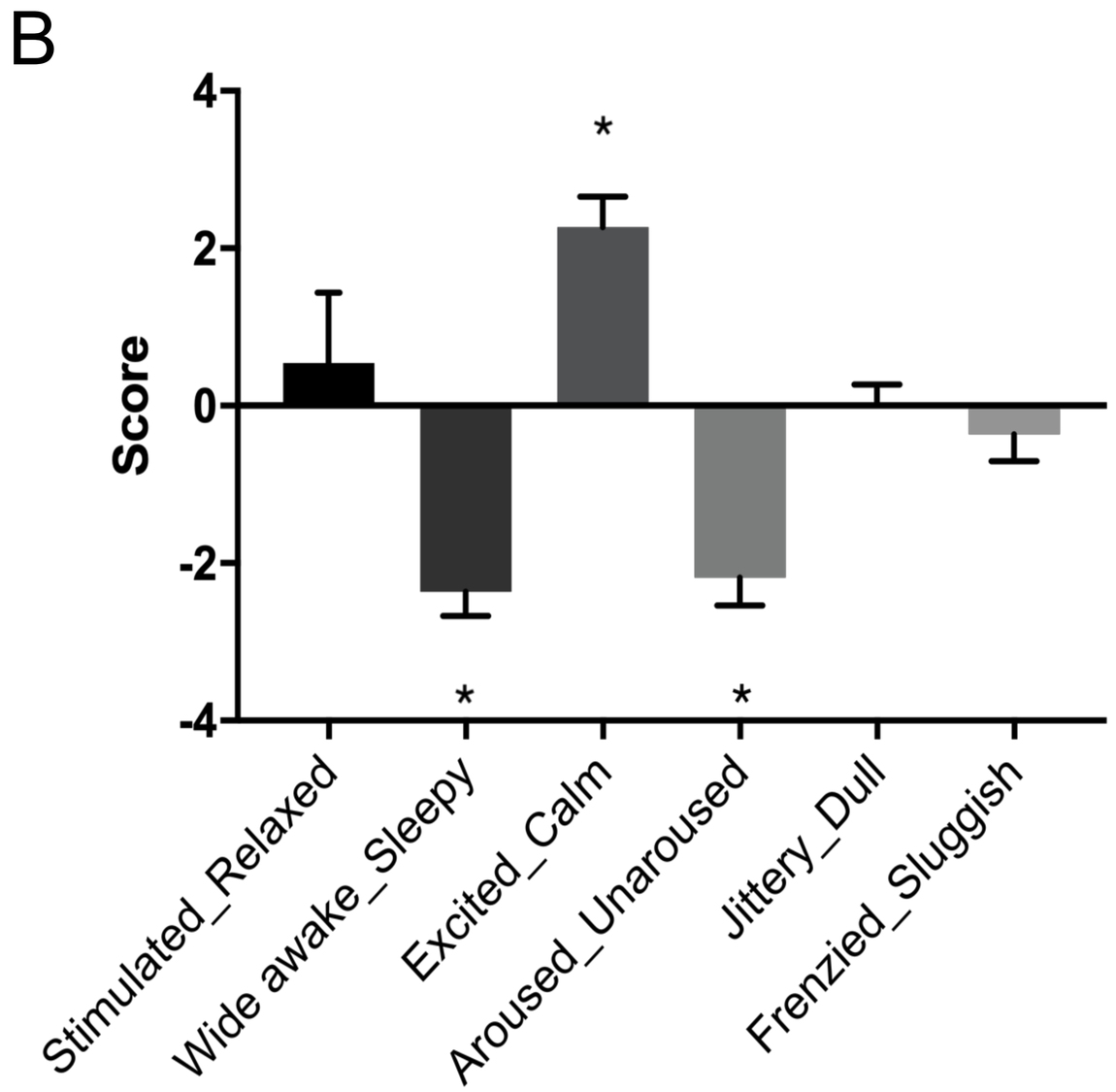

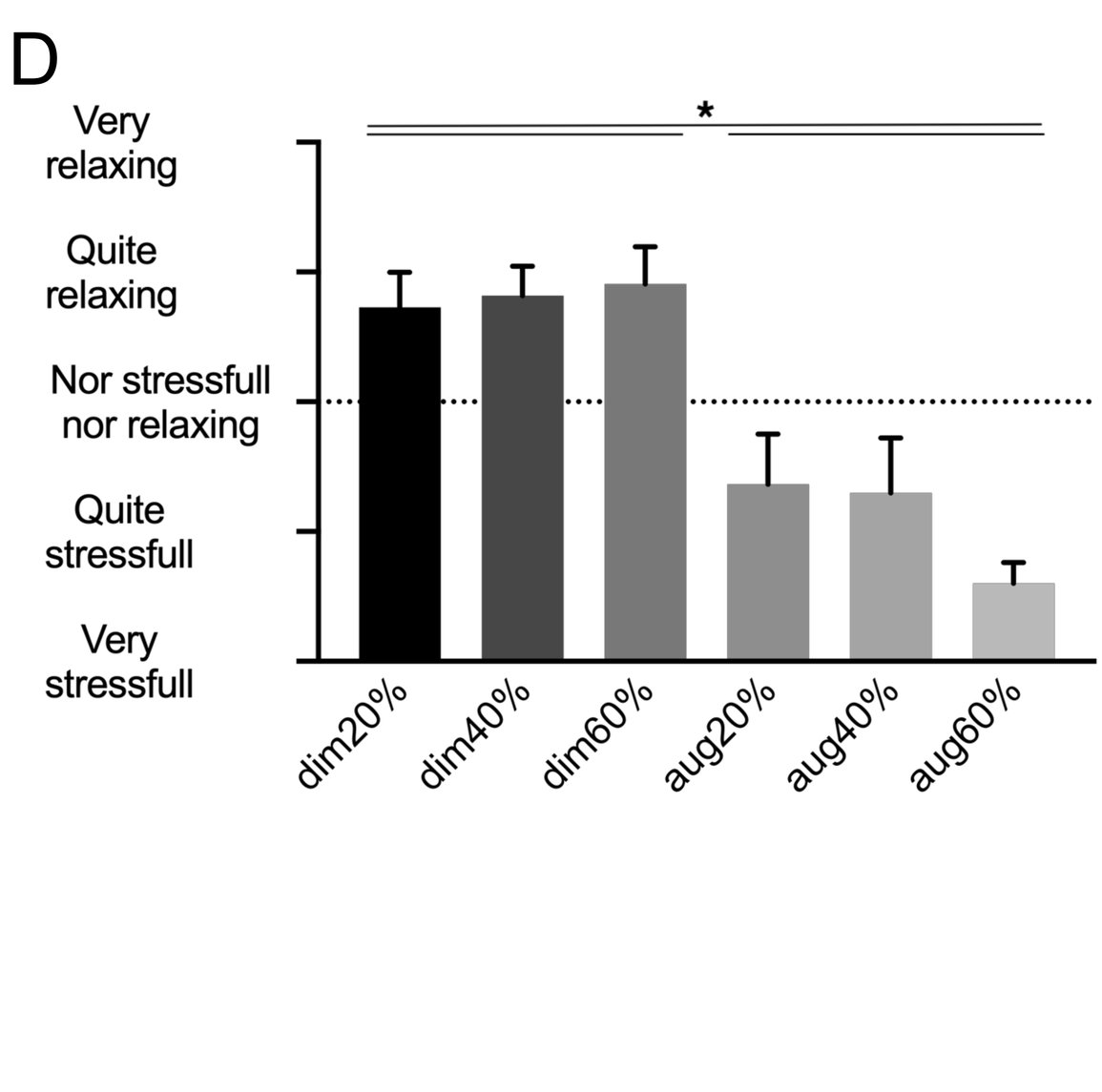

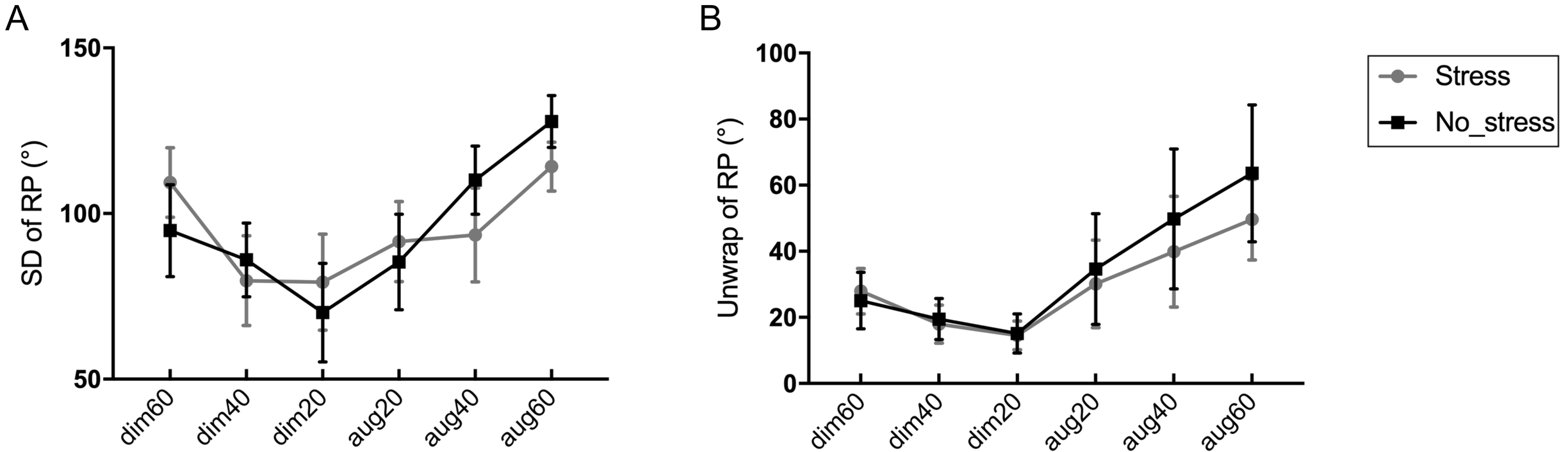

Figure7

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