

Affective CT-touch attenuates cortical responses and subjective attention during temporal summation of second pain

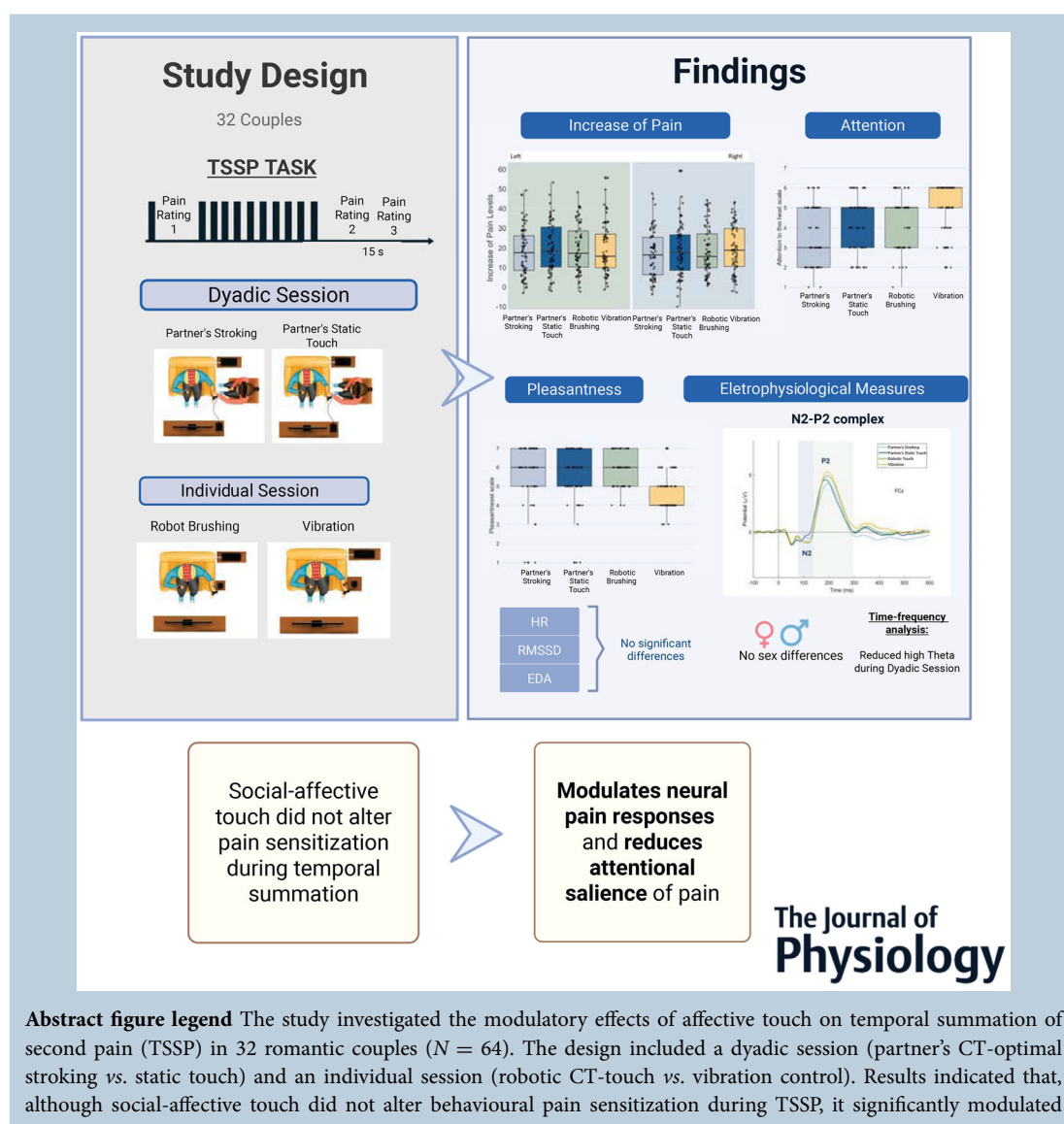
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neural pain responses. Specifically, partner touch attenuated the N2–P2 event-related potentials complex and reduced high-theta power compared to control conditions. These electrophysiological changes were accompanied by decreased attentional salience toward the noxious stimuli. No significant differences were found for autonomic measures (heart rate variability, root mean square of successive differences and electrodermal activity) or sex. Collectively, these findings suggest that affective touch downregulates the cortical processing and attentional salience of pain, even when subjective sensitization remains unchanged.

Abstract The activation of C-tactile (CT) mechanoreceptors is typically experienced as pleasant touch and has been proposed to have analgesic effects. However, its influence on central sensitization across social and non-social contexts remains unclear. We investigated whether CT-touch in social (romantic partner) and non-social (robotic arm) contexts influences the development of temporal summation of second pain (TSSP), a paradigm associated with central sensitization. Thirty-two couples completed a TSSP protocol across four conditions in two sessions: dyadic session (TSSP during CT-optimal stroking or static touch by the participant's romantic partner) and individual session (TSSP during robotic CT-touch or vibration). Outcomes included subjective pain ratings, attention to heat stimuli, pleasantness, electroencephalographic activity (N2–P2 event-related potentials and midfrontal theta activity), autonomic responses and sex-related effects. No condition differences were found in the reported pain increase. Attention to painful heat was lower during partner's stroking and higher during vibration, the least pleasant stimulus. At the neural level, the smallest N2–P2 amplitudes occurred during partner's stroking, followed by static touch, robot brushing and vibration. Reduced midfrontal theta activity was observed in dyadic compared to individual contexts. No differences emerged in autonomic indices or sex comparisons. Using a large sample and naturalistic stimuli, we found that affective CT-touch does not affect pain levels or autonomic activity during TSSP, yet it decreases attentional focus on the nociceptive input and associated neural responses. These findings underscore social-affective touch as a naturalistic mechanism for modulating pain salience, raising new questions about how it shapes neural dynamics of pain regulation.

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Key points

- Affective C-tactile (CT) touch has no effect on temporal summation of second pain.
- Social context matters: partner-administered CT-touch reduced attention to nociceptive heat and attenuated N2–P2 event-related potentials compared with robotic or vibration stimuli.
- Midfrontal theta activity was lower in dyadic (social) vs. individual (non-social) contexts, suggesting neural markers of pain salience are context-dependent.
- Findings highlight social-affective touch as a naturalistic mechanism for modulating the salience of painful stimuli, offering insights into pain regulation and the neural dynamics of central sensitization.

Márcia Silva is a PhD candidate in Psychological Neuroscience at the University of Minho, with a background in Biochemistry and a Master's degree in Neurobiology. Her research investigates the analgesic effects of affective touch and the role of C-tactile (CT) afferents in pain modulation, focusing on paradigms foundational to chronic pain, including temporal summation of second pain and secondary hyperalgesia. She employs individual and dyadic experimental designs, integrating behavioural, electrophysiological (EEG), and autonomic measures (ECG and electrodermal activity).



Introduction

Temporal summation of second pain (TSSP) refers to the increase of pain perception caused by repetitive noxious stimuli at constant intensities, at a specific frequency (≥ 0.33 Hz) (Price, 1972). This frequency corresponds to the natural discharge frequency of the peripheral C-nociceptors under minimal painful stimulations (Torebjörk & Hallin, 1974). The repeated activation of C-fibres induces a progressive increase in the excitability of dorsal horn neurons, a phenomenon known as ‘wind-up’, which is the neurophysiological basis of the TSSP. As such, TSSP is considered a psychophysical model for studying central sensitization and hyperalgesia (Herrero et al., 2000). Importantly, however, TSSP also engages supraspinal processes. Neuroimaging studies demonstrated that TSSP is associated with the activation of brain regions involved in the affective and cognitive dimensions of pain (e.g. insula, anterior cingulate cortex or prefrontal cortex), as well as areas related to somatosensory processing (e.g. contralateral thalamus, S2) (Staud et al., 2007a, 2008).

Over the last few years, several studies have begun to investigate the analgesic effects of affective touch, initially within acute pain paradigms (Krahé et al., 2016; Liljencrantz et al., 2017; López-Solà et al., 2019; von Mohr et al., 2018b) and more recently in the context of chronic pain (Fusaro et al., 2022). This research has focused particularly on C-tactile (CT) afferents, comprising C-fibres that respond preferentially to slow gentle stroking (1 and 10 cm s⁻¹, peaking around 3 cm s⁻¹), which are implicated in the pleasant and socially relevant aspects of touch (Ackerley et al., 2014; Löken et al., 2009; McGlone et al., 2014). We previously demonstrated that CT-targeted stimulation modulates cortical correlates of nociceptive processing, during a TSSP paradigm, reflected in reduced N2–P2 event-related potentials (ERPs) complex compared to no touch and vibratory conditions (da-Silva et al., 2024). Specifically, we observed a decrease in the N2–P2 ERPs complex during CT-targeted stimulation, both compared to TSSP presented without concurrent stimulation and to TSSP delivered concomitantly with vibration. Wakui et al. (2025) further corroborated these findings by showing that neutral CT-stimulation produced specific EEG changes during TSSP, such as reductions in beta frequency power, when compared with discriminative touch, and a decrease in delta, theta and beta when compared with no touch. Moreover, frontal theta oscillations have been shown to be attenuated during affective touch compared to non-affective touch (von Mohr et al., 2018a). According to the model proposed by Meijer et al (2022), such effects probably involve the integration of bottom-up CT afferent signals with top-down contextual information within overlapping affective-motivational pain networks. CT-related input is processed in the insular cortex and

interacts with anterior cingulate and prefrontal regions, which are implicated in affective appraisal, attention and pain salience. Within this framework, CT-targeted stimulation primarily modulates cortical processing of nociceptive input during TSSP, via supraspinal attentional and affective processes, rather than spinal sensitization mechanisms per se.

Although CT-targeted stimulation in experimental settings is often referred to as ‘affective touch’, it is important to distinguish between the neurophysiological properties of the fibres themselves and the emotional valence of the touch experience (Schirmer et al., 2023). It is not the CT input alone that makes touch affective, but rather the context, social relevance and emotional meaning attributed to it (Sailer & Leknes, 2022). In this sense, affective touch is a multidimensional phenomenon, shaped by both bottom-up sensory signals and top-down cognitive-affective processes. This social-affective dimension of CT-stimulation is better captured using social experimental settings that simulate natural/real social interactions.

One of the social contexts in which the potential effect of affective touch on pain modulation can be studied is the context of romantic relationships. Physical touch provided by a significant other attenuates the activation of brain regions involved in emotional and behavioural threat responses (Coan et al., 2006). It can reduce the perception of pain (Mazza et al., 2023b) and promote physiological synchrony between partners (Chatel-Goldman et al., 2014). Affective touch, provided by a partner, elicits robust and consistent changes in physiological activity, reflected in both heart rate variability (HRV) and electrodermal activity (EDA) (Chatel-Goldman et al., 2014). It is possible that touch provided by a romantic partner may serve as a subtle, yet effective channel for conveying and receiving emotional support, reducing distress even in the absence of explicit communication (Robinson et al., 2015). Furthermore, touch from a romantic partner that serves as an attachment figure may act as a safety signal (Eisenberger et al., 2011), which could, overall, provide a socially supportive environment and, in this way, down-regulate the saliency of a forthcoming painful stimulus.

Additionally, exploring sex differences in both pain perception and social touch is essential for interpreting behavioral and neural responses in both clinical and experimental settings. Previous studies, particularly in the context of social touch research, have included only female participants (Krahé et al., 2015; von Mohr et al., 2018b). Evidence suggests a notable sex-related asymmetry in the perceived pleasantness of affective touch, where women demonstrate higher pleasantness ratings compared to men (Russo et al., 2020). Women not only tend to react more positively to touch (Stier & Hall, 1984), but also report a greater frequency of positive tactile interactions throughout their lives (Webb & Peck,

2015). Similarly, in the field of pain research, women have been shown to exhibit greater sensitivity to subtle temperature changes and enhanced sensitivity to pain, having a better capacity to discriminate the intensity of painful thermal stimuli compared to men (Feine et al., 1991; Meh & Denislic, 1994). Lastly, some chronic pain conditions appear to be more prevalent among women, such as temporomandibular disorder, fibromyalgia and osteoarthritis (GBD 2021 Osteoarthritis Collaborators, 2023; Sarlani & Greenspan, 2005; Tsang et al., 2008).

In this study we investigated whether the presence and active involvement of a romantic partner, through stroking or static touch, modulated cortical processing of repeated nociceptive input during TSSP compared to matched tactile conditions delivered in the absence of social interaction (vibratory or CT-optimal stimulation delivered by a robot). By incorporating both a dyadic and an individual setting, our design allowed us to disentangle the contribution of social-affective factors from purely sensory input. We predicted that touch delivered by a romantic partner, at an optimal CT-velocity, would produce stronger attenuation of TSSP than static touch, robot-delivered CT-targeted touch or vibrotactile stimulation. We also predicted that this attenuation would be observed at the neural level, in both ERPs and time-frequency data. We expected to observe reduced amplitude of the nociceptive-related N2–P2 ERPs complex, which is sensitive to the salience and modulation of pain (Iannetti et al., 2008; Lorenz & Garcia-Larrea, 2003). Furthermore, we anticipated that affective partner touch would result in distinct patterns in time–frequency EEG dynamics, such as a decrease in theta power, that is associated with the salience and attentional processing of pain. Given the established role of these electrophysiological measures in indexing supraspinal processing, these predictions concerned cortical modulation of nociceptive input rather than direct modulation of spinal wind-up or central sensitization mechanisms. At the level of autonomic arousal, we further hypothesized that affective touch delivered by a romantic partner would be associated with reduced physiological arousal during TSSP, reflected in lower EDA and increased parasympathetic cardiac control, indexed by higher HRV, compared to non-affective and non-social tactile conditions.

We assessed the attention toward the noxious stimuli and the perceived pleasantness of the stimulations applied concomitant with TSSP. We predicted that, even in the presence of a nociceptive stimulus, touch from a romantic partner would capture more attentional resources than other types of stimulation and would be rated as more pleasant. Furthermore, considering sex differences in pain research, we aimed to explore sex differences across all variables, anticipating distinct patterns in behavioural, physiological and neural responses between men and

women. In this study, we provide a novel multimodal insight into how a dyadic TSSP paradigm allows the dissociation of social-affective influences from purely sensory stimulation, by directly contrasting CT-targeted affective touch delivered by a romantic partner with matched CT-targeted or non-CT tactile inputs delivered in non-social conditions. By combining behavioural reports with autonomic (ECG and EDA) and cortical (EEG) measures, this approach enables a comprehensive assessment of how socially embedded touch modulates pain processing across multiple levels, extending beyond self-reported experience.

Methods

Ethical approval

The study was conducted in accordance with the *Declaration of Helsinki* and received approval by the Ethics Committee for Social and Human Sciences of the University of Minho (CEICSH 030/2022). All participants provided their written informed consent before the experiment, acknowledging the voluntary nature of their participation and their right to withdraw at any time. The study was preregistered on the Open Science Framework prior to data collection (osf.io/ebtj7/).

Participants

Sixty-four participants (32 couples, 18–41 years old, mean \pm SD = 25.3 \pm 5.7 years; 33 male, 31 female) participated in the study. Couples were recruited through the University of Minho Credits platform, social media, advertising flyers and a snowball procedure. To be eligible, both partners had to be in a stable romantic relationship for at least 1 year. Participants with previous history of cardiac, psychiatric or neurological conditions, history of chronic pain, substance abuse, pain on the day of the experiment, or injured skin on the forearms or hands were excluded from the study. Additionally, participants were required to be in a stable relationship for a minimum of 1 year. The participants were not informed about the actual hypotheses of the study. Participants who were University students were rewarded with course credits, whereas non-student participants received vouchers for a value of €60.

Experimental procedure

Upon arriving at the laboratory, participants were briefed on the study protocol and signed the informed consent. They were then taken to a room where an EEG cap was fitted and the electrodes were attached for electrophysiological recording. During this process,

they completed sociodemographic questionnaires. Subsequently, participants were seated comfortably in a chair within a room with controlled lighting, electrical shielding, and soundproofing. A 4 min resting state period, with eyes open, was recorded before the task.

TSSP task. The study consisted of four conditions, divided into two separate sessions: a dyadic session and an individual session. The order of both sessions was counterbalanced across participants.

Before the experiment, participants had straps placed on both wrists to secure the heat stimulator in place, allowing their hands to remain free. The heat stimulator was positioned on the dorsal aspect of the first interdigital web space. A calibration of the temperature was performed for both sessions and on both hands and then kept constant throughout the task. The method of limits was used for calibration, with the initial temperature set at 47°C. It was then adjusted upward or downward until participants rated the pain between 30 and 50 on a scale of 0–100 following a block of 10 thermo-nociceptive stimuli. Then, participants switched the heat stimulator to the other hand to ensure consistency of the pain levels at the same temperature.

Initially, in each block, the screen displayed instructions indicating which hand the participants had to attach the nociceptive stimulator to. Afterwards, participants received a single nociceptive heat stimulus lasting 900 ms and had to evaluate the intensity of the pain on a numerical pain scale (NPS1) with verbal anchors ranging from 0 to 100. On the scale 0 represented 'no sensation'; 10 – 'warm'; 20 – 'mildly painful sensation' (i.e., pain threshold); 30 – 'very weak pain'; 40 – 'weak pain'; 50 – 'moderate pain'; 60 – 'slightly strong pain'; 70 – 'strong pain'; 80 – 'very strong pain'; 90 – 'nearly intolerable pain'; and 100 – 'unbearable pain'. The 0–100 NPS scale was decided based on previous studies using similar protocols (Staud et al., 2007a, 2007b). After providing their initial rating, participants received a block of eleven consecutive stimuli, delivered at a frequency of 0.33 Hz. Each stimulus had 900 ms of contact duration with the skin, followed by 2100 ms of no contact.

Following the final stimulus in the block, participants were asked to provide a second pain rating (NPS2), followed by a third NPS presented 15 s later (NPS3).

Across the two sessions, each condition consisted of six blocks. During all conditions, touch (stroking, static, robot or vibration) was applied to the left forearm, whereas nociceptive heat stimuli were alternated between the left and right hands. For each condition, participants received three blocks with heat on the left hand and three blocks with heat on the right hand. To reduce potential carry-over effects, blocks of the same condition were presented consecutively (e.g. two consecutive blocks of static touch

with alternating hand stimulation), followed by blocks of the next condition. The order of blocks and hand laterality was counterbalanced across participants and sessions to ensure consistency and control for order effects (Fig. 1).

Heat stimulation. The nociceptive stimulation was performed using an in-house-built stimulator comprising a 1.4×1.4 cm Peltier thermode. Temperature monitoring was achieved through a thermistor (TT6-10KC8-9-25; Tewa Sensors, Lublin, Poland) attached to the Peltier, designed to measure temperature changes with high sensitivity and accuracy.

Additionally, the device also incorporated a solenoid motor housed, enclosed within a casing to move the Peltier plate up and down, facilitating precise contact with the skin or withdrawal as required.

Individual session. In the individual session, participants remained alone during the entire session. In this session, participants received stroking with a brush or vibration on the left dorsal forearm during the 11 consecutive heat stimuli.

Stroking. The stroking was performed using a cosmetic brush ($\sim 2.5 \times 2.5$ cm), on the participants' right dorsal forearm (covering an area of 14 cm in length-proximal to distal and 2.5 cm wide). The brush was attached to a stimulator arm, ensuring a consistent optimal stroking velocity of 3.5 cm s^{-1} , which closely approximates the CT-optimal velocity reported in the literature ($\sim 3 \text{ cm/s}$) for eliciting maximal activation of C-tactile afferents (Ackerley et al., 2014). The entire stroking had a duration of 4100 ms and the brush was not in contact with the arm while changing direction. During the TSSP block, a total of six strokes were applied.

Vibration. The vibration was carried out using a custom-built vibrotactile stimulator composed of two small linear resonant actuators at a frequency of ~ 200 Hz. The actuators were housed in a 3D printed plate (6×2.5 cm) attached to the participant's forearm (adjacent in the medial direction) using adhesive tape.

Before the task, participants had to calibrate the intensity of the vibrotactile stimulation to match the perceived intensity of the stroking. The speed or pressure of the stroking remained constant and participants could only adjust the intensity of the vibration. They had to increase or decrease the intensity of the vibration using the computer mouse on a visual analogue scale (VAS) until it matched the perceived intensity of the stroking. The VAS ranged from '0,' described as 'minimum,' to 10, described as 'maximum.' When they were confident that the two intensities were similar, they clicked the 'accept' button. The calibration was repeated three times, and the intensity was set as the average of the three calibrations.

Participants could repeat the procedure if they felt that it was not calibrated properly.

As a result of the design of the stimulation devices and for simplification of the experimental protocol, the non-nociceptive stimulation (brushing or vibration) was always applied to the left arm.

The vibration condition was included as a non-affective, non-social and dynamic sensory control. High-frequency vibrotactile stimulation primarily activates fast-conducting $A\beta$ low-threshold mechanoreceptors and minimally engages CT afferents, particularly at frequencies above 50 Hz (Wiklund Fernström et al., 2002). Using vibration at 200 Hz therefore allowed us to control for the presence of concurrent dynamic somatosensory input at the same time as minimizing CT afferent recruitment and affective touch processing.

Dyadic session. In this session, participants were accompanied by their romantic partners throughout the entire procedure. During the eleven consecutive heat stimuli, participants received partner-mediated hand stroking or static touch on their left dorsal forearm.

For the stroking condition, an area of 14 cm in length was drawn on the participants' left forearm. The partner performing the stroking wore headphones that played auditory cues to guide their movements. Verbal commands ('start stroking' and 'stop stroking') indicated when to begin and end each movement. Between these commands, a series of brief pacing beeps (200 ms duration, 500 Hz frequency) was played to help them maintain the required pace.

In the static hand condition, the partners followed the same auditory instructions to start and stop the movement. Additionally, they were instructed to avoid applying any force and simply rest their hand on the participant's forearm.

During both stimulations, when the partners were instructed to stop the movement, they had to raise their arm to prevent any possible contact.

To ensure that the partner understood the instructions and executed the movements accurately, as well as to make sure participants receiving the nociceptive stimulation understood all the instructions, a short training task was performed. This training consisted of one block for each condition. A training session was also performed in the individual session.

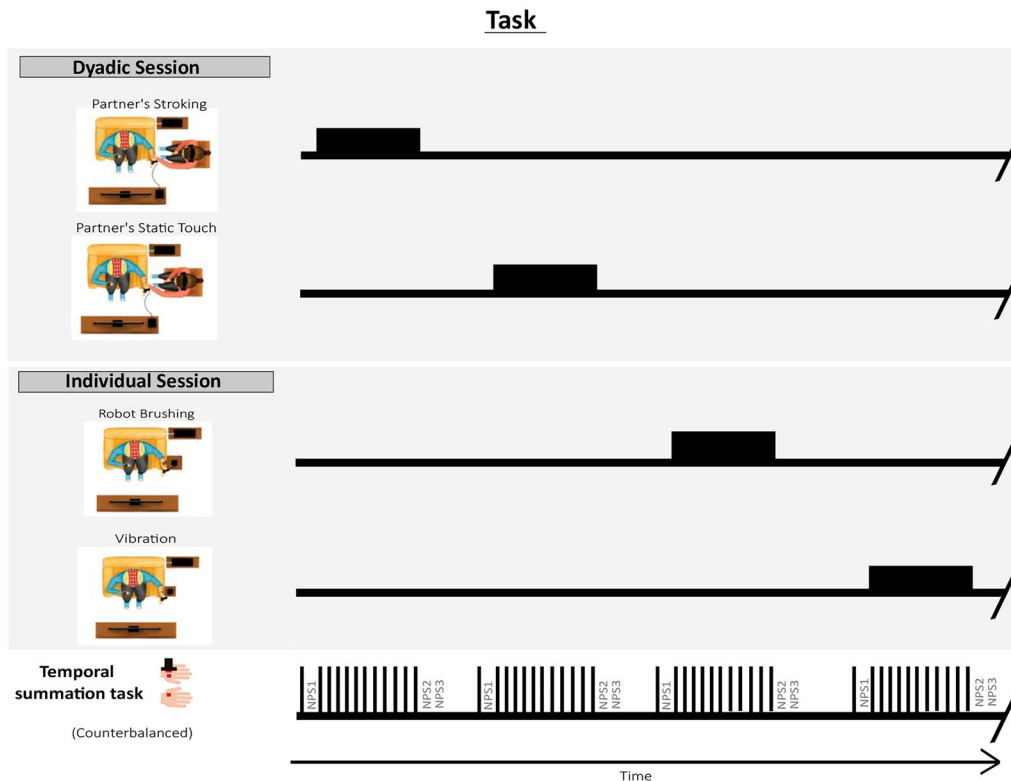


Figure 1. Schematic representation of the TSSP task experimental conditions

The task was divided into two sessions: a dyadic session where participants were accompanied by their romantic partner and an individual session where participants were alone. In the dyadic session, experimental conditions were: TSSP concomitant with partner's stroking or partner's static touch. In the individual session, experimental conditions were: TSSP concomitant with robot brushing or vibration. The order of the sessions was counterbalanced among the participants.

The inclusion of both dynamic (stroking) and static partner-mediated touch conditions was intended to dissociate the contribution of CT-optimal sensory input from the broader social-affective meaning of interpersonal touch. Although slow stroking at CT-optimal velocities maximizes CT afferent recruitment, static touch is considered non-CT-optimal in terms of dynamic activation yet retains high social relevance and support salience when delivered by a romantic partner. This design allowed us to examine whether modulation of nociceptive processing during TSSP depends primarily on the sensory characteristics of touch (i.e., dynamic CT-targeted stimulation) or whether socially meaningful, static contact, despite minimal movement, can exert comparable effects through contextual and affiliative mechanisms. By contrasting dynamic and static partner touch, we aimed to disentangle CT-related mechanisms from the social-affective dimension inherent to interpersonal touch.

Attention to heat and pleasantness measurements. At the end of each session, participants had to answer a short questionnaire where they were asked about their level of attention to the heat stimuli in each task condition, using a seven-point Likert scale (where '1' indicated that 'attention was not at all on the thermal stimulus but on other things' and '7' indicated that 'attention was completely on the thermal stimulus').

They also replied about the pleasantness of each type of stimulation (partner's stroking, partner's static touch, robot brushing and vibration) using a seven-point Likert scale (where '1' indicated 'very unpleasant' and '7' indicated 'very pleasant').

Electrophysiological data

EEG recordings. The recording of EEG data was performed using the BioSemi ActiveTwo system (Biosemi, Amsterdam, The Netherlands). The system was composed of a nylon cap with 64 active Ag/AgCl scalp electrodes and the location of the electrodes followed the international standard 10–10 system. Electrodes were referenced to the driven right leg (DLR) and common mode sense (CMS) Biosemi electrodes. Five additional active electrodes were positioned above the left eye (vertical electrooculogram – VEOG), in the lateral canthi of both eyes (horizontal electrooculogram – HEOG) and at the tip of the nose.

The electrocardiographic activity (ECG) was recorded by placing an electrode on the left clavicle.

Electrophysiological signals were sampled at a rate of 512 Hz, with an online bandpass filter applied between 0.01 and 100 Hz. Electrode offsets were kept below 30 mV prior to recording.

EDA was recorded using the James Four wireless psychophysiological device (MindProber Labs, Porto, Portugal) (Silva Moreira et al., 2019), with disposable electrodes placed on the participant's left palm. The signal was acquired using a sampling rate of 10 Hz.

EEG analysis. All electrophysiological data were analysed with the EEGLAB toolbox for Matlab (2024b) (MathWorks Inc., Natick, MA, USA). The data were imported and referenced to the tip of the nose, followed by a visual inspection of all the recording. An offline bandpass filter, from 0.1 to 30 Hz, was applied. Then epochs were extracted from the continuous data, with a time window of –1000 to 2000 ms relative to the onset of the stimulus, and a baseline correction was applied using a pre-stimulus interval from –200 to 0 ms. Epochs that remained noisy after the previous step were deleted. We then performed extended independent component analysis. Artefacts caused by eye blinks, ocular movements, muscle activity, or transient channel noise were identified using the ICLLabel toolbox (Pion-Tonachini et al., 2019) and manually removed after visual inspection.

The data were referenced to the average of all the scalp electrodes, and the mean of the extracted epochs was computed to obtain the ERP waveforms. The peak amplitude of both N2 and P2 components at the FCz electrode was measured. The N2 was considered the most negative peak from 90 to 150 ms, and P2 was considered the most positive peak from 150 to 300 ms after stimulus onset. The selection of the amplitudes and the electrodes was based on one of our previous studies where we used the same type of heat stimulation (da-Silva et al., 2024). To analyse the potential vertex amplitude of the N2–P2 complex, we computed the difference between the P2 and N2 amplitudes.

For the time–frequency analysis, we epoched the EEG data in the interval from –600 to 1500 ms relative to stimulus onset. The analysis was performed by convolving the epoched data with a family of complex Morlet wavelets ranging in frequency from 2 to 30 Hz in 25 logarithmically increasing steps, and with logarithmically increasing cycles, from three cycles at the lowest frequency to eight at the highest frequency. Following convolution, power data were baseline corrected by transforming the power change of each time-frequency pixel to decibels (dB), relative to the mean power in the baseline interval of each frequency. The baseline interval was from –300 to –100 ms to stimulus onset.

Because midfrontal theta activity is typically observed in frontocentral regions, we decided to focus the time-frequency analysis on the FCz electrode (Duprez et al., 2020). We averaged the power values across trials for the four conditions, generating a grand average to visually

inspect the overall pattern of activity and avoid biased selection. After visual inspection of this time-frequency window, we selected a frequency band of 4.4–7 Hz (theta frequency) and a temporal window from 140 to 240 ms post-stimulus. The selected region was used for statistical analysis.

ECG data were preprocessed with EEGbeats plugin implemented in EEGLAB. We applied an offline band-pass filter between 3 and 20 Hz, then the data were epoched in 33 s segments after the first noxious stimulus within the block of 11 nociceptive stimuli. A visual inspection across all trials was performed to guarantee that all R-peaks were detected. For each condition we extracted mean heart rate (HR) and measures of heart rate variability (HRV), such as: root mean square of successive differences (RMSSD) and high frequency (HF-HRV). These measures were chosen considering that HR refers to the average number of beats per minute and is widely used as a marker of physiological arousal, whereas RMSSD quantifies the variability in the time intervals between consecutive heartbeats, providing insight into the autonomic regulation of cardiac function (McCraty & Shaffer, 2015). The HF-HRV component represents the power of heart rate fluctuations within the high-frequency band (typically 0.15–0.4 Hz) and reflects parasympathetic (vagal) activity, which is associated with relaxation and restorative processes (Shaffer & Ginsberg, 2017).

EDA signals were preprocessed and analysed using custom scripts in Python with the NeuroKit2 library (Makowski et al., 2021). Raw galvanic skin response data were segmented per participant, condition and session. The segmentation was based on behavioural markers (synchronized timestamps) that were generated during the task. The data were interpolated to a uniform sampling rate of 10 Hz before processing. Each segment was decomposed into tonic and phasic components using NeuroKit's *eda_process* function, followed by peak detection on the phasic signal using *eda_peaks* function. From each segment, we extracted phasic features: number of skin conductance responses (SCRs), average and total SCR amplitude. These features were chosen given their relevance as indicators of sympathetic nervous system activity: SCR metrics reflect transient responses to discrete stimuli (Boucsein, 2012). Segments with signal artefacts detected visually were eliminated.

Statistical analysis

To explore the increase in pain levels across the different conditions, we followed a similar approach to one study from our research group (da-Silva et al., 2024). To evaluate the increase in pain levels, we subtracted NPS2 – NPS1 for each of the four conditions. Additionally, to investigate the possible effects on the return to baseline of pain levels after

Table 1. Descriptive statistics for the difference NPS2 – NPS1, averaged across left and right hands, for all experimental conditions

	N	Mean	SD	SE	Coefficient of variation
Partner's stroking	64	19.3	12.3	1.5	0.637
Partner's static touch	64	17.5	11.4	1.4	0.652
Robot brushing	64	19.3	11.7	1.5	0.605
Vibration	64	19.5	11.7	1.5	0.597

Note: N = number of participants; SD = standard deviation; SE = standard error.

the offset of nociceptive stimulation, we subtracted NPS3 – NPS2. Considering that the heat stimuli were applied in both hands and all somatosensory stimulation was applied only in the left arm, we computed a 2×4 mixed ANOVA, where hand (left and right) was entered as a factor, and the conditions (vibration, robot brushing, partner stroking and partner static touch) were entered as another factor. To further examine potential sex differences in pain ratings, sex was included as a between-subjects factor in the analysis.

To directly compare dyadic (partner stroking, partner static touch) vs. individual (robot brushing, vibration) conditions, we conducted a contrast within the 2×4 repeated measures ANOVA (the same factors as the previous ANOVA). The contrast weights were defined as +0.5, +0.5, –0.5 and –0.5 for the four conditions, effectively comparing the combined means of dyadic vs. individual conditions. Additional orthogonal contrasts (partner stroking vs. partner static touch, robot brushing vs. vibration) were included to satisfy model requirements. This dyadic vs. individual comparison was exploratory and was not included in the pre-registration.

To analyse the attention levels, the pleasantness, the difference in amplitudes of the N2–P2 complex, theta power and the ECG and EDA measures for the different conditions, we performed a mixed ANOVA where the four conditions were entered as a factor, and sex was entered as a between-subject factor. Then, *post hoc* comparisons were conducted using the Holm correction to control for multiple comparisons to explore differences between conditions. When the assumption of sphericity was violated, we performed a Greenhouse–Geisser correction.

Results

Reported pain levels

NPS2 – NPS1. Regarding the increase of pain ratings during the different conditions (for descriptive statistics, see Table 1) no significant condition effect was observed

($F_{1,268,78.596} = 0.840, P = 0.388, \eta_p^2 = 0.013$), neither an interaction of condition with sex ($F_{1,268,78.596} = 1.694, P = 0.200, \eta_p^2 = 0.027$). Even though the total increase of pain levels was higher in the left hand, this was not statistically significant ($F_{1,62} = 3.580, P = 0.063, \eta_p^2 = 0.055$; Fig. 2A and Table 1). By contrast to our hypothesis, partner's stroking did not significantly reduce the increase in pain ratings during TSSP when compared to robot-delivered CT stimulation, partner's static touch or vibration.

The contrasting analysis directly comparing dyadic conditions (partner's stroking, partner's static touch) with individual conditions (robot brushing, vibration) did not reveal significant differences in pain ratings ($t_{62} = -0.636, P = 0.527, \text{Cohen's } d = -0.086$).

We did not find any differences between the task temperatures between the two sessions ($W = 376, z = 0.676, P = 0.495, \text{SE} = 0.189$). These last two analyses were not included in the preregistration.

NPS3 – NPS2. To assess pain relief following the cessation of nociceptive stimulation, we analysed the difference between NPS3 and NPS2. Note that in the preregistration mistakenly stated NPS3 – NPS1 as the intended comparison. Contrarily to our hypothesis, we did not find a significant effect of condition ($F_{1,231,76.312} = 0.959, P = 0.349, \eta_p^2 = 0.015$) nor a significant interaction between condition and participants' sex ($F_{1,231,76.312} = 3.420, P = 0.060, \eta_p^2 = 0.052$).

Subjective ratings of the experimental conditions

Attention to the heat stimuli. We observed a significant condition effect on attention ($F_{3,183} = 21.892, P < 0.001, \eta_p^2 = 0.264$), but no significant interaction between attention and sex ($F_{3,183} = 1.126, P = 0.340, \eta_p^2 = 0.018$).

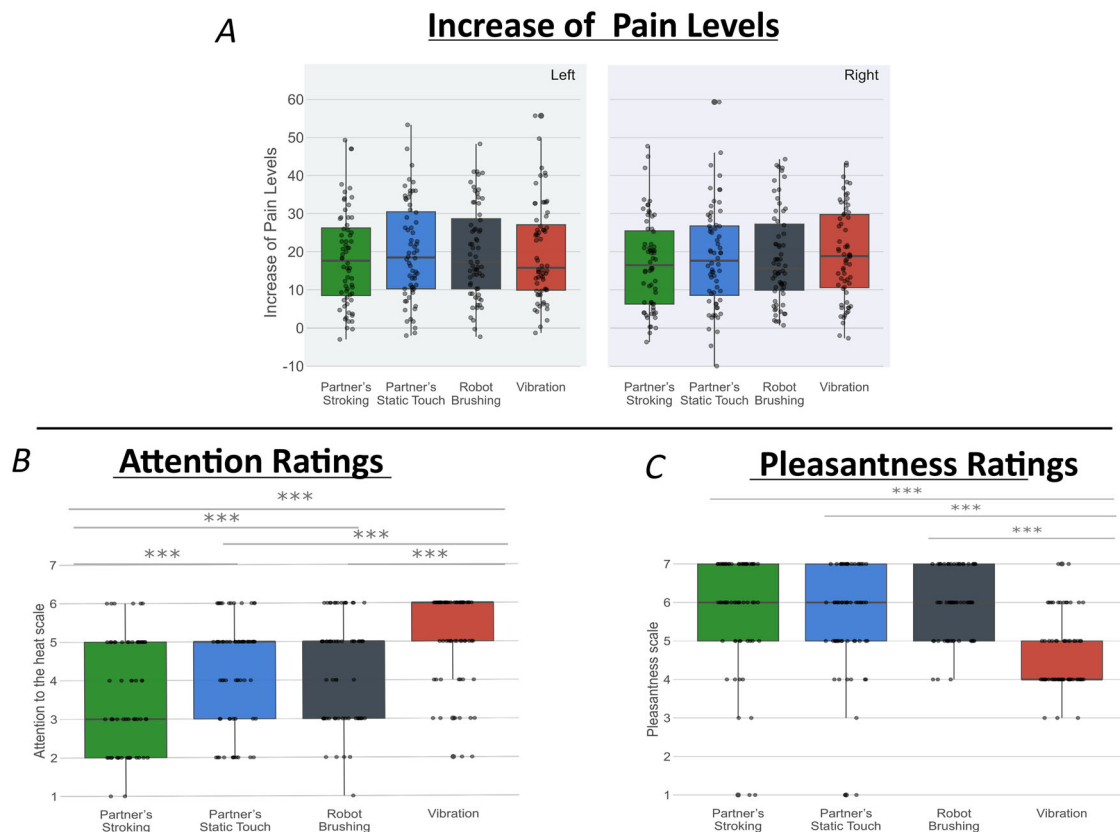


Figure 2. Boxplot with raw subjective ratings
 A- increase in the reported pain levels in both hands during the four experimental conditions (NPS2 – NPS1).
 B- reported attention levels to the heat stimuli across the different conditions. The scores of the heat attention questionnaire ranged from '1' ('attention was not all on the thermal stimulus but on other things') to '7' ('attention was completely in the thermal stimulus').
 C- pleasantness ratings of the somatosensory stimuli presented with the heat stimuli: partner's stroking, partner's static touch, robot brushing and vibration. The score of the pleasantness questionnaire ranged from '1' ('Very unpleasant') to '7' ('Very pleasant').

Table 2. *Post hoc* comparisons of the N2–P2 complex amplitudes between the four experimental conditions

Post hoc comparisons		<i>t</i>	Cohen's <i>d</i>	<i>P</i> _{Holm}
Partner's stroking	Partner's static touch	−2.489	−0.167	0.034*
	Robot brushing	−2.621	−0.334	0.034*
	Vibration	−3.780	−0.494	0.002**
Partner's static touch	Robot brushing	−1.484	−0.167	0.143
	Vibration	−3.078	−0.328	0.016*
Robot brushing	Vibration	−2.750	−0.160	0.032*

Post hoc analysis revealed that participants reported significantly lower attention to the heat stimuli during the partner's stroking compared to the other conditions ($P < 0.001$ for all comparisons). By contrast, they paid more attention to the heat during the vibration conditions compared to all the other conditions ($P < 0.001$ for all comparisons). No significant differences in attention were found between the brush stroking and hand rested conditions ($P = 0.813$; Fig. 2B). Consistent with our hypothesis, partner's stroking was associated with a reduced attentional focus on the nociceptive stimulus.

Pleasantness of the conditions. A significant condition effect of pleasantness was observed ($F_{2,187, 133.382} = 17.404$, $P < 0.001$, $\eta_p^2 = 0.222$) and the effect did not vary by sex ($F_{2,187, 133.382} = 0.962$, $P = 0.391$, $\eta_p^2 = 0.016$). Partially supporting our hypothesis, *post hoc* analysis revealed that the vibration condition was considered significantly less pleasant compared to the other conditions ($P < 0.001$ for all comparisons). However, no differences between the remaining conditions were observed (robot brushing vs partner's stroking: $P = 0.873$; robot brushing vs partner's static touch $P = 0.310$ and partner's stroking vs partner's static touch $P = 0.310$; Fig. 2C). Partner's stroking was not rated as more pleasant than robot-delivered CT stimulation or partner static touch.

Electrophysiological results

N2–P2 complex. At neural level, the results revealed a significant main effect of condition in the N2–P2 complex amplitude ($F_{1,595, 89.321} = 8.347$, $P = 0.001$, $\eta_p^2 = 0.028$). However, there was no significant interaction between conditions and participants' sex ($F_{1,595, 89.321} = 1.468$, $P = 0.236$, $\eta_p^2 = 0.005$). Note that six participants were eliminated from the analysis due to technical problems during EEG recording, making a total of 58 participants.

Post hoc analysis showed significant differences between all conditions (for detailed results, see Table 2) except between partner's static touch and robot brushing.

Consistent with our hypothesis, partner's stroking elicited the smallest N2–P2 amplitudes, followed by partner's static touch, robot brushing and, finally, vibration condition (Fig. 3 and Table 2).

N2–P2 complex: effects of lateralization. Given that TSSP heat stimuli were applied in a counter-balanced manner to both body sides, and that the additional somatosensory stimulation was consistently delivered to the left arm, we conducted an exploratory, non-preregistered analysis to examine lateralized effects. Specifically, we separated trials according to whether the somatosensory stimulation was applied contralaterally or ipsilaterally to the site of TSSP induction. Because the N2–P2 complex is a centrally distributed ERP component, we assessed its amplitude again in the FCz electrode. It is important to note that this approach decreases the signal-to-noise ratio of the ERPs, as splitting the data resulted in only half the number of trials compared to the original analysis.

A repeated-measures ANOVA was conducted on N2–P2 amplitudes with condition (partner's stroking, partner's static touch, robot brushing, vibration) and side (contralateral vs. ipsilateral to TSSP stimulation) as within-subjects factors. Across all conditions except vibration, N2–P2 amplitudes tended to be lower when somatosensory stimulation was delivered on the same side as the TSSP stimulation, suggesting potential lateralized modulation (Fig. 4). However, the main effect of side was not statistically significant, $F_{1,57} = 0.928$, $P = 0.340$, $\eta_p^2 = 0.016$. Means amplitudes were: partner's stroking (ipsilateral: $6.3 \pm 3 \mu\text{V}$, contralateral: $7.1 \pm 3 \mu\text{V}$), static touch (ipsilateral: $6.9 \pm 3 \mu\text{V}$, contralateral: $7.4 \pm 3 \mu\text{V}$), robot brushing (ipsilateral: $7.5 \pm 4 \mu\text{V}$, contralateral: $7.8 \pm 4 \mu\text{V}$) and vibration (ipsilateral: $8.7 \pm 4 \mu\text{V}$, contralateral: $7.8 \pm 4 \mu\text{V}$).

The analysis revealed a significant main effect of condition ($F_{1,570, 135.572} = 7.943$, $P = 0.002$, $\eta_p^2 = 0.122$), indicating that N2–P2 amplitudes significantly differed across the types of somatosensory stimulation (for *post hoc* comparisons, see Table 3). A significant

interaction between condition and side emerged ($F_{2,378,135.572} = 7.714, P < 0.001, \eta_p^2 = 0.119$), suggesting that the effect of somatosensory condition on N2–P2 amplitude varied depending on whether the stimulation was ipsilateral or contralateral to the TSSP application. *Post hoc* comparisons revealed that, when TSSP stimulation was applied ipsilaterally to the somatosensory stimulation, vibration elicited significantly greater N2–P2 amplitudes than partner’s stroking ($P < 0.001, \text{Cohen’s } d = -0.654$), partner’s static touch ($P = 0.002, \text{Cohen’s } d = -0.500$) and robot

brushing ($P = 0.001, \text{Cohen’s } d = -0.316$). Furthermore, vibration ipsilateral also produced significantly higher amplitudes than the partner’s stroking ($P = 0.023, \text{Cohen’s } d = 0.448$) and static touch ($P = 0.043, \text{Cohen’s } d = 0.355$), when both the partner’s stroking and the static touch were applied contralateral to the TSSP stimulation. Additionally, partner’s stroking on the ipsilateral side elicited significantly lower N2–P2 amplitudes than robot brushing on the contralateral ($P = 0.046, \text{Cohen’s } d = -0.421$). The comparison between affective-ipsilateral and static-contralateral did

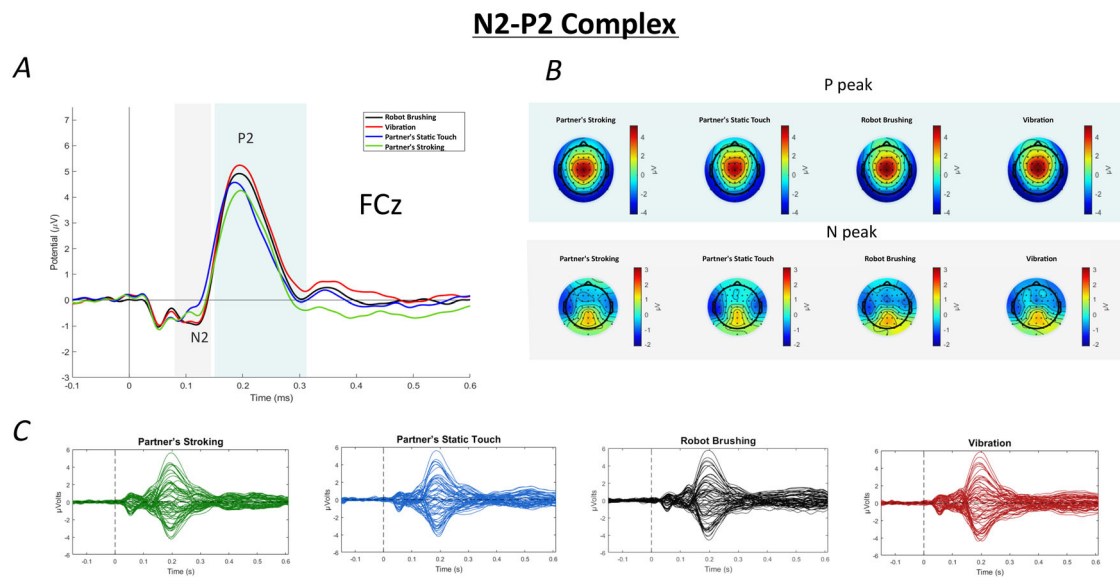


Figure 3. Results for the N2–P2 complex
 A, event-related potentials evoked by the presentation of nociceptive stimuli measured at the Fcz electrode. B, scalp topographies of the four experimental conditions corresponding to the P2 component (top) and N2 component (bottom), measured in the same time window as the ERP. C, butterfly plots with the overall ERP waveforms across all electrodes for each condition.

N2–P2 Complex at FCz

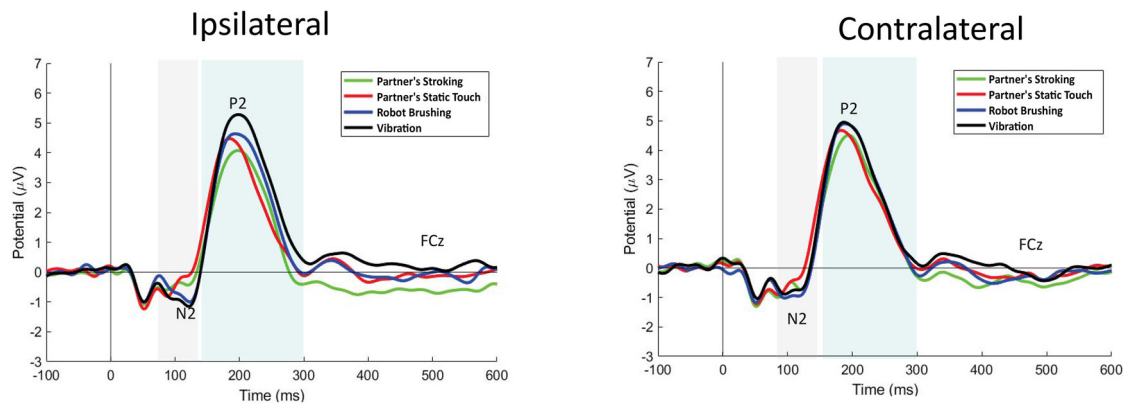


Figure 4. Results for the N2–P2 complex when nociceptive and tactile stimuli were applied to the same arm (ipsilateral) and when they were applied to different arms (contralateral)
 Nociceptive stimulations were performed in both arms while tactile stimulations were always performed on the left arm.

Table 3. *Post hoc* comparisons of the N2–P2 complex amplitudes between the four experimental conditions, considering when nociceptive and tactile stimuli were presented ipsilaterally or contralaterally

Post hoc comparisons		<i>t</i>	Cohen's <i>d</i>	<i>P</i> _{Holm}
Partner's stroking	Partner's static touch	−2.152	−0.123	0.071
	Robot brushing	−2.491	−0.276	0.047*
	Vibration	−3.606	−0.425	0.004**
Partner's static touch	Robot brushing	−1.563	−0.153	0.124
	Vibration	−3.060	−0.302	0.017*
Robot brushing	Vibration	−2.867	−0.149	0.023*

Table 4. *Post hoc* comparisons of the time-frequency midfrontal theta power between the four experimental conditions

Post hoc comparisons		<i>t</i>	Cohen's <i>d</i>	<i>P</i> _{Holm}
Partner's stroking	Partner's static touch	0.403	0.043	1.000
	Robot brushing	−2.676	−0.400	0.029*
	Vibration	−3.106	−0.466	0.015*
Partner's static touch	Robot brushing	−3.061	−0.443	0.015*
	Vibration	−3.567	−0.508	0.004**
Robot brushing	Vibration	−0.589	−0.065	1.000

not reach significance ($P = 0.064$). Full *post hoc* results are provided in the Appendix (Table A1).

Electroencephalographic time-frequency data. We analysed theta power from 4.4 to 7 Hz and 140–240 ms post-stimulus, and the mixed ANOVA results revealed a significant condition effect ($F_{2,384, 133.479} = 7.670$, $P < 0.001$, $\eta_p^2 = 0.120$); however, there was no significant interaction between conditions and participants' sex ($F_{2,384, 133.479} = 0.775$, $P = 0.483$, $\eta_p^2 = 0.014$). *Post hoc* analysis showed significant differences between the conditions that were performed in the different sessions (for the *post hoc* results, see Table 4), but it did not capture significant differences between conditions performed in the same session. Descriptive statistics revealed the lowest theta power during the dyadic conditions (partner's stroking: 1.84 ± 1.4 dB; partner's static touch: 1.76 ± 1.2 dB) and higher power levels in the individual setting conditions (robot brushing: 2.4 ± 1.7 dB; vibration: 2.5 ± 1.3 dB), suggesting more neural engagement in response to nociceptive input in the individual setting (Fig. 5 and Table 4). These results are partially consistent with our hypothesis because reduced theta power was observed in the dyadic relative to the individual setting, although no differences emerged between tactile conditions within the same session.

Table 5. Results of the mixed ANOVA performed for the analysis of the ECG measurements

		d.f.	<i>F</i>	<i>P</i>	η_p^2
HR	Condition	1.034	0.075	0.794	0.001
	Condition × Sex	1.034	1.971	0.166	0.035
rMSSD	Condition	1.089	0.966	0.337	0.017
	Condition × Sex	1.089	0.061	0.826	0.001
HF	Condition	1.082	0.587	0.460	0.012
	Condition × Sex	1.082	0.690	0.421	0.014

Abbreviations: HR, heart rate; HF-HRV, high frequency-heart rate variability; rMSSD, root mean square of successive differences.

ECG

In addition to the six participants who were eliminated from the EEG analysis, one further participant was excluded because of the poor quality of the signal, resulting in a total of 57 participants. Mixed ANOVA did not reveal any significant effect of condition on any of the ECG measures examined, including HR, rMSSD and HF-HRV. Additionally, no effect of sex was observed in the analysis (Table 5). In the rMSSD analysis, we excluded one outlier that was common in all conditions. By contrast to our hypothesis, partner's stroking was not associated with changes in cardiac autonomic indices measured.

Table 6. Results of the mixed ANOVA performed for the analysis of the EDA phasic component measurements

		d.f.	F	P	η_p^2
SCRs	Condition	1.336	0.769	0.419	0.012
	Condition × Sex	1.336	3.157	0.067	0.049
Average SCR amplitude	Condition	1.645	0.544	0.548	0.009
	Condition × Sex	1.645	1.409	0.248	0.023
Total SCR amplitude	Condition	1.501	0.795	0.422	0.013
	Condition × Sex	1.501	1.699	0.195	0.027

Abbreviation: SCR, skin conductance response.

EDA

One participant was eliminated from the analysis due to the poor quality of the signal, resulting in a total of 63 participants.

Mixed ANOVA did not reveal any significant effect of condition on any of the EDA measures examined (i.e. number of SCRs, average and total SCR amplitude) and no effect of sex was observed in the analysis (Table 6). Our hypothesis that partner’s stroking would

modulate electrodermal responses during TSSP was not supported.

Discussion

The present study examined whether social-affective touch modulates pain processing during TSSP using a multimodal approach. The adopted design enabled us to explore how affective touch modulates pain processing

Time-frequency analysis

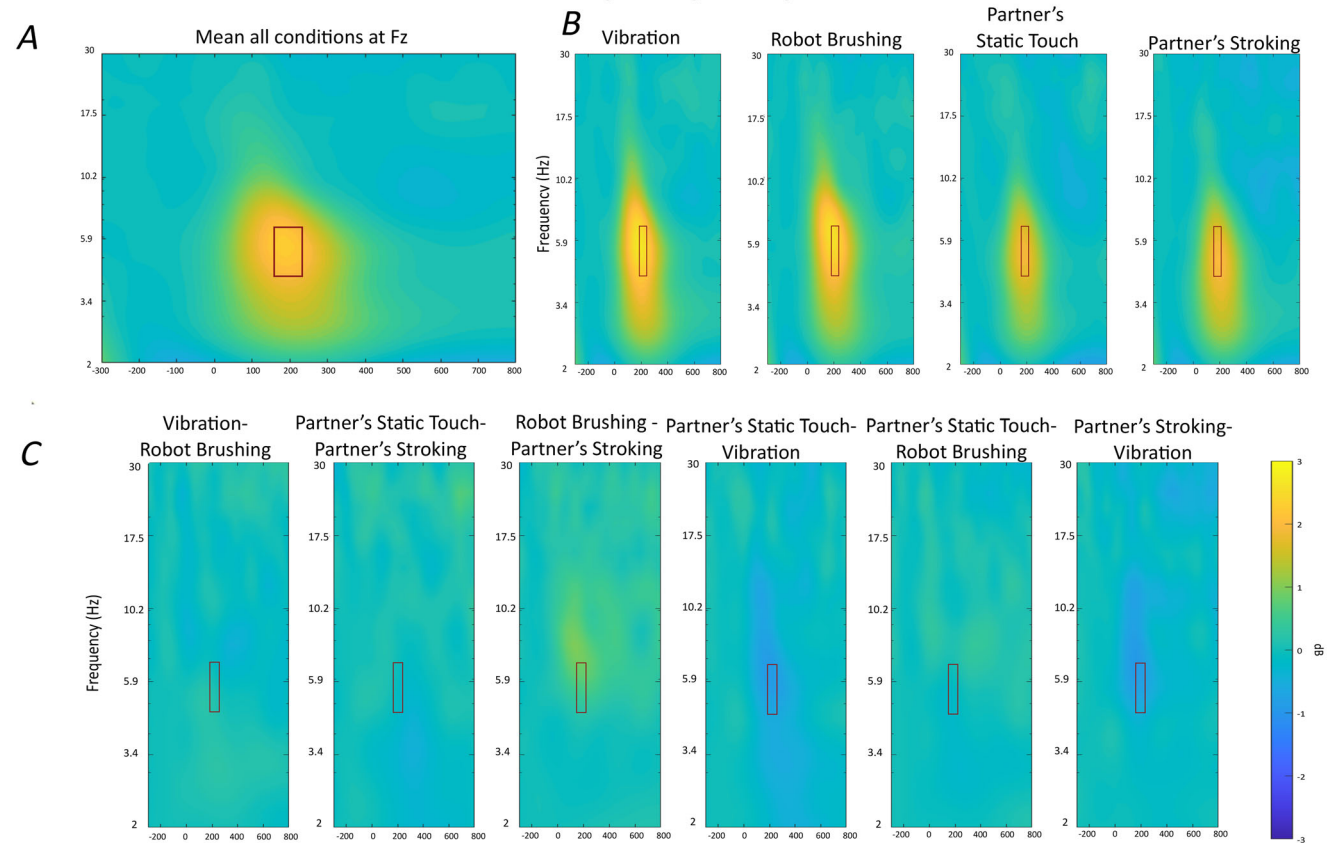


Figure 5. Spectrogram obtained by time-frequency analysis of the EEG evoked by nociceptive stimuli, measured at the FCz electrode
 A, mean of all conditions (used to select the window of interest- red rectangle). B, time-frequency plots for each condition. C, differences between each of the conditions.

at multiple levels. CT-optimal stimulation, whether social or non-social, did not affect pain ratings or autonomic measures (EDA and ECG-based). However, partner stroking at CT-optimal velocity significantly reduced reported attention towards noxious heat stimuli compared to static touch and non-affective tactile conditions (robotic stroking and vibration). Subjective pleasantness ratings did not significantly differ between partner stroking and the other conditions; vibration was consistently rated as the least pleasant. Clear differences emerged at the neural level. Partner's stroking elicited the lowest N2–P2 amplitudes, followed by partner's static touch, robot stroking and vibration, suggesting a graded modulation of salience-related cortical responses. In the time-frequency domain, we also found differences between the social and non-social conditions in the theta band. No sex differences were found in any outcomes, indicating the presence of similar effects across male and female participants. Importantly, these neural effects occurred in the absence of changes in behavioural or autonomic indices of TSSP, indicating modulation of cortical processing rather than spinal sensitization.

Humans naturally stroke their partners at CT-optimal velocities (Croy et al., 2016). Touch at CT-optimal velocities, whether delivered by human or a robot, has been shown to elicit similar levels of pleasantness (Triscoli et al., 2013), suggesting that both the sensory properties and the social context of touch contribute to its affective and regulatory potential. Previous studies have shown that social support in both implicit (e.g. presence) and explicit (e.g. physical contact) forms can attenuate pain perception (Goldstein et al., 2018; López-Solà et al., 2019). Considering the robust link established between the activation of CT-fibres and the perceived pleasantness of touch, this positive valence somatosensory modality might alter the significance of the sensation of pain and activate top-down analgesic mechanisms associated with pleasure (Björnsdotter et al., 2010). Pain modulation by CT-fibres may involve complex interactions among the somatosensory cortex, insula and anterior cingulate cortex (Meijer et al., 2022), with downregulation of these brain regions influencing motivational, emotional and autonomic aspects of pain processing (Sewards & Sewards, 2002). These effects should be observable in one of the most studied models of pain sensitization, the TSSP, which involves ascending facilitation mechanisms and descending inhibitory structures (Eckert et al., 2017; Rubal-Otero et al., 2024).

However, our study found no effect on TSSP, which was elicited equally across all conditions, even when touch was provided by romantic partners, whose touch may be more salient and pleasant than that of a neutral touch provider, such as a robot. These results do not align with previous literature, which has reported a decrease in TSSP in response to CT-optimal stimulation (Fidanza et al., 2021).

Despite using a relatively large sample and incorporating a naturalistic touch from real partners, TSSP was not reduced by CT-optimal stimulation, nor was the increase in pain smaller than without affective touch. This suggests that, under the present experimental conditions, social-affective touch did not modulate spinal wind-up or behavioural expressions of central sensitization, despite robust effects at the cortical level.

Even when applied during noxious stimuli, both the dyadic conditions and the robot stroking were generally rated as pleasant. Although CT afferent activation is known to contribute to the pleasant component of touch, our findings highlight that pleasantness is not exclusively determined by CT-optimal stimulation. Notably, static non-CT-optimal touch with higher support salience (occurring in the partner's static touch condition) elicited levels of pleasantness comparable to dynamic stroking. Although static touch does not provide the dynamic, velocity-dependent input that maximally engages CT afferents, it may still weakly recruit CTs through sustained skin contact and temperature, particularly in socially meaningful contexts (Ackerley et al., 2014; McGlone et al., 2014; Olausson et al., 2010). Importantly, touch delivered by a romantic partner carries high social and emotional salience, which can elicit pleasant experiences even in the absence of optimal CT stimulation. Therefore, the pleasantness associated with touch is not exclusively dependent on CT-fibre activation but is also shaped by contextual and meaningful factors surrounding the touch (Ali et al., 2023; Sailer & Leknes, 2022). By contrast, vibrotactile stimulation, dominated by $A\beta$ fibre activation and minimal CT engagement (Vallbo et al., 1999), was rated as the least pleasant sensation in our study. This aligns with previous studies reporting that vibration at 200 Hz is considered unpleasant (Nagi et al., 2011; Shaikh et al., 2015).

Nevertheless, at the neural level, nociceptive stimulation during the partner's stroking evoked the lowest amplitude of the N2–P2 complex, followed by the partner's static touch, the robot stroking, and the vibration. This aligns with our previous results (da-Silva et al., 2024) and indicates a graded modulation of cortical salience responses, possibly reflecting the combined influence of the social-emotional aspects of touch (e.g. partner stroking) and the sensory properties of the tactile stimulus (e.g. vibration or robotic stroking) on cortical nociceptive processing. The N2–P2 complex is considered a cortical signature of the conscious perception of nociceptive stimuli, reflecting both multimodal processing activity (Mouraux & Iannetti, 2009) and pain-related salience, with probably sources in the insula (N2) and anterior cingulate cortex (P2) (Garcia-Larrea et al., 2003; Lee et al., 2009). The attenuation of the N2–P2 complex has also been linked to $A\beta$ fibre stimulation, suggesting that such modulation may occur via

subcortical mechanisms regulating nociceptive input, which in turn results in a modulation of cortical responses, with minimal contribution at the spinal level (Inui et al., 2006; Krabbenbos et al., 2009; Mancini et al., 2015; Mouraux & Plaghki, 2007). Our findings support previous studies reporting reduced N2–P2 during affective touch by a romantic partner in response to laser-evoked pain (von Mohr et al., 2018b), suggesting a modulation of neural responses related to the salience and perception of pain during stroking (Lee et al., 2009; Mouraux & Iannetti, 2009). The N2–P2 complex amplitude is enhanced under attentive states in contrast to distractive conditions (García-Larrea et al., 1997). Our EEG data show a significant decrease in amplitude during stroking, aligning with participants' self-reported attention to heat stimuli. Attention to heat was highest during vibration and lowest during affective stroking. These results suggest that socially meaningful affective touch may capture attentional resources and engage emotion-related mechanisms, thereby attenuating nociceptive processing. Importantly, attenuation of the N2–P2 complex should not be interpreted as evidence for reduced spinal nociceptive transmission or diminished central sensitization, but rather as reflecting changes in supraspinal processing of pain-related salience.

To isolate the effect of CT afferent activation, we compared stroking with static touch within the dyadic context. Static touch was chosen as it lacks CT-optimal velocity but retains social and affective meaning. While we did not include handholding as a condition, resting a hand on the skin may convey a similar positive valence and serve as a meaningful form of social support (Coan et al., 2006; Goldstein et al., 2018; López-Solà et al., 2019). Nevertheless, we found that being stroked by a romantic partner was associated with reduced N2–P2 amplitude compared to static touch, an effect that could be related to the activation of CT afferents. This pattern suggests that the gradual engagement of multiple CT afferent units could be important for shaping the neural processes underlying social-affective touch.

Additional analysis of the N2–P2 complex suggests that different somatosensory afferents modulate nociceptive cortical processing in a lateralized manner. Vibration produced larger N2–P2 amplitudes, particularly when the thermal TSSP stimulus was applied ipsilaterally. Although $A\beta$ fibre activation is commonly associated with spinal inhibition of nociceptive transmission (Melzack & Wall, 1965), the increase in N2–P2 amplitude may reflect enhanced sensory salience and attentional engagement. This interpretation is supported by our behavioural findings, showing higher self-reported attention to heat stimuli during the vibration condition. Vibrotactile input can create a multisensory context that increases the cortical response to the noxious input. By contrast,

partner or robot stroking, which activates CT afferents, decreased ipsilateral N2–P2 amplitudes, suggesting cortical or subcortical inhibitory modulation of pain via affective-nociceptive integration (Mancini et al., 2015). Thus, although $A\beta$ fibres are usually linked to spinal inhibitory mechanisms, our findings indicate that vibrotactile stimulation can also enhance cortical nociceptive processing through sensory salience, whereas CT afferent activation promotes a lateralized reduction in cortical responses to noxious stimuli.

In the time–frequency domain, dyadic conditions were associated with reduced theta-band activity compared to individual conditions. However, no within-session differences were identified across conditions. This pattern suggests that the social context of touch, namely the presence of another person, possibly modulates pain-related neural processing, potentially by providing additional contextual information that attenuates attentional focus on the noxious input. Theta oscillations have been implicated in emotional and motivational processing (Klimesch, 2012; Knyazev, 2007) and are enhanced in response to affectively valenced stimuli (Aftanas et al., 2001, 2004; Balconi & Pozzoli, 2009), as well as in response to both pain and $A\beta$ -discriminative touch (Michail et al., 2016). This increase in theta oscillations is assumed to reflect the involuntary allocation of attention to novel or significant sensory input (Iannetti et al., 2008; Wang et al., 2010). Previous studies have shown that affective touch, compared to non-affective touch, leads to reductions in theta-band activity (Hewitt et al., 2025; von Mohr et al., 2018a) and that robot stroking during TSSP, compared to TSSP alone, also results in reductions in theta-band activity (Wakui et al., 2025). Thus, the reduced theta activity observed in dyadic conditions may reflect general changes in attentional engagement and affective processing because of the social context, rather than being exclusively mediated by CT-specific mechanisms. Importantly, these results indicate modulation of supraspinal attentional and affective processes, without implying changes in spinal wind-up or central sensitization mechanisms underlying temporal summation.

Caressing a partner has been shown to reduce autonomic responses and anxiety levels, suggesting a calming effect (Mazza et al., 2023a). In the present study, we analysed the effects of affective touch during TSSP on autonomic activity by measuring both ECG and EDA responses. HR is a common measure of arousal, RMSSD is related to both sympathetic and parasympathetic influences on cardiac function, whereas HF-HRV is related to parasympathetic (vagal) modulation (McCraty & Shaffer, 2015; Shaffer & Ginsberg, 2017). We did not find significant differences between conditions in any of these three ECG measures. Consistent with this, no

significant differences were observed for skin conductance response indices (number of SCRs, average and total SCR amplitude), which are related to the salience of emotional stimuli, regardless of their valence (Anders et al., 2004; Juuse et al., 2024). The lack of autonomic differences contrasts with our previous findings (da-Silva et al., 2024), where we reported a reduced HR during CT stimulation. One possible explanation for this discrepancy is the absence of a no-touch TSSP baseline in the present study. Our previous work revealed significant effects only when affective robot stroking was compared to TSSP alone. It is also possible that the combination of nociceptive input with the tactile stimulation elevated autonomic activity across all conditions, limiting the detectability of subtle modulatory effects, underscoring the importance of a baseline condition for detecting autonomic modulation. In the present study, the absence of significant differences across conditions indicates that social-affective touch did not exert a marked influence on arousal or autonomic regulation during TSSP, further supporting the conclusion that the observed effects of affective touch are primarily cortical and attentional in nature.

By contrast to some reports of sex-related variability in the perception of affective touch (Jönsson et al., 2017; Stier & Hall, 1984), our study found no significant sex differences across the measures assessed. This may be explained by both methodological and contextual factors, although limited statistical power to detect small sex-related effects cannot be excluded. While some studies have highlighted greater tactile sensitivity and higher pleasantness ratings in women, most studies have not found significant effects of sex on pleasantness ratings (Croy et al., 2014; Jönsson et al., 2015; Tricoli et al., 2013). Moreover, the relational and emotionally meaningful context of our study, where touch was delivered by a romantic partner, may have led to similar levels of emotional engagement across male and female participants, thereby reducing the influence of sex-based variability. This is related to previous observations in the validation of the Touch Experiences and Attitudes Questionnaire (Pereira et al., 2023), where the Attitudes to Intimate Touch subscale (referring to attitudes towards touch experiences between people who are emotionally close or in a romantic relationship) was the only subscale that showed no sex differences. Additionally, individual factors such as attachment style, touch familiarity or previous tactile experiences may have played a more prominent role in shaping responses to affective touch than biological sex alone (Eisenberger et al., 2011; Krahe et al., 2015; Sailer & Leknes, 2022).

One limitation of our study was the nature of the nociceptive stimulator; specifically, the brief contact and separation of the Peltier thermode from the skin, which probably elicited responses not only from nociceptive afferents, but also from rapidly conducting $A\beta$ fibres due to sudden mechanical contact. This probably explains the earlier N2–P2 latencies observed in our study compared to those reported for laser-evoked potentials. However, this does not influence the interpretation of our findings, because the ERP components explored in this study reflect the processing of salient sensory events and are not exclusive markers of $A\delta$ or C-fibre activity (Mouraux & Iannetti, 2018). Additionally, the lack of a no-touch TSSP baseline condition without any concurrent tactile stimulation limits our ability to assess the absolute magnitude of pain modulation elicited by each experimental condition. However, to maintain equal session durations and ensure comparability across sessions, we opted to include a vibration condition as a control. This condition was selected for its preferential activation of mechanoreceptive fibres and low likelihood of CT afferent activation. Touch was applied concurrently with nociceptive stimulation to approximate naturalistic pain–touch interactions, whereas attention to heat was assessed retrospectively and should therefore be interpreted with caution.

Future studies should explore how individual differences in attachment, touch aversion, or chronic pain conditions may alter the cortical modulation of pain by social-affective touch. Moreover, the integration of CT-targeted robotic touch in therapeutic settings could redefine how we design human–machine interactions for emotional and physical support.

Conclusions

Our findings provide compelling evidence that affective touch does not modulate autonomic outputs during a temporal summation paradigm under the tested conditions. However, affective touch was associated with distinct cortical modulations involved in attention. Our results suggest a role for affective touch in shaping the neural processing of nociceptive input within socially meaningful contexts. These results highlight a dissociation between spinal mechanisms underlying TSSP and supraspinal modulation of pain-related salience, underscoring the importance of distinguishing these levels when interpreting neural effects during TSSP paradigms.

Appendix

Table A1. Post hoc comparisons of the interaction between experimental conditions and stimulus sides (ipsilateral vs. contralateral to the TSSP stimulation) for N2–P2 complex amplitudes, showing mean differences, standard errors (SE), t values and Holm-corrected p values (P_{Holm})

		Mean difference	SE	t	P_{Holm}
Partner's stroking, ipsilateral	Partner's static touch, ipsilateral	-0.546	0.242	-2.257	0.418
	Robot brushing, ipsilateral	-1.198	0.433	-2.769	0.144
	Vibration, ipsilateral	-2.321	0.484	-4.799	< 0.001***
	Partner's stroking, contralateral	-0.729	0.269	-2.713	0.158
	Partner's static touch, contralateral	-1.060	0.341	-3.111	0.064
	Robot brushing, contralateral	-1.494	0.461	-3.242	0.046*
	Vibration, contralateral	-1.429	0.491	-2.913	0.107
	Robot brushing, ipsilateral	-0.652	0.381	-1.711	1.000
Partner's static touch, ipsilateral	Vibration, ipsilateral	-1.776	0.414	-4.289	0.002**
	Partner's stroking, contralateral	-0.183	0.241	-0.760	1.000
	Partner's static touch, contralateral	-0.514	0.247	-2.080	0.547
	Robot brushing, contralateral	-0.948	0.414	-2.290	0.412
	Vibration, contralateral	-0.883	0.400	-2.210	0.436
	Vibration, ipsilateral	-1.123	0.254	-4.430	0.001***
Robot brushing, ipsilateral	Partner's stroking, contralateral	0.469	0.432	1.086	1.000
	Partner's static touch, contralateral	0.138	0.375	0.369	1.000
	Robot brushing, contralateral	-0.295	0.287	-1.028	1.000
	Vibration, contralateral	-0.231	0.318	-0.726	1.000
	Partner's stroking, contralateral	1.592	0.454	3.504	0.023*
Vibration, ipsilateral	Partner's static touch, contralateral	1.262	0.385	3.279	0.043*
	Robot brushing, contralateral	0.828	0.317	2.611	0.196
	Vibration, contralateral	0.892	0.318	2.811	0.135
	Partner's static touch, contralateral	-0.331	0.258	-1.281	1.000
Partner's stroking, contralateral	Robot brushing, contralateral	-0.765	0.435	-1.756	1.000
	Vibration, contralateral	-0.700	0.440	-1.589	1.000
	Robot brushing, contralateral	-0.434	0.412	-1.054	1.000
Partner's static touch, contralateral	Vibration, contralateral	-0.369	0.417	-0.885	1.000
	Vibration, contralateral	0.065	0.232	0.279	1.000
Robot brushing, contralateral	Vibration, contralateral	0.065	0.232	0.279	1.000

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Additional information

Data availability statement

The conditions of our ethical approval do not include the public archiving of anonymized participant data. The EEG, EDA and behavioural data, as well as the MATLAB code used for its analysis, are available upon request to the corresponding author, with the sole condition that compliance with ethical procedures governing the reuse of the data must be maintained.

Competing interests

The authors declare that they have no competing interests.

Author contributions

Experiments were performed at the Psychology Research Centre (CIPsi), University of Minho. M.d.S. and A.J.G.V.

were responsible for methodology. M.d.S. and A.J.G.V. were responsible for software. M.d.S. was responsible for formal analysis. M.d.S., A.R.C. and M.O. were responsible for investigations. M.d.S. was responsible for data curation. M.d.S. was responsible for writing the original draft. M.d.S. was responsible for visualization. A.R.C., M.O., A.S., J.C. and A.J.G.V. were responsible for reviewing and editing. J.C. and A.J.G.V. were responsible for conceptualization. A.J.G.V. was responsible for resources. A.J.G.V. was responsible for supervision. A.J.G.V. was responsible for project administration. A.J.G.V. was responsible for funding acquisition. All authors approved the final version of the manuscript submitted for publication.

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Keywords

affective CT-touch, attention modulation, midfrontal theta activity, N2–P2 complex, temporal summation second pain

Supporting information

Additional supporting information can be found online in the Supporting Information section at the end of the HTML view of the article. Supporting information files available:

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