Observing being touched enhances the neural processing and perception of digital gentle stroking

Brais Gonzalez Sousa[1,2,3*], Daniel Senkowski[4] & Shu-Chen Li[1,2,3,*]

[1]Chair of Lifespan Developmental Neuroscience, TUD Dresden University of Technology, 01062 Dresden, Germany

[2]6G-life Research Hub, TUD Dresden University of Technology, 01062 Dresden, Germany

[3]Centre for Tactile Internet with Human-in-the-Loop, TUD Dresden University of Technology, 01062 Dresden, Germany

[4]Department of Psychiatry and Neurosciences, Charité – Universitätsmedizin Berlin, 10117 Berlin, Germany

*Corresponding authors: Brais Gonzalez Sousa, Chair of Lifespan Developmental Neuroscience, TUD Dresden University of Technology, 01062 Dresden, Germany, e-mail address: brais.gonzalez_sousa@tu-dresden.de; Shu-Chen Li, Chair of Lifespan Developmental Neuroscience, TUD Dresden University of Technology, 01062 Dresden, Germany, e-mail address: shu-chen.li@tu-dresden.de

ORCID Brais Gonzalez Sousa: https://orcid.org/0000-0002-9097-6378
ORCID Daniel Senkowski: https://orcid.org/0000-0002-1467-8264
ORCID Shu-Chen Li: https://orcid.org/0000-0001-8409-5390

Author Notes:

Conflicts of interest: All authors declare no conflicts of interest.

Acknowledgments: We would like to thank Anna Weinert and Elitsa Boneva for their help with data collection. Brais Gonzalez Sousa and Shu-Chen Li acknowledge the financial support by the Federal Ministry of Research, Technology and Space of Germany in the programme of “Souverän. Digital. Vernetzt.”. Joint project 6G-life, project identification number: 16KISK001K. Shu-Chen Li is also funded by the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft) as part of Germany’s Excellence Strategy – EXC 2050/1 – Project ID 390696704 – Cluster of Excellence “Centre for Tactile Internet with Human-in-the-Loop” (CeTI) of Technische Universität Dresden. Daniel Senkowski acknowledges support by the German Research Foundation (Project ID: SE1859/10-1).

Ethics statement: All participants provided written informed consent before the study, which was approved by the Ethics Committee of the TUD Dresden University of Technology (Approval number: SK-EK-5012021-Amendment).

Data availability: All the processed data and analysis scripts are available upon request.

Author contributions: Brais Gonzalez Sousa: Conceptualization, Data curation, Formal analysis (lead), Investigation, Methodology, Software, Visualization, Writing - original draft. **Daniel Senkowski:** Conceptualization, Methodology, Formal analysis (supporting), Writing - review & editing. **Shu-Chen Li:** Conceptualization, Funding acquisition, Methodology, Resources, Formal analysis (supporting), Writing - review & editing.

Word count (main body): 4944; Figures: 4

ABSTRACT

Observing touch activates similar brain regions as experiencing an actual touch, suggesting that visual information can cross-modally influence tactile perception. This electroencephalography (EEG) study investigated how observing being touched affects the processing and perception of digitally delivered tactile stimuli resembling affective stroking or non-affective tapping. Thirty-three participants received touch patterns on their left forearm via a wearable sleeve while viewing spatiotemporally aligned videos of touch or a photo of an arm. Continuity and pleasantness ratings were higher for stroking than tapping. Correlations between continuity and pleasantness ratings for stroking or tapping conditions were stronger when presented with touch videos than with photos. Analysis of evoked brain activity revealed cross-modal effects after 0.6 seconds at centro-parietal and frontal electrodes for stroking, which differed from the effects observed for tapping. Visual modulation of pleasantness ratings correlated positively with processing differences between stroking and tapping in two right frontal clusters in later time windows around 1.36 and 1.8 s. These results suggest that visual inputs influence tactile pleasantness through somatosensory and multisensory processing, as well as frontal valuation of pleasantness. Our study extends previous research on affective touch by demonstrating informative visual cross-modal influences on digitally actuated touch at behavioural and neural levels.

Keywords: social affective touch, cross-modal influence, visuotactile, EEG, touch actuation

Introduction

Perceiving touch during social interactions is inherently multisensory, with touch conveying different social messages that receivers intuitively categorize and interpret (McIntyre et al., 2022). Slow, gentle stroking typically reflects social-affective intentions (Morrison et al., 2010) with favourable physiological and emotional outcomes (Ellingsen et al., 2016; Fotopoulou et al., 2022), while tapping is mostly perceived as neutral or attention-seeking (McIntyre et al., 2022). Of particular note, tactile perception could be influenced by concurrent visual information, such as improved tactile acuity when viewing a photo of the stimulated body part during tactile stimulation (Eads et al., 2015). However, the influence of observing being touched on the perception and processing of gentle versus neutral touch is still not well understood.

Physiologically, the positive hedonic characteristics of slow strokes are primarily mediated by unmyelinated C-tactile (CT) fibres in non-glabrous skin, which preferentially respond to stroking velocities between 1-10 cm/s (Löken et al., 2009; Vallbo et al., 1999). Tapping rarely activates CT-afferents (Hauser et al., 2019) and is typically perceived as non-affective (Etzi et al., 2018). While CT-fibres respond to slow affective touch, faster-conducting myelinated Aß afferents mediate processing of non-affective features like pressure and texture to support rapid responding, discrimination, and identification of haptic information (McGlone et al., 2014).

Neuroimaging and electrophysiological studies have revealed that both affective and non-affective touch involve somatosensory processing, but they diverge in terms of their temporal dynamics and subsequent neural pathways. The primary somatosensory cortex (S1) is activated by both types of touch (Morrison, 2016), with early activity within 100 ms reflecting rapid detection of tactile stimuli (Auksztulewicz et al., 2012; Eriksson Hagberg et al., 2019). Furthermore, slow stroking elicits a later negative amplitude peaking around 400 ms (sN400) that correlates with pleasantness ratings, indicating its role in affective processing (Schirmer et al., 2022; Schirmer & McGlone, 2019). Beyond basic tactile detection, affective touch uniquely activates the insular cortex (Björnsdotter et al., 2009; Morrison et al., 2010; Morrison, 2016; Olausson et al., 2002; Voos et al., 2013) associated with interoceptive perception (Craig, 2009) and the posterior temporal sulcus (Bennett et al., 2014; Bjornsdotter et al., 2014; Miguel et al., 2020; Voos et al., 2013) supporting social interactions (Frith & Frith, 2003; Isik et al., 2017; Yang et al., 2015). These signals relay to frontal regions like the orbitofrontal (Rolls et al., 2003; Voos et al., 2013) or medial prefrontal cortex (Gordon et al., 2013; Voos et al., 2013) for higher-order valuation processing. Electrophysiological studies further identify a late positive potential over the frontal cortex approximately 700 ms after touch onset (Ackerley et al., 2013; Schirmer et al., 2022), localized to the superior frontal gyrus and frontal motor areas (Eriksson Hagberg et al., 2019), distinguishing affective from non-affective touch processing.

Thus far, cross-modal visual influences on tactile perception have mainly been studied for neutral and noxious stimuli (Cardini et al., 2012; Eads et al., 2015; Höfle et al., 2012, 2013; Pomper et al., 2013). For neutral stimuli, sensory acuity improved when participants were

concurrently presented with photos of the stimulated body part (Eads et al., 2015), but not when they were presented with neutral objects (Cardini et al., 2012). This effect of 'visual enhancement of touch' (Kennett et al., 2001) was associated with larger N140 amplitudes at central electrodes, indicating increased processing of tactile stimuli in the somatosensory cortex (Taylor-Clarke et al., 2002). Other studies showed that cross-modal enhancement could also involve the posterior parietal cortex supporting integration of visual and tactile signals (Nakashita et al., 2008; Pasalar et al., 2010). For noxious stimuli, visual information has been found to modulate local pain representations in sensorimotor areas and salience networks (Senkowski et al., 2014). Furthermore, participants reported greater unpleasantness when seeing a painful versus a neutral object approaching their hand (Höfle et al., 2012). Cross-modal influences on pleasant tactile stimuli showed sex-dependent modulations of tactile pleasantness in the S1 (Gazzola et al., 2012). During unisensory visual presentation of social touch interactions the S1 was also active despite not having actual tactile inputs (McCabe et al., 2008; Peled-Avron et al., 2016; Schirmer & McGlone, 2019). The social components of these visually transmitted interactions are likely processed in association areas such as the posterior superior temporal sulcus or the temporo-parietal junction (Masson & Isik, 2023), which are also involved in visual motion processing (Kaiser et al., 2012) and understanding others' mental states (Frith & Frith, 2003; Isik et al., 2017; Yang et al., 2015). While the neural mechanisms underlying cross-modal visual effects on neutral and noxious stimuli, as well as the processing of visual social touch has been well characterized, it has not been studied how visual input influences affective touch processing.

This electroencephalography (EEG) study extended prior research by examining how cross-modal visual information affects the processing and perception of digitally rendered affective and non-affective touch. We actuated two touch types, i.e., stroking and tapping, via a wearable shape-memory alloy arm-sleeve (Muthukumarana et al., 2020) that enables precise synchronization of digital tactile patterns with visual stimuli. We recently showed that stroking stimulations actuated by such arm-sleeve elicited facial muscle activities of positive affect (Sousa et al., 2024). While human-to-human touch (e.g., Gazzola et al., 2012) offers greater ecological validity, its temporal precision is limited and difficult to control. Contrarily, robotic touch devices (e.g., Schirmer et al., 2022) allow for more precise manipulation of stimulation parameters but are mechanically complex and compromise ecological validity. Our wearable arm-sleeve strikes a balance by providing better experimental control than human touch while maintaining ecological validity through aligning physical arm position with visual stimuli. Based on previous findings showing enhancing effects of cross-modal visual information (Eads et al., 2015; Höfle et al., 2012, 2013; Pomper et al., 2013), we hypothesized that adding visual inputs that are informative of being stroked to tactile stimulation would amplify differences in perceived continuity and pleasantness between conditions with digitally rendered stroking and tapping. We also predicted that these behavioural effects would be accompanied by associated effects in cortical regions implicating multisensory perception of social touch, such as visual, somatosensory, multisensory, and frontal areas.

Materials and methods

Participants

Forty-two young adults participated in this study and were reimbursed for their participation. Except for one participant, all were right-handed, i.e., values $\geq +50$ measured by the Edinburgh Handedness Inventory (Oldfield, 1971) and none reported clinical symptoms or took prescription drugs in the four weeks prior to the experiment. All participants provided written informed consent before the study, which was approved by the Ethics Committee of the TUD Dresden University of Technology (Approval number: SK-EK-5012021-Amendment). Nine participants had to be excluded after EEG preprocessing and artefact correction/rejection because their dataset contained less than 75% of trials per condition. These exclusions can be mostly attributed to sweating-related artifacts and head/body movement because of fatigue/discomfort towards the end of the experiment. Thus, the effective sample consisted of 33 participants (mean (M) age = 23.36; standard deviation (SD) = 3.24 years; 18 women and 15 men). On average 216 (90%) epochs (SD: 15 epochs) remained for the EEG data analyses for participants in this final sample.

Experimental setup

The experiment comprised two tactile conditions that manipulated touch types, i.e.,stroking ($\mathrm{T_{Str}}$) and tapping ($\mathrm{T_{Tap}}$), which were crossed with two visual conditions that manipulated the type of visual information, i.e., visual-video ($\mathrm{V_V}$) and visual-photo ($\mathrm{V_P}$). This resulted in a 2 x 2 within-subject design with four bisensory conditions: $\mathrm{V_V T_{Str}}$, $\mathrm{V_V T_{Tap}}$, $\mathrm{V_P T_{Str}}$, and $\mathrm{V_P T_{Tap}}$. Additionally, two video-only (unisensory visual) conditions ($\mathrm{V_{V-Str}}$, $\mathrm{V_{V-Tap}}$) were presented to compare and identify brain activity unrelated to tactile stimulation (Fig. 1A). During the experiment, the participants' task was to rate the continuity and pleasantness after bisensory trials (see Procedure). When reporting main effects, $\mathrm{T_{Str}}$ or $\mathrm{T_{Tap}}$ refer to tactile conditions of touch type collapsed across visual conditions, that is: $\mathrm{T_{Str}}$ encompasses both $\mathrm{V_V T_{Str}}$ and $\mathrm{V_P T_{Str}}$ conditions, whereas $\mathrm{T_{Tap}}$ entails both $\mathrm{V_V T_{Tap}}$ and $\mathrm{V_P T_{Tap}}$ conditions. Individual experimental conditions are henceforth denoted by their respective abbreviations (e.g., $\mathrm{V_V T_{Str}}$, $\mathrm{V_P T_{Str}}$, $\mathrm{V_V T_{Tap}}$, $\mathrm{V_P T_{Tap}}$, see also Fig. 1A).

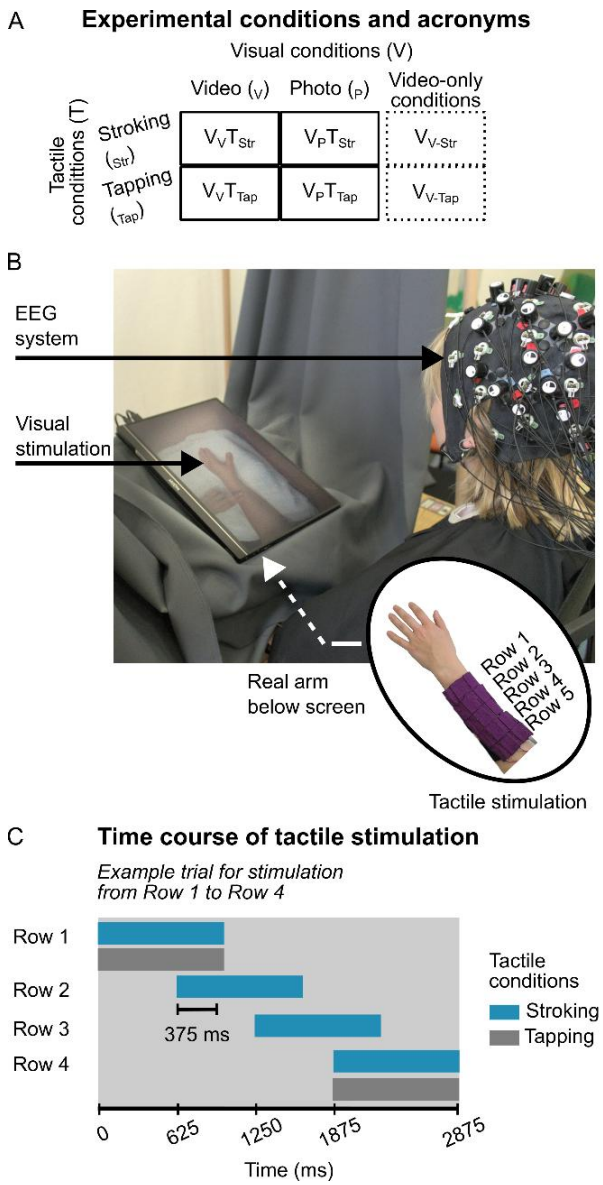

Fig.1. Experimental setup and conditions. (A) Illustration of how tactile and visual stimuli were crossed to obtain experimental conditions (labelled in cells). Experimental conditions that are part of the main analyses are inside solid cells, while video-only conditions, as part of the comparison analysis, are within dotted cells. (B) On the left forearm, each participant wore a wearable shape-memory alloy-based arm-sleeve that actuated two types of touch patterns, i.e., stroking or tapping. They placed the left arm below a screen that displayed visual stimuli and also wore a black cape to occlude participants from seeing the wooden apparatus and their own forearm, while EEG data were recorded. (C) The time course of tactile actuations shows example trials for stroking (blue) and tapping (grey). Rows are numbered on the sleeve shown on the lower right of (A). Stroking was generated by consecutively actuating e.g., row 1 to 4 with a 375 ms overlap between rows, while for tapping only row 1 and 4 were actuated with an 875 ms delay in between. Both stimuli lasted for 2.875 s.

Tactile stimuli

Two touch patterns were digitally actuated and presented as tactile stimuli on the left forearm of the participant: (i) slow stroking, which resembles slow, gentle strokes targeting primarily the CT-afferents, and (ii) tapping, which mostly activates Aß afferents (Hauser et al., 2019) and is perceived as less affective than stroking (Etzi et al., 2018; Sousa et al., 2024). These two touch patterns were generated with a shape-memory alloy-based arm-sleeve (see Fig. 1B for our setup and Srivastava et al., 2022 for an overview). Stroking was elicited by successively actuating across four rows on the sleeve resulting in a duration of 2.875 s at an average velocity of 4.17 cm/s. For tapping, the first and fourth row were actuated with a delay of 0.875 s in between, which also resulted in a trial duration of 2.875 s (see Fig. 1C). We use the same duration for both touch types to avoid on-/offset related differences that may confound the analyses and results of EEG data. To reduce tactile habituation, the onset location and movement direction of the touch stimulations varied across trials (for details on the tactile device, see Supplementary material).

Visual stimuli

Visual stimuli were presented simultaneously with the touch onset elicited by the arm-sleeve. Two types of visual stimuli were used: videos of touch or a photo of the forearm. The videos showed two fingers of a right hand performing strokes or taps on a left forearm resting at the same position and in the same orientation as the participants' arm. The videos were recorded for the different variations of touch onset/movement direction, resulting in four clips per touch type. All clips lasted 2.875 s and were edited in Davinci Resolve (v. 17.4.6) for spatiotemporal alignment with tactile stimuli. Additionally, as a control of basic visual input of the touched body part, a photo of the left forearm not informative of being touched was displayed for the $\mathrm{V_P T_{Str}}$ and $\mathrm{V_P T_{Tap}}$ conditions (c.f. Kennett et al., 2001). The fingers and arm shown in the video clips and photos were sex neutral.

Procedure

The participants underwent the experiment individually. Each participant read instructions about the experiment and filled out the Edinburgh Handedness Inventory (Oldfield, 1971) before being seated in front of a wooden apparatus on which a 15.6 inch LED screen (141 pixels per inch, refresh rate: 144 Hz, contrast ratio: 1200:1, brightness: 300 cd/m^2) was placed (Fig. 1B). Visual stimuli were presented at 120 Hz. For trials with tactile stimulation, the arm-sleeve was triggered via serial commands one second before the end of a fixation cross shown on the display screen. This one-second interval corresponded to the latency needed to energize the shape-memory alloy (Muthukumarana et al., 2020).

Participants rested their left forearm comfortably below the screen on a Styrofoam pad wrapped in a towel with the arm-sleeve strapped onto their left dorsal forearm. For assessing brain correlates, an actiCAP was used to place EEG and near-infrared spectroscopy optodes. The current study focused explicitly on the analysis of behavioural

and EEG data. During the experiment, pink noise was presented via earphones to mask the low-volume sound of the tactile device.

The experiment ran on a custom-made script in PsychoPy (v2022.2.5, Peirce et al., 2019) that also sent serial commands to the arm-sleeve and triggered EEG acquisition. It entailed five blocks, each with 48 trials that were presented in a random order with eight trials per condition per block. The eight trials in each block of a given condition consisted of two repetitions of the four different variations of touch onset/movement direction. Overall, this resulted in 40 trials in each of the six conditions. On average the experiment lasted 51.1 minutes (SD = 7.4 minutes).

Before the experimental blocks, each participant was presented with the position of the visually displayed virtual arm and was asked to align their left forearm with the visual display. Subjective embodiment was rated after completing all experimental blocks as a manipulation check (see Supplementary material). A trial started with a fixation cross with randomized durations of 2.5, 2.75, or 3 s. In the bisensory trials, visual display and tactile stimulation started simultaneously and lasted for 2.875 s. After stimulus presentation, participants viewed a 0.5 s fixation cross, and only after bisensory trials, responded to two rating scales of pleasantness and continuity (for details of the rating scales, see Supplementary material). In every block, at the end of three randomly selected trials, participant's visual attention was assessed by the multiple-choice question, 'Which video/photo was presented during the last trial?' At the end of each block, participants were able to take a break with a self-determined duration.

EEG data acquisition

EEG data were recorded with a 32-channel EEG system (LiveAmp; Brain Products) with active Ag/AgCl electrodes mounted according to the international 10-20 system and acquired via BrainVision Recorder (Version 1.25.0001; Brain Products). The FCz and FPz electrodes served as online reference and ground electrodes, respectively. EEG data were sampled at 500 Hz and online filtering consisted of a low-pass filter at 131 Hz with no high-pass filter (DC recording). The average impedance across 25 participants and all electrodes was 7.37 $k\Omega$ (SD: 7.09 $k\Omega$). Due to a technical issue of the recording software the impedance measurements of 8 participants were not saved with the EEG data files but were still kept below a predefined threshold of 25 $k\Omega$ prior to data collection (for details, see Supplementary material).

Statistical analysis

Behavioural analysis

To investigate cross-modal visual effects on behavioural ratings of continuity and pleasantness, we analysed tactile, visual conditions (see Fig. 1A) and their interaction as fixed effects in two separate linear mixed models (LMMs). Both LMMs included participants' gender and age as covariates. The random effect structure was maximal with a random slope per participant for the interaction effect of tactile by visual condition. To

evaluate the significance of fixed effects, F-tests were performed for both LMMs using Satterthwaite approximation for degrees of freedom at an alpha threshold of .05. Post-hoc t-tests tested differences between estimated marginal means (EMM) of the significant fixed effects while correcting for multiple testing via Tukey adjustments (Luke, 2017). Effect sizes for these models were calculated based on the formula presented by Westfall et al. (2014).

Analysis of event-related potentials

For the analysis of event-related potentials (ERP), epochs were baseline corrected by the mean voltages in the time-window from -0.3 to 0 s prior to the simultaneous onset of tactile and/or visual stimuli. Subsequently, the ERPs for every condition were calculated by averaging baseline-corrected epochs for every condition. We first investigated cross-modal visual effects (i.e., having a video showing touch actions or only a photo of the arm) on the tactile conditions of stroking or tapping separately by conducting cluster-based permutation tests (Maris & Oostenveld, 2007). For each condition, ERP differences ($\mathrm{V_VT}$ - $\mathrm{V_PT}$) between the visual-video and the visual-photo condition were tested at each sampling point using paired t-tests (two-tailed, cluster-forming threshold = .05). Clusters formed in these analyses were tested against a null distribution obtained by Monte-Carlo sampling at 1000 permutations and using a Bonferroni corrected alpha threshold of $\alpha_{\mathrm{Bonferroni}}$ = .05/2 = .025. Furthermore, we were also interested in how cross-modal visual information may affect the tactile perception between touch types. Thus, clusters of ERP double-differences in cross-modal visual processing between tactile conditions of stroking and tapping, i.e., ($\mathrm{V_VT_{Str}}$ - $\mathrm{V_PT_{Str}}$) - ($\mathrm{V_VT_{Tap}}$ - $\mathrm{V_PT_{Tap}}$), were tested in a cluster-based permutation test (two-tailed paired t-test, cluster-forming threshold = .05) against a null distribution obtained from Monte-Carlo sampling at 1000 permutations.

Next, we tested whether processing differences due to video information of touch (i.e., $\mathrm{V_VT}$ vs. $\mathrm{V_PT}$) are associated with differences in pleasantness ratings separately for each of the two touch types. For each participant, pleasantness ratings were averaged across trials to calculate the difference between $\mathrm{V_VT}$ and $\mathrm{V_PT}$. Significance of spatiotemporal clusters of correlations between ERP differences ($\Delta\mathrm{ERP_{V_VT-V_PT}}$) and pleasantness differences ($\Delta\mathrm{PLE_{V_VT-V_PT}}$) were assessed separately for conditions of stroking and tapping with a cluster-based permutation test (Spearman's rank correlation, cluster-forming threshold = .01). A cluster indicated a significant correlation if the cluster-level statistic exceeded the corrected critical alpha of $\alpha_{\mathrm{Bonferroni}}$ = .05/2 = .025 in a null distribution obtained from Monte-Carlo sampling at 1000 permutations. We also investigated whether neural differences between stroking and tapping in processing $\mathrm{V_VT}$ and $\mathrm{V_PT}$ were correlated with differences in pleasantness ratings between those conditions. Thus, the double-differences (($\mathrm{V_VT_{Str}}$ - $\mathrm{V_PT_{Str}}$) - ($\mathrm{V_VT_{Tap}}$ - $\mathrm{V_PT_{Tap}}$)) were calculated for ERPs and pleasantness ratings. Significant correlations between ERP and pleasantness double-differences were obtained from a cluster-based permutation test (Spearman's rank correlation, cluster-forming threshold = .01) where the cluster statistic was tested against a Monte-Carlo sampled null distribution (1000 permutations).

Results

Behavioural ratings of continuity, pleasantness, and embodiment subscales

The LMM for continuity ratings showed a significant main effect for tactile conditions ($F_{1,31.97}$ = 195.82, $p < .001$, d = 0.87). Post-hoc comparisons revealed that stroking conditions collapsed across visual conditions (EMM = 4.28, SE = 0.41) were perceived as more continuous than tapping conditions (EMM = -4.22, SE = 0.31; $\mathrm{T_{Str}}$ - $\mathrm{T_{Tap}}$: t_{Inf} = 8.5, $p < .001$). Moreover, a significant interaction between tactile and visual conditions ($F_{1,32}$ = 233.2, $p < .001$, d = 0.39) revealed that the difference in continuity ratings between $\mathrm{T_{Str}}$ and $\mathrm{T_{Tap}}$ increased from the photo conditions ($\mathrm{V_P T_{Str}}$ - $\mathrm{V_P T_{Tap}}$: t_{Inf} = 4.73, $p < .001$) to the conditions with touch videos ($\mathrm{V_V T_{Str}}$ - $\mathrm{V_V T_{Tap}}$: t_{Inf} = 12.26, $p < .001$, see Fig. 2A). Furthermore, age ($F_{1,29.99}$ = 0.52, $p = .48$, d = 0.006) and gender ($F_{1,29.99}$ = 0.52, $p = .55$, d = 0.017) included as covariates did not show any significant effects.

For pleasantness ratings, significant fixed effects were observed for the main effects of tactile conditions ($F_{1,33.31}$ = 9.80, p = .004, d = 0.04) and visual conditions ($F_{1,31.99}$ = 21.22, $p < .001$, d = 0.13). For visual conditions collapsed across stroking and tapping, post-hoc comparisons revealed significant differences in pleasantness ratings between $\mathrm{V_V T}$ (EMM = 2.98, SE = 0.55) and $\mathrm{V_P T}$ (EMM = 1.84, SE = 0.56; t_{Inf} = 1.13, $p < .001$). Tactile conditions collapsed across visual conditions showed that $\mathrm{T_{Str}}$ (EMM = 2.58, SE = 0.55) was perceived as more pleasant than $\mathrm{T_{Tap}}$ (EMM = 2.23, SE = 0.53; t_{Inf} = 0.35, p = .002). The interaction effect between tactile and visual conditions showed a non-significant trend-level ($F_{1,56.98}$ = 3.9, p = .053). To further explore the effects of stroking versus tapping on pleasantness ratings, we conducted follow-up analyses of simple effects within each visual condition. These revealed a significant difference between tactile conditions in the touch video condition ($\mathrm{V_V T_{Str}}$ - $\mathrm{V_V T_{Tap}}$: t_{Inf} = 0.53, p = .001) but not in the photo condition ($\mathrm{V_P T_{Str}}$ - $\mathrm{V_P T_{Tap}}$: t_{Inf} = 0.18, p = .14, see Fig. 2B). Additionally, fixed effects for age ($F_{1,30.06}$ = 1.0, $p = .33$, d = 0.07) and gender ($F_{1,30.06}$ = 3.44, $p = .07$, d = 0.12) as covariates were not significant. In summary, stroking was perceived to be more continuous and pleasant. Informative cross modal information in videos further enhanced these effects.

We also explored the relationship between continuity and pleasantness ratings in a LMM with pleasantness ratings as the outcome variable and continuity ratings, tactile and visual conditions, and their interactions as predictors, and gender and age as covariates. A three-way interaction showed that the relationship between continuity and pleasantness ratings varied across types of tactile and visual conditions ($F_{1,29.62}$ = 16,81, $p < .001$, d = 0.027, Fig. 2C, for additional results, see Supplementary material). On average participants correctly answered 85.5% (SD = 10.86%) of the attention questions asked after 6.25% of the trials.

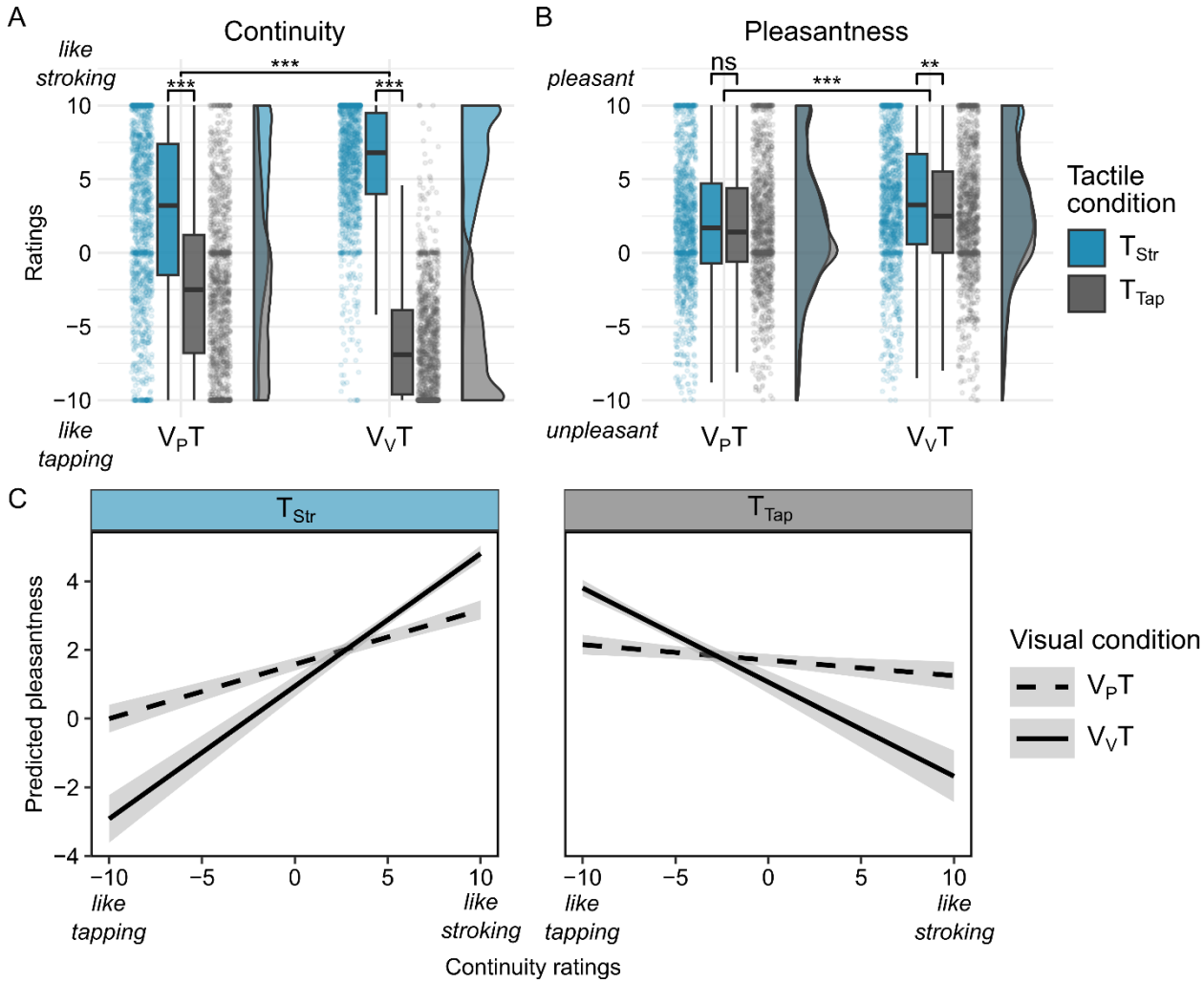

Fig. 2. Continuity and pleasantness ratings plotted for tactile (T) and visual (V) conditions. (A-B) Boxplots show median (centre bar), first-to-third quartile (box), and 1.5 inter-quartile range (whiskers) for continuity (A) and pleasantness ratings (B). Single-trial data are shown as dots and its distribution as half-violin plots next to the boxplots. Post-hoc comparisons from linear mixed models are shown with brackets between individual or groups of boxplots. Note that significance of comparisons refers to marginal means as estimated from linear mixed models and not to the median that is shown in the boxplots. (C) Lines show the relationship between continuity ratings and predicted pleasantness in bisensory visual-photo (V_PT, (dashed line) and visual-video (V_VT, solid line) conditions for stroking (T_{Str}) and tapping (T_{Tap}) separately. Shaded areas represent the 95% confidence interval. ns: not significant ($p > .05$), ** $p < .01$, *** $p < .001$

ERP effects of cross-modal visual information type differ between touch types

The analysis of data from the stroking condition revealed two significant clusters: the first cluster (p = .023) displayed larger amplitudes for the condition of visual-videos ($\mathrm{V_V T}$) from around around 0.672 to 1.272 s at eight frontal to left frontotemporal sensors (Fig. 3A). The second cluster (p = .005) reflected a negative amplitude difference ($\mathrm{V_P T} > \mathrm{V_V T}$) occurring from about 0.756 to 1.264 s at twelve left-parietal to central electrodes (Fig. 3B). Analysis of tapping conditions revealed one significant cluster (p = .021) spanning approximately 1.008 to 1.36 s at nine occipital electrodes which showed more positive ERPs for $\mathrm{V_P T}$ compared to $\mathrm{V_V T}$ (Fig. 3C).

The double-difference contrast between $\mathrm{T_{Str}}$ and $\mathrm{T_{Tap}}$ revealed a significant cluster exhibiting negative t-values from about 0.62 to 0.9 s across eleven central electrodes (p = .04, Fig. 3D).Visual inspection of the time-series reveals that ERPs for the visual conditions in $\mathrm{T_{Str}}$ show the opposite pattern ($\mathrm{V_V T} < \mathrm{V_P T}$) compared to those observed in $\mathrm{T_{Tap}}$ ($\mathrm{V_V T} > \mathrm{V_P T}$). As additional comparison analysis, we examined potential touch type effects in the unisensory video-only conditions ($\mathrm{V_{V-Str}}$ - $\mathrm{V_{V-Tap}}$) in a cluster-based permutation test (two-tailed paired t-test, cluster-forming threshold = .05, 1000 permutations). No significant cluster emerged for this comparison. This suggests that the double-difference cluster found for visuotactile stimuli was not driven by unisensory visual processing differences between stroking and tapping.

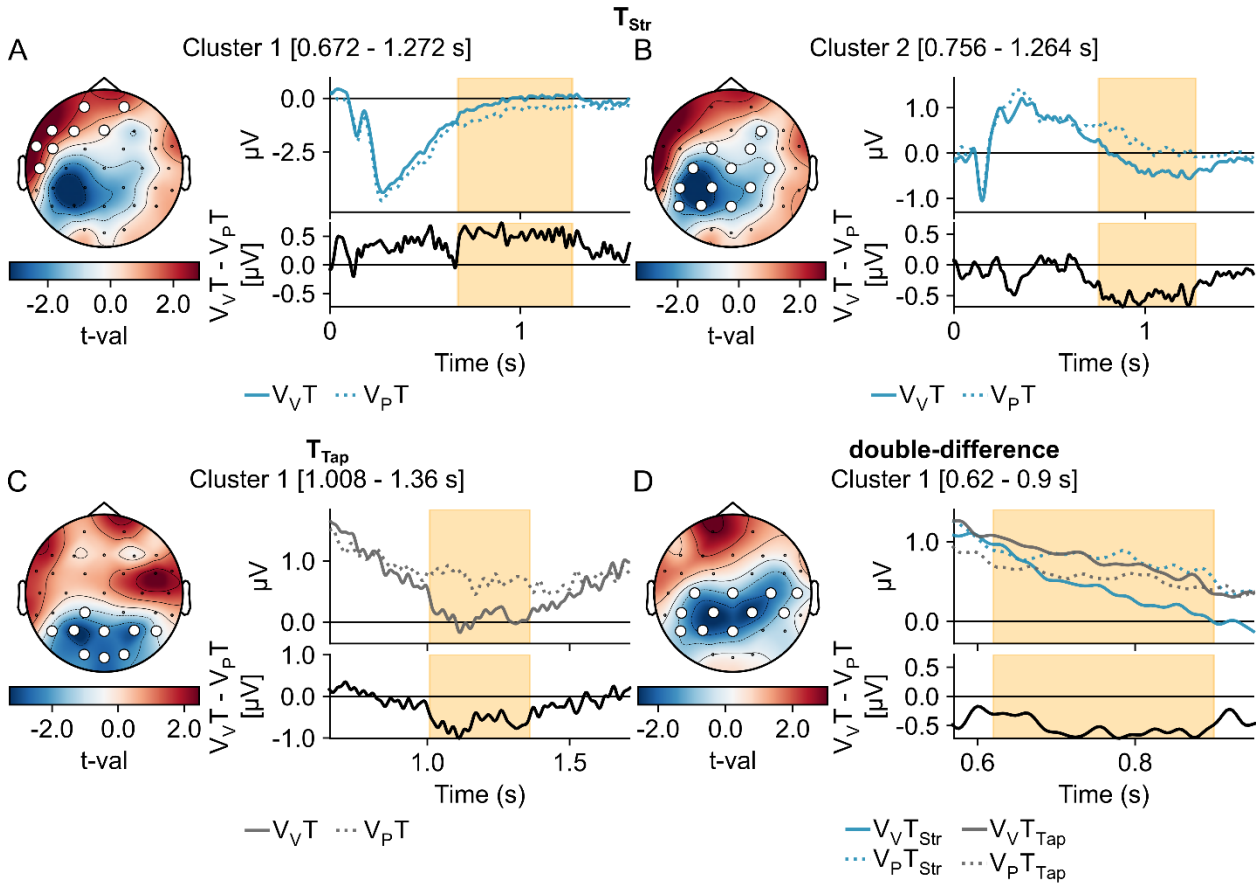

Fig. 3. ERP differences between V_VT and V_PT for the stroking and tapping conditions separately (T_{Str}, T_{Tap}, respectively) and between tactile conditions (double-difference). Significant clusters are shown for differences between visual-video (V_VT) and visual-photo conditions (V_PT) for tactile-stroking (T_{Str}) (A, B) and tactile-tapping (T_{Tap}) (C), and the double-difference between T_{Str} and T_{Tap} ((V_VT_{Str} - V_PT_{Str}) - (V_VT_{Tap} - V_PT_{Tap})) (D). A topographic map plots the average t-values for the cluster time-window with significant sensors highlighted as white dots. On the right of each panel, the top plots show the time course of average amplitudes across significant sensors compares V_VT and V_PT within each tactile condition and the double-difference, whereas the plot below shows the difference in the time course between visual conditions.

Correlation between ERP differences of cross-modal visual information type and pleasantness ratings

Cluster-based permutation tests showed no significant correlation between ERPs and pleasantness in visual condition differences for stroking or tapping. The cluster-based permutation tests on double-differences between T_{Str} and T_{Tap}, revealed two significant positive correlations: the first cluster at three right frontal electrodes lasted from around 1.356 to 1.428 s ($p = .046$, Fig. 4A) and the second cluster also at two right frontal electrodes spanned approximately from 1.804 to 1.948 s ($p = .038$, Fig. 4B). These positive correlations for the double-differences reflect that larger ERP differences between video and photo-conditions for stroking compared to tapping, were associated with larger pleasantness differences between video- and photo-conditions for stroking than for tapping.

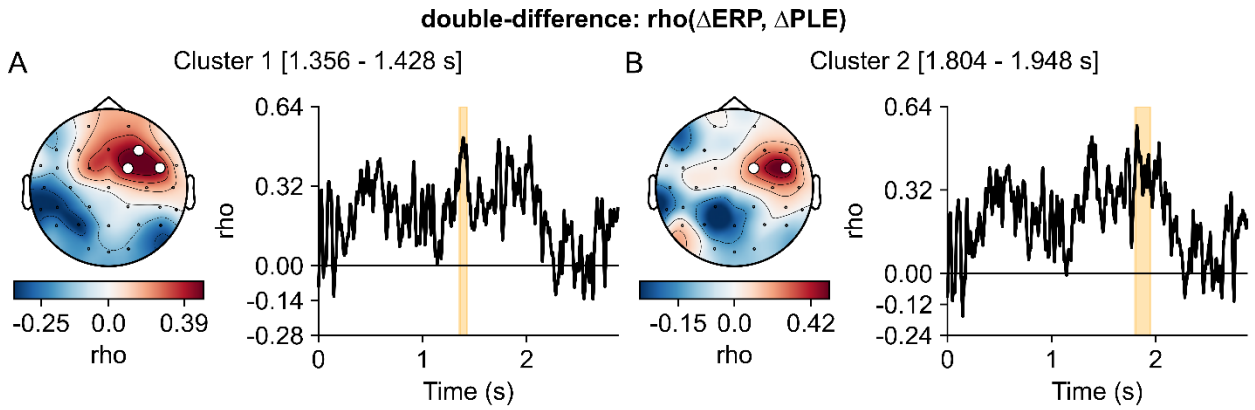

Fig. 4. Correlation between ERP (ΔERP) and pleasantness differences (ΔPLE) as a function of cross-modal visual information type ($V_V T$ - $V_P T$). (A,B) Significant clusters for the double-difference addressing interactions between tactile conditions (stroking vs. tapping) and visual information type. These clusters reveal correlations (Spearman's rank correlation, rho) between ERP and pleasantness rating differences, where both difference sets were calculated as: ($V_V T_{Str}$ - $V_P T_{Str}$) - ($V_V T_{Tap}$ - $V_P T_{Tap}$). A topographic map plots the average correlation coefficient for the cluster time-window with significant sensors highlighted as white dots. The time course of average correlation across significant sensors is plotted on the right side of each panel.

Discussion

This study investigated the visual cross-modal influence of observing being touched on pleasantness ratings and neural processes of digitally actuated affective and non-affective touch. At the behavioural level, stroking was perceived as more continuous and more pleasant than tapping; of note, these differences were more pronounced in visual conditions in which the cross-modal inputs were more informative of touch type and movement. Within the first second after touch onset, evoked brain responses that reflect cross-modal visual information processing, i.e., $V_V T$ - $V_P T$, differed between affective and non-affective touch conditions at occipital, central, and frontal electrodes. Furthermore, neural responses associated with cross-modal visual influence on digitally rendered touch correlated with subjective touch pleasantness in a cluster of fontal electrodes around 1.35 s after stimulation. This suggests that cross-modal informative visual inputs modulate frontal higher-order valuation processing of tactile pleasantness.

The behavioural ratings of location and ownership from the embodiment scale obtained in the current study were consistent with earlier visuotactile experiments (Höfle et al., 2012), reflecting the successful embodiment of the virtual arm in conditions with informative spatiotemporal aligned visuoactile inputs. In terms of touch presented with a photo of the arm, the shape-memory alloy-based arm-sleeve's stroking and tapping stimulations yielded significant differences in the perception of continuity, replicating results from a previous proof-of-concept study (Sousa et al., 2024). Whereas some prior studies found that stroking is perceived as more pleasant than tapping (Etzi et al., 2018) and is associated with positive affective physiological responses (Etzi et al., 2018; Sousa et al., 2024), another study did not find differences in physiological markers of positive affect between stroking and tapping (McIntyre et al., 2022). In the present study, we did not find significant differences in pleasantness ratings between these touch types in the visual-photo conditions. In contrast, in the video conditions, stroking was perceived as more continuous and pleasant than tapping. While tactile acuity improves by showing a photo of the stimulated body part (Eads et al., 2015), we extend these findings by comparing photos to touch videos containing information about touch type and movement, specifically for pleasant and neutral touch. The spatiotemporally aligned visual information may have improved tactile acuity, making it easier to distinguish touch types and enhancing pleasantness perception in stroking conditions (see Fig. 2A,B). Supporting this, continuity-pleasantness correlations varied across visual conditions for both touch types (see Fig. 2C), demonstrating that tactile-visual resemblance increased perceived pleasantness. When photos were presented with the tactile input, participants did not benefit from informative cross-modal cues and may increase cognitive effort to interpret tactile information, resulting in lower pleasantness ratings (David et al., 2024). The enhanced visual informativeness in video conditions could have amplified pleasantness rating differences by highlighting semantic differences between the touch messages (McIntyre et al., 2022).

At the neural level, characteristic EEG features associated with affective touch, like the sN400 (Schirmer et al., 2022; Schirmer & McGlone, 2019) and a late positive potential

(Ackerley et al., 2013; Schirmer et al., 2022, 2023; Schirmer & McGlone, 2019), have previously been identified for unisensory tactile stimuli. In the present study, comparing tactile perception for stroking with cross-modal visual influence from videos versus photos revealed two distinct patterns of enhanced neural activity. First, larger left frontal evoked activity emerged approximately around 0.672 s post-stimulus, with spatiotemporal properties resembling previously reported late positive potentials (Ackerley et al., 2013) and likely emerging for emotionally arousing stimuli (Hajcak et al., 2010). Second, temporally overlapping left parietal processing (characterized by more broadly distributed electrodes) differentiated the bisensory condition with visual-videos ($\mathrm{V_V T}$) from that with visual-photos ($\mathrm{V_P T}$). This parietal involvement aligns with findings showing parietal cortex activation for visuotactile integration (Gentile et al., 2011; Pasalar et al., 2010) during the processing of visual socio-affective information (Masson & Isik, 2023). Taken together, these findings suggest that cross-modal visual information during affective touch modulates brain areas and ERP components linked to emotional processing and multisensory integration.

For non-affective touch (tapping), ERP differences between visual conditions at occipital electrodes may reflect visual hand motion processing at occipital or lateral occipital cortices (Wurm & Caramazza, 2022), with the cluster onset coinciding with the moment when fingers were elevated to move between tapping locations. The relatively late onset and control for basic visual features suggest these effects represent higher-order motion processing rather than low-level visual feature or simple contrast processing (Di Russo et al., 2002).

Another important finding of this study involves interaction effects between touch type and the type of cross-modal visual information. Specifically, cross-modal visual stimuli were processed differently during affective versus non-affective touch, as evidenced by distinct brain activity in the $\mathrm{V_V T}$ minus $\mathrm{V_P T}$ contrasts for stroking versus tapping. Together these results suggest that the cross-modal visual influence on affective touch engages brain processes for multisensory integration and affective valuation (Masson & Isik, 2023), whereas cross-modal effects on non-affective touch may primarily involve visual motion processing. These processing differences were further supported by the central cluster from the double-difference contrast, which showed enhanced amplitude differences between bisensory conditions of stroking and tapping. The cluster's central topography resembles somatosensory processing patterns like the sN400 observed during unisensory tactile perception (Schirmer et al., 2022), although here it is observed in a later time window (0.6-0.9 s). We interpret this spatiotemporally extended central cluster as reflecting later modulation of somatosensory processing of touch types by cross-modal visual information (Taylor-Clarke et al., 2002).

In further analyses, we examined brain-behaviour correlations. These analyses revealed that cross-modal visual processing associated with different touch types relates to the pleasantness of touch. Significant correlations emerged in two right frontal clusters with late onsets at 1.356 and 1.804 s post-stimulus. Crucially, these correlations explained why pleasantness rating differences between stroking and tapping emerged with visual-videos

but not with visual-photos. Participants showing larger ERP differences between visual information types for stroking versus tapping in frontal regions exhibited corresponding patterns in pleasantness ratings. The spatiotemporal characteristics suggest a sustained late positive potential (Ackerley et al., 2013) that may reflect late affect-related valuation processing, aligning with findings that reward-based value computations implicate the orbitofrontal cortex (Grabenhorst & Rolls, 2011). Since affective touch can be rewarding, these frontal activations might reflect reward processing (Rolls et al., 2003). Overall, our findings suggest that informative cross-modal visual information modulates frontal valuation processes that mediate enhanced subjective pleasantness perception of affective relative to non-affective touch.

When interpreting the results, one has to consider that we focussed on tactile stimuli presented via a previously validated arm-sleeve (Sousa et al., 2024). While shape-memory alloy-based wearables offer advantages in flexibility and weight (Chernyshov et al., 2018), some limitations in the speed, duration and type of touch presentation (Boyraz et al., 2018) may constrain future applications of this technology in other experimental designs. Shorter pleasant and unpleasant visuotactile stimuli would have allowed more direct comparisons of EEG patterns with studies on unisensory visual processing (Masson & Isik, 2023). Importantly, the results obtained by adding semantically meaningful visual information to affective touch highlight potential avenues for future studies in presenting visuotactile stimuli with larger differences in valence and arousal (Spence, 2022).

In conclusion, our study shows that visual input cross-modally enhances perceptual differences between continuous stroking and discrete tapping tactile stimuli that were digitally generated through an arm-sleeve. This cross-modal enhancement effect is mediated by distinct processing over occipital, central, parietal and frontal electrodes. While previous research has demonstrated that observing social touch activates areas involved in the processing of social perception, like the posterior superior temporal sulcus (Masson & Isik, 2023), we show here that visually informative inputs influence social touch perception over somatosensory and parietal regions already before the perception of touch pleasantness is associated with processing over frontal areas. Crucially, our findings establish that pleasantness is significantly influenced by visual cross-modal input. Recognizing the complexity of social interactions, translational research must investigate how wearables might address the lack of physical contact in virtual reality (Li & Fitzek, 2023), for example, by investigating how visually complex stimuli from virtual avatars affect touch, which could be relevant for developing new applications in e-healthcare (McGlone et al., 2024).

Competing interests

No competing interest is declared.

Data availability

All the processed data and analysis scripts are available upon request.

CRediT authorship contribution statement

Brais Gonzalez Sousa: Conceptualization, Data curation, Formal analysis (lead), Investigation, Methodology, Software, Visualization, Writing - original draft. **Daniel Senkowski:** Conceptualization, Methodology, Formal analysis (supporting), Writing - review & editing. **Shu-Chen Li:** Conceptualization, Funding acquisition, Methodology, Resources, Formal analysis (supporting), Writing - review & editing.

Acknowledgments

We would like to thank Anna Weinert and Elitsa Boneva for their help with data collection. Brais Gonzalez Sousa and Shu-Chen Li acknowledge the financial support by the Federal Ministry of Research, Technology and Space of Germany in the programme of “Souverän. Digital. Vernetzt.”. Joint project 6G-life, project identification number: 16KISK001K. Shu-Chen Li is also funded by the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft) as part of Germany’s Excellence Strategy – EXC 2050/1 – Project ID 390696704 – Cluster of Excellence “Centre for Tactile Internet with Human-in-the-Loop” (CeTI) of Technische Universität Dresden. Daniel Senkowski acknowledges support by the German Research Foundation (Project ID: SE1859/10-1).

References

Ackerley, R., Eriksson, E., & Wessberg, J. (2013). Ultra-late EEG potential evoked by preferential activation of unmyelinated tactile afferents in human hairy skin. *Neuroscience Letters*, *535*, 62–66. https://doi.org/10.1016/j.neulet.2013.01.004

Auksztulewicz, R., Spitzer, B., & Blankenburg, F. (2012). Recurrent Neural Processing and Somatosensory Awareness. *The Journal of Neuroscience*, *32*(3), 799–805. https://doi.org/10.1523/JNEUROSCI.3974-11.2012

Bennett, R. H., Bolling, D. Z., Anderson, L. C., Pelphrey, K. A., & Kaiser, M. D. (2014). fNIRS detects temporal lobe response to affective touch. *Social Cognitive and Affective Neuroscience*, *9*(4), 470–476. https://doi.org/10.1093/scan/nst008

Bjornsdotter, M., Gordon, I., Pelphrey, K., Olausson, H., & Kaiser, M. (2014). Development of brain mechanisms for processing affective touch. *Frontiers in Behavioral Neuroscience*, *8*. https://www.frontiersin.org/articles/10.3389/fnbeh.2014.00024

Björnsdotter, M., Löken, L., Olausson, H., Vallbo, A., & Wessberg, J. (2009). Somatotopic organization of gentle touch processing in the posterior insular cortex. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *29*(29), 9314–9320. https://doi.org/10.1523/JNEUROSCI.0400-09.2009

Boyraz, P., Runge, G., & Raatz, A. (2018). An Overview of Novel Actuators for Soft Robotics. *Actuators*, *7*(3), 48. https://doi.org/10.3390/act7030048

Cardini, F., Longo, M. R., Driver, J., & Haggard, P. (2012). Rapid enhancement of touch from non-informative vision of the hand. *Neuropsychologia*, *50*(8), 1954–1960. https://doi.org/10.1016/j.neuropsychologia.2012.04.020

Chernyshov, G., Tag, B., Caremel, C., Cao, F., Liu, G., & Kunze, K. (2018). Shape memory alloy wire actuators for soft, wearable haptic devices. *Proceedings of the 2018 ACM International Symposium on Wearable Computers*, 112–119.

Craig, D. A. (2009). How do you feel — now? The anterior insula and human awareness. *Nature Reviews Neuroscience*, *10*(1), 59–70. https://doi.org/10.1038/nrn2555

David, L., Vassena, E., & Bijleveld, E. (2024). The unpleasantness of thinking: A meta-analytic review of the association between mental effort and negative affect. *Psychological Bulletin*, *150*(9), 1070–1093. https://doi.org/10.1037/bul0000443

Di Russo, F., Martínez, A., Sereno, M. I., Pitzalis, S., & Hillyard, S. A. (2002). Cortical sources of the early components of the visual evoked potential. *Human Brain Mapping*, *15*(2), 95–111. https://doi.org/10.1002/hbm.10010

Eads, J., Lorimer Moseley, G., & Hillier, S. (2015). Non-informative vision enhances tactile acuity: A systematic review and meta-analysis. *Neuropsychologia*, *75*, 179–185. https://doi.org/10.1016/j.neuropsychologia.2015.06.006

Ellingsen, D.-M., Leknes, S., Løseth, G., Wessberg, J., & Olausson, H. (2016). The Neurobiology Shaping Affective Touch: Expectation, Motivation, and Meaning in the Multisensory Context. *Frontiers in Psychology*, *6*, 1986. https://doi.org/10.3389/fpsyg.2015.01986

Eriksson Hagberg, E., Ackerley, R., Lundqvist, D., Schneiderman, J., Jousmäki, V., & Wessberg, J. (2019). Spatio-temporal profile of brain activity during gentle touch investigated with magnetoencephalography. *NeuroImage*, *201*, 116024. https://doi.org/10.1016/j.neuroimage.2019.116024

Etzi, R., Carta, C., & Gallace, A. (2018). Stroking and tapping the skin: Behavioral and electrodermal effects. *Experimental Brain Research*, *236*(2), 453–461. https://doi.org/10.1007/s00221-017-5143-9

Fotopoulou, A., Mohr, M. von, & Krahé, C. (2022). Affective regulation through touch: Homeostatic and allostatic mechanisms. *Current Opinion in Behavioral Sciences*, *43*, 80–87. https://doi.org/10.1016/j.cobeha.2021.08.008

Frith, U., & Frith, C. D. (2003). Development and neurophysiology of mentalizing. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *358*(1431), 459–473. https://doi.org/10.1098/rstb.2002.1218

Gazzola, V., Spezio, M. L., Etzel, J. A., Castelli, F., Adolphs, R., & Keysers, C. (2012). Primary somatosensory cortex discriminates affective significance in social touch. *Proceedings of*

the National Academy of Sciences, *109*(25), E1657–E1666. https://doi.org/10.1073/pnas.1113211109

Gentile, G., Petkova, V. I., & Ehrsson, H. H. (2011). Integration of Visual and Tactile Signals From the Hand in the Human Brain: An fMRI Study. *Journal of Neurophysiology*, *105*(2), 910–922. https://doi.org/10.1152/jn.00840.2010

Gordon, I., Voos, A. C., Bennett, R. H., Bolling, D. Z., Pelphrey, K. A., & Kaiser, M. D. (2013). Brain mechanisms for processing affective touch. *Human Brain Mapping*, *34*(4), 914–922. https://doi.org/10.1002/hbm.21480

Grabenhorst, F., & Rolls, E. T. (2011). Value, pleasure and choice in the ventral prefrontal cortex. *Trends in Cognitive Sciences*, *15*(2), 56–67. https://doi.org/10.1016/j.tics.2010.12.004

Hajcak, G., MacNamara, & Olvet, D. M. and. (2010). Event-Related Potentials, Emotion, and Emotion Regulation: An Integrative Review. *Developmental Neuropsychology*, *35*(2), 129–155. https://doi.org/10.1080/87565640903526504

Hauser, S. C., Nagi, S. S., McIntyre, S., Israr, A., Olausson, H., & Gerling, G. J. (2019). From Human-to-Human Touch to Peripheral Nerve Responses. *2019 IEEE World Haptics Conference (WHC)*, 592–597. https://doi.org/10.1109/WHC.2019.8816113

Höfle, M., Hauck, M., Engel, A. K., & Senkowski, D. (2012). Viewing a needle pricking a hand that you perceive as yours enhances unpleasantness of pain. *PAIN*, *153*(5), 1074–1081. https://doi.org/10.1016/j.pain.2012.02.010

Höfle, M., Pomper, U., Hauck, M., Engel, A. K., & Senkowski, D. (2013). Spectral signatures of viewing a needle approaching one's body when anticipating pain. *European Journal of Neuroscience*, *38*(7), 3089–3098. https://doi.org/10.1111/ejn.12304

Isik, L., Koldewyn, K., Beeler, D., & Kanwisher, N. (2017). Perceiving social interactions in the posterior superior temporal sulcus. *Proceedings of the National Academy of Sciences*, *114*(43), E9145–E9152.

Kaiser, M. D., Shiffrar, M., & Pelphrey, K. A. (2012). Socially tuned: Brain responses differentiating human and animal motion. *Social Neuroscience*, *7*(3), 301–310. https://doi.org/10.1080/17470919.2011.614003

Kennett, S., Taylor-Clarke, M., & Haggard, P. (2001). Noninformative vision improves the spatial resolution of touch in humans. *Current Biology*, *11*(15), 1188–1191. https://doi.org/10.1016/S0960-9822(01)00327-X

Li, S.-C., & Fitzek, F. H. P. (2023). Digitally embodied lifespan neurocognitive development and Tactile Internet: Transdisciplinary challenges and opportunities. *Frontiers in Human Neuroscience*, *17*, 1116501. https://doi.org/10.3389/fnhum.2023.1116501

Löken, L. S., Wessberg, J., Morrison, I., McGlone, F., & Olausson, H. (2009). Coding of pleasant touch by unmyelinated afferents in humans. *Nature Neuroscience*, *12*(5), 547–548. https://doi.org/10.1038/nn.2312

Luke, S. G. (2017). Evaluating significance in linear mixed-effects models in R. *Behavior Research Methods*, *49*(4), 1494–1502. https://doi.org/10.3758/s13428-016-0809-y

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*, *164*(1), 177–190. https://doi.org/10.1016/j.jneumeth.2007.03.024

Masson, H. L., & Isik, L. (2023). Rapid Processing of Observed Touch through Social Perceptual Brain Regions: An EEG-fMRI Fusion Study. *Journal of Neuroscience*, *43*(45), 7700–7711. https://doi.org/10.1523/JNEUROSCI.0995-23.2023

McCabe, C., Rolls, E. T., Bilderbeck, A., & McGlone, F. (2008). Cognitive influences on the affective representation of touch and the sight of touch in the human brain. *Social Cognitive and Affective Neuroscience*, *3*(2), 97. https://doi.org/10.1093/scan/nsn005

McGlone, F., Uvnäs Moberg, K., Norholt, H., Eggart, M., & Müller-Oerlinghausen, B. (2024). Touch medicine: Bridging the gap between recent insights from touch research and clinical medicine and its special significance for the treatment of affective disorders. *Frontiers in Psychiatry*, *15*, 1390673. https://doi.org/10.3389/fpsyt.2024.1390673

McGlone, F., Wessberg, J., & Olausson, H. (2014). Discriminative and Affective Touch: Sensing and Feeling. *Neuron*, *82*(4), 737–755. https://doi.org/10.1016/j.neuron.2014.05.001

McIntyre, S., Hauser, S. C., Kusztor, A., Boehme, R., Moungou, A., Isager, P. M., Homman, L., Novembre, G., Nagi, S. S., Israr, A., Lumpkin, E. A., Abnousi, F., Gerling, G. J., & Olausson, H. (2022). The Language of Social Touch Is Intuitive and Quantifiable. *Psychological Science*, *33*(9), 1477–1494. https://doi.org/10.1177/09567976211059801

Miguel, H. O., Gonçalves, Ó. F., & Sampaio, A. (2020). Behavioral response to tactile stimuli relates to brain response to affective touch in 12-month-old infants. *Developmental Psychobiology*, *62*(1), 107–115. https://doi.org/10.1002/dev.21891

Morrison, I. (2016). ALE meta-analysis reveals dissociable networks for affective and discriminative aspects of touch. *Human Brain Mapping*, *37*(4), 1308–1320. https://doi.org/10.1002/hbm.23103

Morrison, I., Löken, L. S., & Olausson, H. (2010). The skin as a social organ. *Experimental Brain Research*, *204*(3), 305–314. https://doi.org/10.1007/s00221-009-2007-y

Muthukumarana, S., Elvitigala, D. S., Forero Cortes, J. P., Matthies, D. J. C., & Nanayakkara, S. (2020). Touch me Gently: Recreating the Perception of Touch using a Shape-Memory

Alloy Matrix. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, 1–12. https://doi.org/10.1145/3313831.3376491

Nakashita, S., Saito, D. N., Kochiyama, T., Honda, M., Tanabe, H. C., & Sadato, N. (2008). Tactile–visual integration in the posterior parietal cortex: A functional magnetic resonance imaging study. *Brain Research Bulletin*, *75*(5), 513–525. https://doi.org/10.1016/j.brainresbull.2007.09.004

Olausson, H., Lamarre, Y., Backlund, H., Morin, C., Wallin, B. G., Starck, G., Ekholm, S., Strigo, I., Worsley, K., Vallbo, Å. B., & Bushnell, M. C. (2002). Unmyelinated tactile afferents signal touch and project to insular cortex. *Nature Neuroscience*, *5*(9), 900–904. https://doi.org/10.1038/nn896

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*(1), 97–113. https://doi.org/10.1016/0028-3932(71)90067-4

Pasalar, S., Ro, T., & Beauchamp, M. S. (2010). TMS of posterior parietal cortex disrupts visual tactile multisensory integration. *The European Journal of Neuroscience*, *31*(10), 1783–1790. https://doi.org/10.1111/j.1460-9568.2010.07193.x

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Peled-Avron, L., Levy-Gigi, E., Richter-Levin, G., Korem, N., & Shamay-Tsoory, S. G. (2016). The role of empathy in the neural responses to observed human social touch. *Cognitive, Affective & Behavioral Neuroscience*, *16*(5), 802–813. https://doi.org/10.3758/s13415-016-0432-5

Pomper, U., Höfle, M., Hauck, M., Kathmann, N., Engel, A. K., & Senkowski, D. (2013). Crossmodal bias of visual input on pain perception and pain-induced beta activity. *NeuroImage*, *66*, 469–478. https://doi.org/10.1016/j.neuroimage.2012.10.040

Rolls, E. T., O'Doherty, J., Kringelbach, M. L., Francis, S., Bowtell, R., & McGlone, F. (2003). Representations of pleasant and painful touch in the human orbitofrontal and cingulate cortices. *Cerebral Cortex (New York, N.Y.: 1991)*, *13*(3), 308–317. https://doi.org/10.1093/cercor/13.3.308

Schirmer, A., Lai, O., Cham, C., & Lo, C. (2023). Velocity-tuning of somatosensory EEG predicts the pleasantness of gentle caress. *NeuroImage*, *265*, 119811. https://doi.org/10.1016/j.neuroimage.2022.119811

Schirmer, A., Lai, O., McGlone, F., Cham, C., & Lau, D. (2022). Gentle stroking elicits somatosensory ERP that differentiates between hairy and glabrous skin. *Social Cognitive and Affective Neuroscience*, nsac012. https://doi.org/10.1093/scan/nsac012

Schirmer, A., & McGlone, F. (2019). A touching Sight: EEG/ERP correlates for the vicarious processing of affectionate touch. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *111*, 1–15. https://doi.org/10.1016/j.cortex.2018.10.005

Senkowski, D., Höfle, M., & Engel, A. K. (2014). Crossmodal shaping of pain: A multisensory approach to nociception. *Trends in Cognitive Sciences*, *18*(6), 319–327. https://doi.org/10.1016/j.tics.2014.03.005

Sousa, B. G., Muthukumarana, S., Rosenkranz, R., Altinsoy, M. E., & Li, S.-C. (2024). Evaluating Affective Touch Generated via a Shape-Memory-Alloy Arm-Sleeve by Subjective Report and Facial Muscle Activity. *IEEE Transactions on Haptics*, 1–8. https://doi.org/10.1109/TOH.2024.3502785

Spence, C. (2022). Multisensory contributions to affective touch. *Current Opinion in Behavioral Sciences*, *43*, 40–45. https://doi.org/10.1016/j.cobeha.2021.08.003

Srivastava, R., Alsamhi, S. H., Murray, N., & Devine, D. (2022). Shape memory alloy-based wearables: A review, and conceptual frameworks on HCI and HRI in industry 4.0. *Sensors*, *22*(18), 6802.

Taylor-Clarke, M., Kennett, S., & Haggard, P. (2002). Vision Modulates Somatosensory Cortical Processing. *Current Biology*, *12*(3), 233–236. https://doi.org/10.1016/S0960-9822(01)00681-9

Vallbo, Å. B., Olausson, H., & Wessberg, J. (1999). Unmyelinated Afferents Constitute a Second System Coding Tactile Stimuli of the Human Hairy Skin. *Journal of Neurophysiology*, *81*(6), 2753–2763. https://doi.org/10.1152/jn.1999.81.6.2753

Voos, A. C., Pelphrey, K. A., & Kaiser, M. D. (2013). Autistic traits are associated with diminished neural response to affective touch. *Social Cognitive and Affective Neuroscience*, *8*(4), 378–386. https://doi.org/10.1093/scan/nss009

Westfall, J., Kenny, D., & Judd, C. (2014). Statistical Power and Optimal Design in Experiments in Which Samples of Participants Respond to Samples of Stimuli. *Journal of Experimental Psychology. General*, *143*. https://doi.org/10.1037/xge0000014

Wurm, M. F., & Caramazza, A. (2022). Two “what” pathways for action and object recognition. *Trends in Cognitive Sciences*, *26*(2), 103–116. https://doi.org/10.1016/j.tics.2021.10.003

Yang, D. Y.-J., Rosenblau, G., Keifer, C., & Pelphrey, K. A. (2015). An integrative neural model of social perception, action observation, and theory of mind. *Neuroscience & Biobehavioral Reviews*, *51*, 263–275.