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Pleasant touch: Behavioural and hemodynamic responses to a protocol for systematic assessment of tactile stimulation

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ABSTRACT

Pleasant touch is a form of tactile stimulation mediated by tactile C afferent fibres. It involves the encoding of the emotional value associated with tactile stimulation and subserves important social functions. Although pleasant touch has gathered increased interest in recent years, no protocol has been proposed to assess it with a robust and reliable method. In the present study we adopted a rigorous protocol for evaluating the pleasantness or unpleasantness of 9 tactile (pleasant, unpleasant, or neutral) stimuli delivered on eight body areas in healthy individuals. We recorded participants' ratings on pleasantness and intensity of the stimulus, as well as their activity in the prefrontal cortex (PFC) by functional near-infrared spectroscopy (fNIRS). A questionnaire evaluated participants' subjective experience of touch in everyday life. The behavioural results confirmed the effectiveness of the protocol as the stimuli selected to evoke pleasantness were perceived as significantly more pleasant than unpleasant and neutral ones, whereas unpleasant stimuli were perceived as more intense than all other stimuli. The participants reported the palm of the hand, particularly the left one, as the most sensitive area to tactile stimulation. Judgements of pleasantness were positively correlated with subjective experience of touch in everyday life. fNIRS data showed increased activity in the prefrontal cortex particularly during stimulation with pleasant and unpleasant stimuli, consistent with behavioural findings. Overall, this study contributes to understand the processing of pleasant touch and its neural correlates, while introducing a rigorous protocol for investigating tactile stimulation. This protocol holds promise for future utilisation in both healthy and clinical populations.

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1. Introduction

Touch allows to perceive, interact and connect with other individuals and with the world (McGlone et al., 2014; Moehring et al., 2018). Indeed touch fuels the exploration of the external environment (Harlow & Harlow, 1962) and is a silent but powerful communication channel, as it plays a central role in forming bonds and establishing the foundation for social interaction (Field, 2002; Montagu, 1986; Myers, 1984). Moreover, touch significantly contributes to emotional well-being and perception of the self (Davidovic et al., 2019).

Two major categories of touch exist, namely the discriminative and the pleasant touch (McGlone et al., 2014; Moehring et al., 2018). Discriminative touch endows information about physical characteristics of an object, such as shape, weight, texture and size, and is crucial for recognition, manipulation and interaction with the stimuli in the surroundings (Yu et al., 2022). This is the reason why it has been defined as the “first” rapid touch system, deemed to be pivotal for survival (Griffin et al., 2001; McGlone et al., 2014). Pleasant touch, instead, is linked to affective processing. Indeed, it is the result of the encoding of the valence of the stimulus (i.e., pleasantness or unpleasantness), with hedonic and motivational value (Klöcker et al., 2012; McGlone et al., 2014; Morrison et al., 2011). Pleasant touch also subserves a social function, as it is prominent in grounding social interactions and in developing socio-affective skills (Field, 2002).

As highlighted by Schirmer et al. (2023), several terms, such as ‘affective touch’ and ‘gentle touch’, are used in the literature on pleasant touch, sometimes interchangeably. However, the terms ‘affective touch’, and to a less extent ‘gentle touch’, often extend beyond sensory quality, encompassing affective and social components that can influence how touch is perceived, particularly in social and relational contexts as conceived in the Social Touch Hypothesis (Olausson et al., 2010). In the present study, the term ‘pleasant touch’ is referred to the subjective perception of tactile stimulation related to the sensory edonic quality resulting from activation of specific sensory fibres.

Tactile inputs from the skin are transmitted to the brain through two types of afferent fibres, each associated with distinct classes of receptors. Large, myelinated afferent fibres (Aβ-fibres) transmit tactile sensation resulting from mechanoreceptors sensitive to skin deformation; these receptors are abundant in areas such as the fingertips and lips, underlining their importance in discriminative touch (Olausson et al., 2002). A distinct subset of unmyelinated afferent fibres (C-fibres), the so-called C-tactile (CT) afferents, exhibit a heightened response rate when the stimulation occurs at slow velocities reminiscent of caressing (3–5 cm/sec), with gentle forces (.8 N), and at temperatures akin to that of the skin (32 °C; Ackerley et al., 2014; Essick et al., 1999; Löken et al., 2009). These fibres are primarily found in the face and hairy skin (Olausson et al., 2002; Vallbo & Johansson, 1984), but CT afferents are also present in glabrous areas, albeit with lower density (Liu et al., 2022; Watkins et al., 2021). Indeed, microneurography studies have shown that CT afferents are present in glabrous areas at a ratio seven times lower than hairy areas, but their response seems to be greater when compared to that arising from hairy areas (Watkins et al., 2021). CT afferents are believed to be specialised for pleasant touch rather than discriminative touch due to their unique response properties and absence from fingertips (Löken et al., 2009; McGlone et al., 2007). This distinction is supported by research indicating their role in mediating the emotional and social dimensions of touch, enhancing the emotional valence of physical closeness to a person, and fostering feelings of pleasure, security, and protection (Vallbo et al., 2016).

Several studies on the neural correlates of touch have shown that discriminative touch and pleasant touch activate distinct brain areas (Francis et al., 1999; Löken et al., 2009; McGlone et al., 2014; Lamm et al., 2015; Olausson et al., 2002; Rolls et al., 2003; Watkins et al., 2021). The former mainly activates the somatosensory cortex, while the latter elicits stronger activation in the orbitofrontal cortex (OFC), the medial prefrontal cortex, the posterior portion of the insular cortex, and the anterior cingulate cortex, which are involved in emotional processing (Craig, 2009; Francis et al., 1999; Gordon et al., 2013; Hua et al., 2008; Rolls et al., 2003; Voos et al., 2013). Importantly, the input from CT unmyelinated fibres bypasses the somatosensory cortex which is primarily reached by Aβ information (Löken et al., 2009; Olausson et al., 2002; 2008). Interestingly, a study demonstrated that both painful and pleasant stimuli elicit notably heightened activation in the OFC compared to neutral stimuli, which mainly prompt activation in the somatosensory cortex (Rolls et al., 2003).

Recently, Taneja et al. (2021) provided a comprehensive review of the stimuli and the methods frequently used to assess pleasant touch. The stimuli perceived as most pleasurable are typically those crafted from soft and smoothy materials, such as a make-up brush, or materials like velvet, satin, and silk (Ackerley et al., 2014; Guest et al., 2009; Jönsson et al., 2015, 2017; Kass-Iliyya et al., 2017; Löken et al., 2011; Luong et al., 2017; Pawling et al., 2017; Triscoli et al., 2013, 2014). Conversely, stimuli perceived as least pleasant often consist of wrinkled and rough textures, such as abrasive sponges, tin foil, rough velcro, or hard plastic mesh (Essick et al., 2010; Etzi et al., 2014; Hua et al., 2008). In terms of velocity, a speed around 3 cm/sec is generally regarded as more enjoyable compared to higher speeds (e.g., 30 cm/sec). This is in keeping with studies showing that CT afferent fibres preferentially respond to stimuli not exceeding a velocity of 10 cm/sec, otherwise stimulation is perceived as less pleasant (Ackerley et al., 2014; Löken et al., 2009; Olausson et al., 2010). To deliver tactile stimulation, many studies have employed robots or rotary tactile stimulators (Ackerley et al., 2014; Essick et al., 2010; Jönsson et al., 2015, 2017; Luong et al., 2017; Triscoli et al., 2014), while others used specifically trained experimenters, to avoid the artificiality of the machines while still controlling both the applied force and the velocity (Bennett et al., 2014; Etzi et al., 2014, 2018; Gordon et al., 2013; Hua et al., 2008; Kass-Iliyya et al., 2017; Pawling et al., 2017; Voos et al., 2013), although this procedure might be biased by experimenters' and examinees' expectations on the type of feelings elicited by the type of stimulus being used (Kida & Shinohara, 2013; Löken et al., 2011; McGlone et al., 2012).

The studies on pleasant touch reviewed by Taneja et al. (2021) addressed different aspects, such as selection of appropriate stimuli, identification of sensitive areas rich in CT fibres, and determination of the optimal administration method for tactile stimulation. However, each study focused on such features separately and did not evaluate the multiple facets of pleasant touch in a unified, single stimulation protocol. Moreover a recent meta-analysis (Cruciani et al., 2021) highlighted that very heterogeneous procedures have been adopted in studies on pleasant touch. Thus a rigorous protocol assessing relevant variables simultaneously would facilitate reliable comparisons across studies and provide a common basis for the study of pleasant touch, with possible applications in different research contexts.

To address both behavioural and neurophysiological responses to pleasant touch, in the present study we devised a tightly controlled protocol based on a double-blind design, to minimize possible biases related to knowledge about the stimulus being delivered. Ineed, tactile perception is known to be influenced by contextual factors and expectations (McGlone et al., 2014; Olausson et al., 2008, 2016). In research contexts the double-blind procedure represents a critical strategy to reduce subjective emotional and cognitive biases stemming from prior knowledge on the stimuli. This is particularly relevant in measuring responses to pleasant touch, as previous studies have shown that the experience of pleasure can be amplified or diminished not only by the nature of the stimulus but also by anticipations related to the type of contact (Schirmer et al., 2023).

Here we employed a selection of stimuli varying in pleasantness (while controlling for intensity), to assess relative sensitivity in eight designated areas of the body, on the right and the left body side with the following three aims: i) to identify the stimuli most effective in eliciting behavioural feelings of pleasantness and unpleasantness to be used in clinical and experimental studies, ii) to determine the body area most sensitive to pleasant and unpleasant tactile stimulation, iii) to examine correlations between behavioural and neurophysiological responses with specific attention to potential lateralization of pleasant touch processing.

We expected that the stimuli pre-selected as pleasant, neutral, and unpleasant would indeed be rated by participants accordingly. Moreover, we expected that pleasantness ratings for specific stimuli would vary according to the area of the body being stimulated. Indeed, we expected that participants would rate tactile stimulation as more pleasant in glabrous skin areas, such as the palm, even though these areas are less densely innervated by CT fibers than hairy skin areas (Watkins et al., 2021). This expectation aligns with findings suggesting that, although CT fibers play a central role in pleasant touch, pleasantness can also be influenced by factors such as high sensory acuity and cultural associations with tactile comfort, which are particularly relevant to glabrous skin (Kida & Shinohara, 2013; McGlone et al., 2014).

As regards the correlations between behavioral and neurophysiological responses, we used the functional near-infrared spectroscopy (fNIRS) to assess hemodynamic responses in the prefrontal cortex (PFC) associated with tactile stimulation. The fNIRS operates by emitting light within the near-infrared spectrum (ranging from 700 to 900 nm) through the skull surface and capturing the reflected light. Due to the absorption of light by hemoglobin at specific wavelengths, the fNIRS can quantify the levels of oxygenated and deoxygenated hemoglobin in the brain areas. This allows to measure the oxygen demand by active brain regions during the sensory stimulations with high temporal resolution (Lloyd-Fox et al., 2010).

We expected that the hemodynamic activation of the PFC would align with the behavioural data, as a function of stimulus, body area, and side. Indeed, based on previous studies (Francis et al., 1999; Kida & Shinohara, 2013; McGlone et al., 2014; Raimo & Cropano, 2022; Rolls et al., 2003; Taneja et al., 2021), we hypothesised that the pleasantness of specific stimuli (intended to be perceived as most pleasant, and confirmed by behavioural assessment) would elicit greater hemodynamic activity than neutral or unpleasant stimuli in the PFC, consistent with previous findings showing that pleasant touch often activates regions including the OFC and the PFC (Kida & Shinohara, 2013; Rolls et al., 2003).

Regarding lateralization, we hypothesized that stimulation on the left side of the body would yield higher pleasantness ratings and stronger neural responses than stimulation on the right side, in line with studies suggesting a lateralization effect in somatosensory perception, potentially related to functional asymmetries in brain processing of sensory and pleasant stimuli (Ackerley et al., 2014; Kida & Shinohara, 2013).

2. Methods

We report how we determined our sample size, all data exclusions (if any), all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study. The study procedures and study analyses were not pre-registered prior to the research being conducted.

2.1. *Participants*

Thirty-nine healthy young adults (21 women; mean age = 26.1; SD = 3.22) were recruited from University of Campania “Luigi Vanvitelli” (Caserta, Italy) to participate in the study. Participants were right-handed, had normal or corrected to normal vision, and had no history of neurological or psychiatric conditions, as reported during a preliminary interview in which participants were required to provide their written informed consent. The participants were unaware of the objectives of the study and were debriefed at the conclusion of the testing session.

The sample size was calculated by an a priori power analysis conducted with G*Power 3 (Faul et al., 2009), which set a minimum sample size of at least 16 participants to conduct repeated measures ANOVAs with three within factors (stimuli: 9 levels; area: 4 levels; side: 2 levels; see thereafter) and detect an effect size of .15, with a power of .95, and an alpha of .05. All procedures were in conformity with the local Ethics Committee requirements (approval n. 1/2023).

2.2. *Experimental procedure*

After having provided their written informed consent, the participants filled in two questionnaires administered by a computer via the Psytoolkit platform (Stoet, 2010, 2017). The first questionnaire was the Edinburgh Handedness Inventory (Oldfield, 1971), to assess participants' handedness. The second questionnaire, named the Pleasant Touch Questionnaire (PTQ), was devised ad hoc for this study on the bases of existing touch questionnaires in the literature (Carter & Wrench, 2010; Casetta et al., 2020; Gladney & Barker, 1979; Guest et al., 2011; Larsen and LeRoux, 1984; Longarzo et al., 2015; Mehling et al., 2012; Trotter et al., 2018; Von Mohr et al., 2021). Although the PTQ has not been validated yet, the need to employ a new questionnaire arose from the observation that available questionnaires focus on specific aspects of touch and could not provide a comprehensive overview of individuals' overall perception of touch in everyday life. The PTQ includes 42 questions exploring how a person experiences the touch in everyday life, ranging from touch in childhood, touch towards others, touch toward oneself, touch towards objects, general cultural considerations about touch, and interoception/exteroception. The questions are rated on a 5-point Likert scale assessing the degree of agreement or disagreement with the statements provided (1 = Completely false, 5 = Completely true). The score ranges 42–141, with higher scores indicating higher attitude to touch experience.

After completing the two above questionnaires, the participants were blindfolded and underwent the somatosensory stimulation protocol and brain activity monitoring by means of fNIRS in a quiet experimental room. At the end of the tactile stimulation session, fNIRS was removed and participants were required to fill in a questionnaire including six questions on a Visual Analogue Scale (VAS, not at all = 1, very much = 10) on the general evaluation of the experiment, stress and sense of ease. In total a single experimental session lasted approximately 1 h and half.

2.3. *Pleasant touch stimulation apparatus and procedure*

To ensure that the procedure of tactile stimulation was as objective as possible, the participants were blindfolded. This allowed us to prevent any visual cues, and helped participants focus solely on the tactile sensations, without biassing their ratings of pleasantness and intensity based on stimulus knowledge. Moreover, the stimuli were delivered within a stimulation box (50 × 40 × 20; Fig. 1) with two openings in one side for inserting participants' left or right arm and two holes in the upper side, used to deliver the stimuli. The same stimulation box was used for all partecipants. The use of a standardized stimulation box ensured that the area being stimulated was consistent across participants, as each movement followed a guided, circular pattern within the designated openings, keeping the stimulation surface, trajectory and application intensity uniform. This procedure minimized non-intentional variations, contributing to a more consistent administration across participants, and could facilitate replication of the study, by applying the same stimulation protocol without customized adjustments.

The stimuli intended to induce a pleasant, neutral or unpleasant sensation were made from a 10 cm wooden stick attached to a circular plastic cork (5 cm diameter) in which the stimulus material was placed. Placing the stimuli under a plastic cork, and the use of the stimulation box, concealed the stimuli to the examiner thus preventing potential variations in stimulation intensity administration related to the knowledge of the stimulus. By concealing the stimuli from both the participants and the examiner, the box minimized visual cues, effectively establishing a double-blind condition that reduced potential biases related to stimulus recognition. Three stimuli, made of satin fabric, make-up brush or plush fabric, were intended to be pleasant; three, made of sponge, rubber fabric and cardboard served as neutral stimuli; three stimuli, consisting of rough sponge, dishnet and hairbrush were intended to be unpleasant. These objects were chosen as the most suitable among those used in previous works (Gordon et al., 2013; Hua et al., 2008; Lindgren et al., 2012; Morrison et al., 2011). Each stick was fitted at the top with a coloured cap, with each colour corresponding to a numerical value. This allowed for easy identification of each type of stimulus at the conclusion of the experiment. After each session, the arrangement of the caps was randomly shuffled by another experimenter not involved in data collection.

Fig. 1 – Stimulation box. The box has two openings to insert the right and left arm. Two holes on the top assure that the stimulus is slided on the proper area. The 9 stimuli are formed by a wooden stick attached to a cork, containing the stimulus material inside. To allow the experimenter selecting the type of stimulus, without recognizing its identity, a colour cap was inserted on the top of each stick.

During tactile stimulation participants were required to sit on a chair in a relaxed position and to focus just on the tactile stimulations delivered in eight body parts: outer and inner forearm, palm and back of the hand, both in the left and right side of the body. Two of the selected areas were glabrous (inner forearm/palm of the hand) and two hairy (outer forearm/back of the hand), to assess how stimulus evaluation varied according to the type of area stimulated. The stimuli were delivered first in one body side (left or right, counterbalanced among the participants) and then in the other side. The total number of stimulation was 72 (nine stimuli delivered to eight body parts).

The stimulation was performed manually, rubbing the body area with circular movements covering a surface of about 5 cm^2, with a light force and velocity of about 5 cm/sec. In order to standardize the stimulation frequency at approximately 5 cm/s, the experimenter engaged in extensive self-training prior to data collection. This training included practicing consistent circular motions to internalize the pace, with the experimenter counting internally to ensure each rotation was completed in approximately 1 sec. Although no external timing device or auditory cues were used during the trials, this training process allowed for reliable application of the target speed across all participants. Each stimulation lasted 15 sec for each body part. After each stimulation, participants were asked to orally report their evaluation of the stimulus on a 10-point Likert scale in terms of pleasantness (unpleasant = 1; neutral = 5; pleasant = 10) and in terms of intensity (mild = 1; moderate = 5; strong = 10).

The entire procedure, together with the stimulation box, ensured a double-blind stimulus administration, as neither the participant nor the experimenter knew the type of stimulus currently delivered, thus minimising potential biases in their evaluations.

2.4. *Functional near-infrared spectroscopy (fNIRS) acquisition and preprocessing*

A 2 × 4-channel continuous wave fNIRS system (Octa-Mon, Artinis Medical Systems, The Netherlands) was used to monitor oxygenated (O2Hb) and deoxygenated hemoglobin (HHb) levels over the bilateral PFC. This device measures changes in light attenuation at two wavelengths (758 and 840 nm), with O2Hb and HHb concentrations displayed in real time using the modified Beer–Lambert law. Data were collected at a frequency of 10 Hz using OxySoft software (Artinis Medical Systems, The Netherlands), with the differential pathlength factor age-adjusted for each participant (Duncan et al., 1996). The fNIRS device was installed on the forehead of participants. Eight LED bundles (four for each hemisphere) were employed, while two photodiodes (one for each hemisphere) with proprietary ambient light protection were used to capture light from the same cortical areas. The detector-illuminator distance was set at 35 mm, resulting in eight recording channels (Ch 1–4 for the right hemisphere, Ch 5–8 for the left hemisphere, Fig. 2). These bundles were integrated into a probe holder to maintain the position of the ten optodes, which were placed over the head to encompass the underlying PFC. The photodiodes were aligned with Fp1 and Fp2 locations according to the international 10–20 system for electroencephalography (EEG) electrode placement (Fig. 2).

The fNIRS data underwent preprocessing in OxySoft using a band-pass filter with a low cut-off frequency set at .01 Hz and a high cut-off frequency at .1 Hz (Brigadoi et al., 2014; Panico et al., 2021; Pinti et al., 2019). This filter preserves the frequency range between a lower and higher cut-off frequency and is utilised to eliminate noise associated with signals at specific frequencies linked to heart rate (~1 Hz) and very low frequencies (<.04 Hz), while also slightly attenuating respiration rates (~.2–.3 Hz; Brigadoi et al., 2014; Pinti et al., 2019). O2Hb and HHb signals derived from each Channel (1–8) were calculated to obtain activity changes in PFC associated with processing of stimuli, across all participants for sequences of the same length (15 sec).

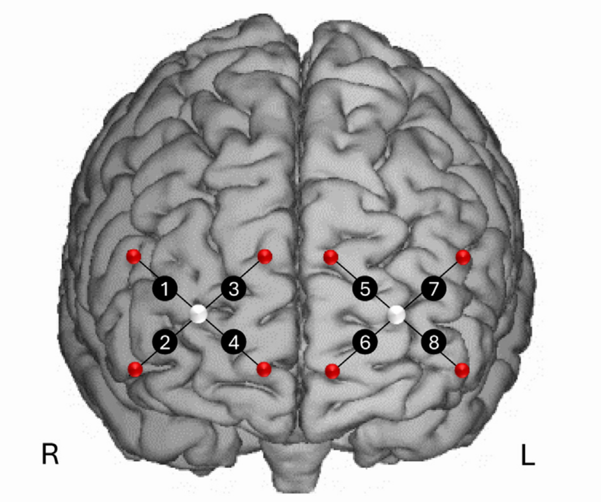

Fig. 2 – fNIRS channel placement over the PFC. Location of the optodes on participant's forehead from channel 1 to channel 8. The two receivers (white dots) are positioned in the center and the eight transmitters (red dots) in the periphery. Receivers are positioned on the line of Fp1 and Fp2 according to the international 10–20 system for the EEG system. R indicates right hemisphere, L indicates left hemisphere.

2.5. *Analyses of behavioural data*

The normality of the distribution of pleasantness and intensity data was assessed by Shapiro–Wilk test ($p > .05$). Then, we compared the 9 stimuli (Dishnet, Hairbrush, Rough Sponge, Rubber, Black Sponge, Cardboard, Plush, Satin, Make-up Brush), the 4 areas of stimulation (Inner Forearm, Outer Forearm, Palm and Back of the hand) and the 2 side of stimulation (Right, Left) with inferential statistics on mean values of reported pleasantness and intensity ratings. Moreover, we ran correlational analyses to explore whether total PTQ scores were associated with pleasantness ratings (obtained as the average of participants' ratings to positive, negative and neutral stimuli), general evaluation of the experiment, stress and sense of ease (as assessed by the post-experimental questionnaire).

2.6. *Analyses of hemodinamic data*

fNIRS analyses aimed to assess whether the activation of the PFC paralleled the behavioural data. As the literature suggests that hedonic values drive PFC activation more than intensity values (McGlone et al., 2014; Raimo and Cropano, 2022; Rolls et al., 2003; Rolls and Grabenhorst, 2008; Rolls, 2010) we based analysis of hemodynamic data on pleasantness results (analysis on the intensity data are provided as a Supplementary file). Specifically, we planned to consider only the stimuli showing more congruent responses within each category (unpleasant, neutral, and pleasant). Since O2Hb seems to provide better contrast and higher variations as compared to HHb (Tachtsidis & Scholkmann, 2016), we will present in the paper only results on O2Hb (see Supplementary file for analyses on HHb). The Shapiro–Wilk test was employed to evaluate the normality of the observed data distribution ($p > .05$). We then compared the mean values of neural activation (O2Hb) associated with the selected stimuli, the body areas and sides in each channel.

The level of significance was set at $p < .05$ for all analyses, which were carried out with *Jamovi* (version 2.5, 2024).

The data that support the findings of this study, are openly available on the Open Science Framework.

3. Results

3.1. Behavioural results

3.1.1. *Pleasantness ratings*

Since data were normally distributed ($p > .05$), we performed two separate 9 (stimulus) x 4 (area) x 2 (side) ANOVAs for pleasantness and intensity. Bonferroni corrected test was used to analyse post-hoc effects with a level of significance set at $p < .05$. The magnitude of the significant effects was indicated by partial eta squared (η^2_p).

For pleasantness, a significant main effect of the Stimulus was found ($F(1,38) = 47.12$, $p < .001$, $\eta^2_p = .56$), with the Make-up Brush being more pleasant than all the other stimuli ($p < .001$; Fig. 3). The Dishnet was found being significantly less pleasant than the three pleasant stimuli ($p < .001$), and than the three neutral stimuli (Rubber, $p = .002$; Black Sponge, $p = .006$; Cardboard, $p < .001$). Also the Hairbrush and the Rough Sponge were judged as less pleasant than the neutral and pleasant stimuli ($p < .01$). The Rubber and the Black Sponge were judged as less pleasant than the pleasant stimuli ($p < .001$), while the Cardboard was evaluated as less pleasant only compared to the Make-up Brush ($p < .001$; see Table 1). A significant main effect of the Area was also found ($F(1,38) = 12.63$, $p < .001$, $\eta^2_p = .25$), with the palm of the hand being significantly more sensitive to pleasantness than the other areas (Inner Forearm, $p = .005$, Outer Forearm, $p < .001$, Back of the hand, $p < .001$; Table 2). A significant Side × Area interaction emerged ($F(1,38) = 4.47$, $p = .005$, $\eta^2_p = .10$). In particular, the left hand resulted as the most sensitive area of the body (Right Inner forearm, $p = .006$; Left inner forearm, $p = .002$; Right Outer forearm, $p < .001$; Left outer forearm, $p < .001$; Right back of the hand, $p < .001$; Left back of the hand, $p = .007$) although it did not differ from Right palm ($p = .35$) (Table 2; Fig. 4). A Side × Stimulus interaction effect was also found ($F(1,38) = 3.23$, $p = .002$, $\eta^2_p = .08$). The post-hoc test revealed that the Dishnet was less pleasant than all the other stimuli (all $p < .05$) except for the unpleasant ones, in both the right and the left side of the body. The Make-up Brush was the most pleasant stimulus on both the right and the left side

Table 1 – Mean and Standard Errors (SE) for Side and Stimulus for pleasantness ratings.

Stimulus	Side			
	Right		Left	
	Mean	SE	Mean	SE
Dishnet	4.09	.29	4.07	.30
Hairbrush	4.20	.28	3.89	.28
Rough sponge	4.34	.25	4.31	.24
Rubber	5.32	.15	5.59	.18
Black sponge	5.22	.17	5.01	.19
Cardboard	5.81	.21	5.86	.17
Plush	6.20	.19	6.64	.21
Satin	5.92	.16	6.28	.18
Make-up brush	7.08	.20	7.15	.22
Total	5.35	.15	5.42	.15

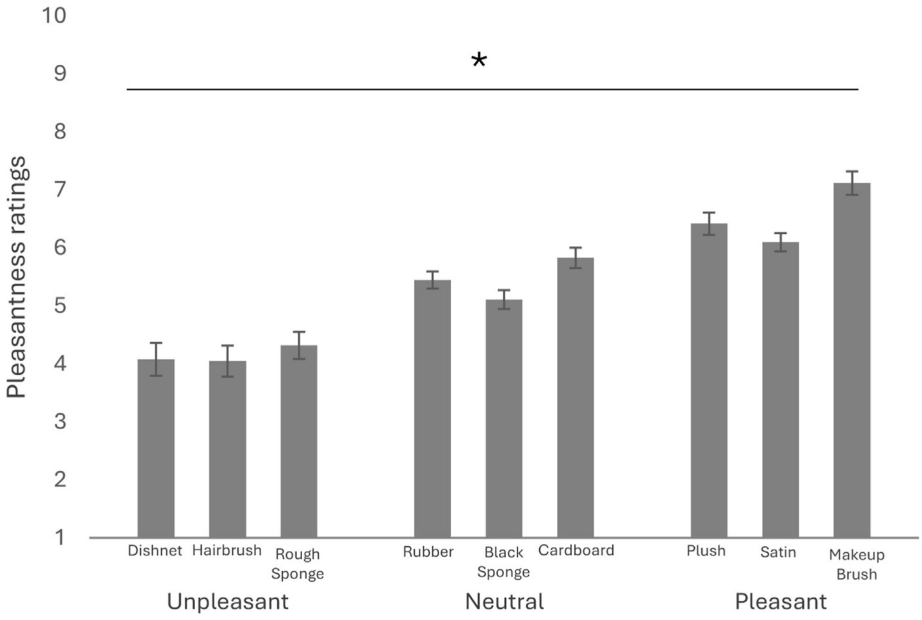

Fig. 3 – Pleasantness ratings for the stimuli. The Makeup Brush was rated as significantly more pleasant than all other stimuli (*: significant at $p < .001$; bars indicate standard error from mean).

Table 2 – Mean and Standard Errors (SE) for Side and Area for pleasantness ratings.

Area	Right		Left	
	Mean	SE	Mean	SE
Inner forearm	5.32	.18	5.18	.20
Outer forearm	5.20	.15	5.16	.16
Back of the hand	5.20	.16	5.38	.15
Palm of the hand	5.68	.18	5.96	.17
Total	5.35	.15	5.42	.15

($p < .001$; Table 1). An Area × Stimulus interaction effect emerged ($F(1,38) = 3.72$, $p < .001$, $\eta^2_p = .09$). The post-hoc comparisons highlighted that the Make-up Brush was rated as more pleasant in all body areas (all $p < .001$; Table 3). The Area x Side × Stimulus interaction effect was not significant ($F(1,38) = .95$, $p = .53$, $\eta^2_p = .02$).

3.1.2. *Intensity ratings*

A significant main effect of the Stimulus ($F(1,38) = 52.67$, $p < .001$, $\eta^2_p = .59$) was found. The three unpleasant stimuli were significantly perceived as more intense than all the other stimuli ($p < .001$; Table 4; Fig. 5). In particular, the Dishnet emerged as the most intense stimulus. The main effect of Area ($F(1,38) = 4.65$, $p = .004$, $\eta^2_p = .11$) was significant. Particularly, the post-hoc comparisons revealed that on the palm of the hand the stimulation was felt as more intense than on the back of the hand ($p = .003$; Table 4). Furthermore, a Stimulus × Area interaction effect emerged ($F(1,38) = 5.70$, $p < .001$, $\eta^2_p = .13$). In the post-hoc

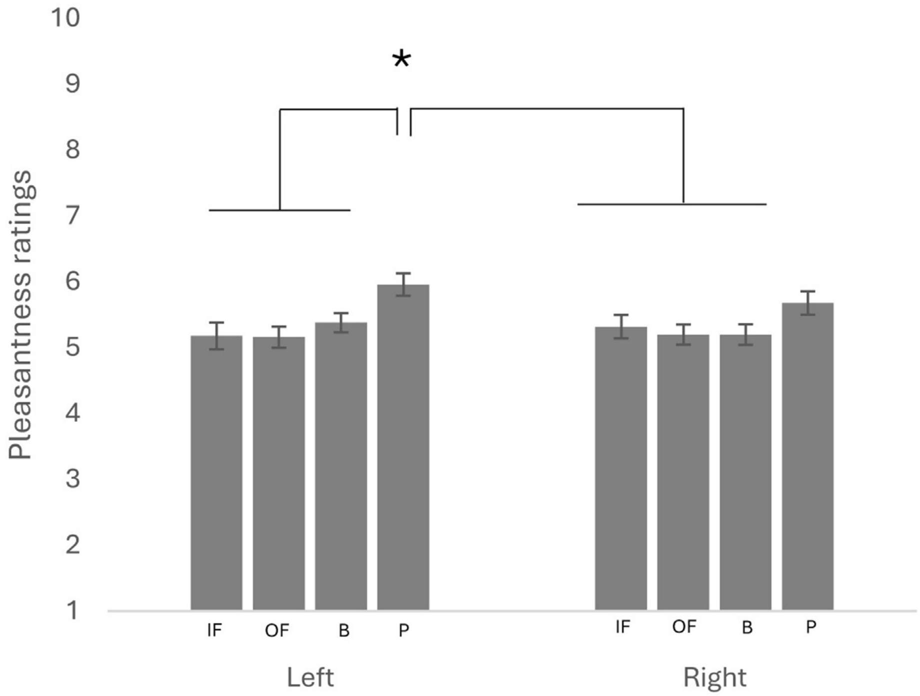

Fig. 4 – Pleasantness ratings according to the side and area of stimulation. The left palm was the most sensitive area to pleasant touch (IF = inner forearm; OF = outer forearm; B = back of the hand; P = palm of the hand; *: significant at $p < .001$; bars indicate standard error from mean).

Table 3 – Mean and Standard Errors (SE) for Stimulus and Area for pleasantness ratings.

Stimulus	Inner forearm		Outer forearm		Palm of the hand		Back of the hand	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Dishnet	3.59	.36	3.72	.32	4.92	.30	4.08	.30
Hairbrush	4.09	.32	3.83	.31	4.66	.35	3.62	.26
Rough sponge	3.99	.31	4.25	.25	4.96	.28	4.09	.25
Rubber	5.26	.21	5.26	.22	5.86	.19	5.43	.19
Black sponge	4.97	.20	4.88	.17	5.58	.22	5.01	.20
Cardboard	5.95	.22	5.87	.19	5.55	.23	5.96	.20
Plush	6.42	.23	6.16	.22	7.00	.24	6.09	.22
Satin	6.04	.22	5.82	.19	6.24	.23	6.30	.18
Make-up brush	6.96	.25	6.83	.25	7.64	.19	7.03	.22

Table 4 – Mean and Standard Errors (SE) for Area and Stimulus for intensity ratings.

Stimulus	Area							
	Inner forearm		Outer forearm		Palm of the hand		Back of the hand	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Dishnet	7.17	.27	6.89	.28	6.32	.30	6.26	.29
Hairbrush	6.67	.27	6.63	.30	6.93	.29	6.42	.29
Rough sponge	6.22	.28	5.89	.28	5.62	.28	5.84	.29
Rubber	4.61	.28	4.70	.28	4.88	.33	4.67	.29
Black sponge	4.84	.25	4.62	.27	4.96	.32	4.62	.27
Cardboard	4.70	.26	4.29	.29	5.34	.27	4.39	.30
Plush	4.53	.29	4.54	.28	4.88	.31	4.72	.29
Satin	4.63	.27	4.50	.26	5.09	.30	4.45	.28
Make-up brush	4.50	.32	4.55	.29	4.83	.32	4.62	.30
Total	5.32	.23	5.18	.24	5.43	.27	5.11	.25

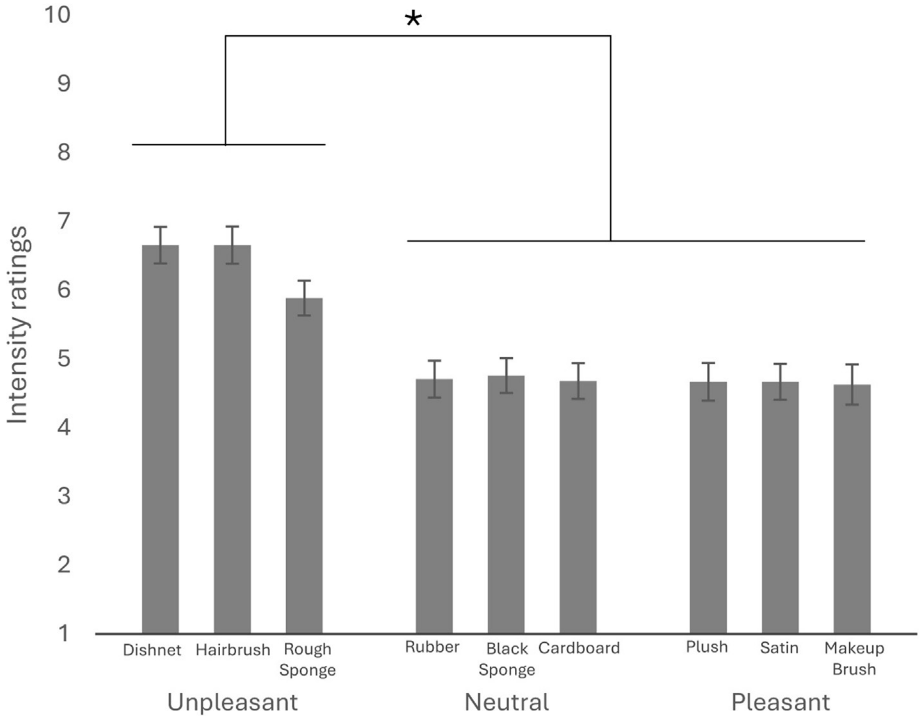

Fig. 5 – Intensity ratings for the stimuli. The unpleasant stimuli were rated as significantly more intense than all the other stimuli (*: significant at $p < .001$; bars indicate standard error from mean).

comparisons, the unpleasant stimuli were judged as significantly more intense than all the other stimuli in all the body areas ($p < .001$; Table 4).

3.1.3. *Correlational analyses*

Correlational analyses were conducted using Pearson's correlation coefficient, as the data met the assumptions of normality (all $p > .05$ of the Shapiro–Wilk test).

Results from correlational analyses showed that PTQ score positively correlated with general judgement to pleasant stimuli ($r = .40$, $p = .012$), but not with the judgement to neutral ($r = .23$, $p = .160$) or unpleasant stimuli ($r = -.01$, $p = .95$). Furthermore, PTQ score positively correlated with a general favourable evaluation of the experiment ($r = .42$, $p = .007$), with a greater sense of ease ($r = .45$, $p = .004$) and negatively correlated with the stress felt ($r = -.34$, $p = .036$).

3.2. *Concentration levels of oxygenated hemoglobin*

Based on the behavioural data on pleasantness, we analysed neural activation associated with the two pleasant (Plush and Make-up Brush), unpleasant (Dishnet and Hairbrush) and neutral stimuli (Rubber and Black Sponge) eliciting more consistent behavioural response. Results from Shapiro–Wilk normality test showed that mean values of O2Hb were not normally distributed ($p > .05$). As a consequence the non-parametric Friedman test was performed to compare the levels of neural activation in the PFC induced by the different stimuli being used, in the different areas and sides. Pairwise comparisons were conducted using the Durbin–Conover test, with a significance level set at $p < .05$. The analyses were carried out on 35 participants since the data of four participants showed low quality signal.

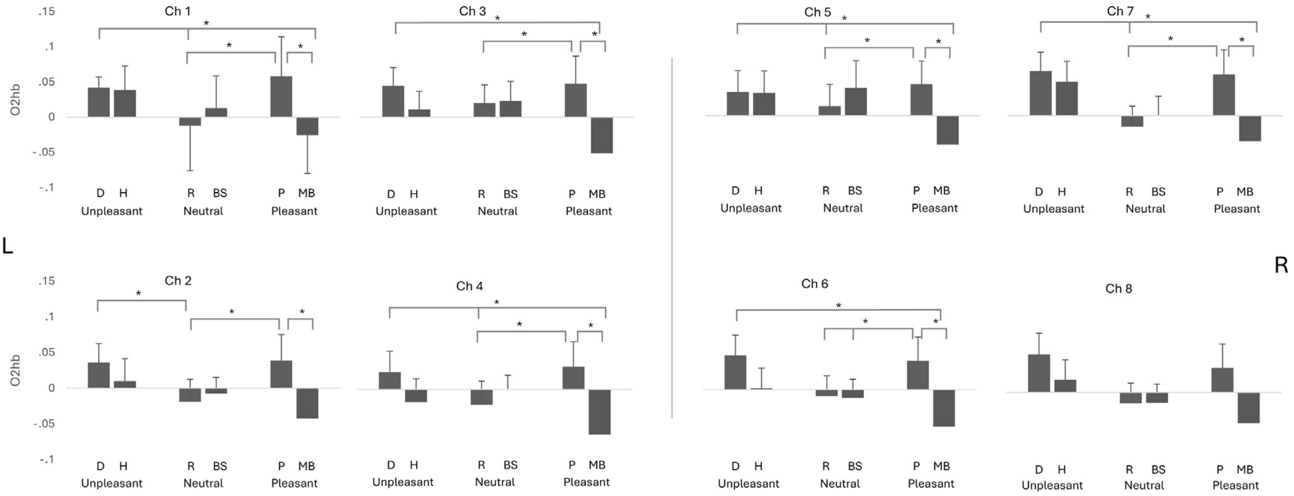

Fig. 6 – Main fNIRS findings. In all channels (except for Ch 8) the Dishnet and the Plush raised the O2Hb concentration more than all other stimuli (D = Dishnet; H = Hairbrush; R = Rubber; BS = Black Sponge; P = Plush; MB = Make-up Brush; *: significant at $p < .05$; bars indicate standard error from mean).

The main effect of the Stimulus emerged in all channels (Ch1: $\chi^2 = 14.9$, df = 5, $p = .011$; Ch2: $\chi^2 = 14$, df = 5, $p = .015$; Ch3: $\chi^2 = 12.5$, df = 5, $p = .029$; Ch4: $\chi^2 = 14.3$, df = 5, $p = .014$; Ch5: $\chi^2 = 14.8$, df = 5, $p = .011$; Ch6: $\chi^2 = 12.3$, df = 5, $p = .031$; Ch7: $\chi^2 = 19.2$, df = 5, $p = .002$) except for the Ch 8 ($\chi^2 = 10.7$, df = 5, $p = .057$; Fig. 6; for the Table see Supplementary file).

For Ch1 O2Hb concentration was higher during the stimulation with the Dishnet compared to Rubber ($p = .019$) and Make-up Brush ($p = .043$). The Hairbrush activated more than the Rubber ($p = .019$) and the Make-up Brush ($p = .043$) and the same as the Plush, which activated more than the Rubber ($p = .002$), and Make-up Brush ($p = .005$).

For Ch2, the O2Hb concentration for Dishnet was higher than the Rubber ($p = .004$). The Hairbrush activated more than the Rubber ($p = .009$) and the Plush activated more than the Rubber ($p = .003$) and the Make-up Brush ($p = .043$).

For Ch3, the O2Hb concentration for Dishnet was higher than the Make-up brush ($p = .032$), for the Black Sponge was higher than the Make-up Brush ($p = .044$). The Plush activated more than the Rubber ($p = .010$) and the Make-up Brush ($p = .002$).

For Ch4, the Dishnet showed higher activation than the Rubber ($p = .016$), and the Make-up Brush ($p = .003$). The Plush activated more than the Rubber ($p = .019$), and the Make-up Brush ($p = .004$).

For Ch5, the Dishnet activated more than the Rubber ($p = .019$), and the Make-up Brush ($p = .002$). The O2Hb concentration for Hairbrush was higher than the Make-up Brush ($p = .011$), and for the Plush it was higher than the Rubber ($p = .031$), and the Make-up Brush ($p = .004$).

For Ch6, the Dishnet activated more than the Make-up Brush ($p = .028$). The O2Hb concentration for the Plush was higher than the Rubber ($p = .015$), the Black Sponge ($p = .044$), and the Make-up Brush ($p = .003$).

For Ch7, the Dishnet activated more than the Rubber ($p = .001$), and then the Make-up Brush ($p = .005$). The O2Hb concentration for Hairbrush was higher than the Rubber ($p = .015$) and the Make-up Brush ($p = .040$), and for the Plush it was higher than the Rubber ($p < .001$), and the Make-up Brush ($p = .003$).

O2Hb levels were not affected by the Area or the Side of stimulation in any of the considered channels ($p > .05$; see Supplementary file).

4. Discussion

The present study systematically investigated the behavioural and neural responses associated with pleasant touch, examining relevant factors including the glabrousness of the body area, the body side being stimulated, and the material of the stimuli. This standardized and double-blind stimulation protocol was designed to reduce the variability observed in prior research (Ackerley et al., 2014; Essick et al., 1999; Guest et al., 2009; Löken et al., 2009, 2011; Luong et al., 2017; Pawling et al., 2017; Rolls et al., 2003). Participants' subjective ratings of tactile stimuli for both pleasantness and intensity were correlated with neural activation data collected via fNIRS in the PFC, so to evaluate whether pleasantness ratings were in line with PFC activation patterns, thereby offering a neurophysiological perspective on pleasant touch.

We expected that participants would rate stimulation as more pleasant in glabrous skin areas (e.g., the palm) than in hairy skin regions, despite glabrous skin having a lower density of CT fibers based on studies suggesting that other factors -such as increased sensory acuity due to the distribution of mechanoreceptors and cultural associations with touch comfort-may contribute to the pleasantness of tactile experiences in these regions (Ackerley et al., 2014; Cruciani et al., 2021; Kida & Shinohara, 2013; McGlone et al., 2014; Watkins et al., 2021). Moreover, we anticipated that the left side of the body would yield higher pleasantness ratings and potentially stronger neural responses than the right side due to hemispheric specialization in the processing of sensory-affective cues or inherent asymmetries in somatosensory processing (Kida & Shinohara, 2013). Finally, we expected PFC activation, as measured by fNIRS, to align with participants' pleasantness ratings across stimuli and body areas, with pleasant stimuli eliciting greater activation compared to neutral or unpleasant stimuli (Francis et al., 1999; McGlone et al., 2014; Rolls et al., 2003).

4.1. *Subjective ratings on pleasant stimulation*

The results from behavioural data showed that stimuli selected to be pleasant were rated as significantly more pleasant compared to both unpleasant and neutral stimuli, confirming suitability of the adopted materials to deliver the intended stimulation. Specifically, the Make-up Brush stimulus was rated as the most pleasant one, while the Dishnet was perceived as the most unpleasant. Intensity ratings showed that the Dishnet was rated as the most intense stimulus, along with the other two unpleasant stimuli, which were significantly more intense compared to all other neutral and pleasant stimuli. These findings are consistent with previous literature showing that softer stimuli tend to be perceived as more pleasant than rougher ones, while the latter are perceived as more intense due to the type of material they are composed of (Essick et al., 2010; Etzi et al., 2014; Hua et al., 2008). As there is growing evidence that not only “bottom-up” but also “top-down” information contributes to pleasant attribution of touch (Kida & Shinohara, 2013; Löken et al., 2011; McGlone et al., 2012), it is important to underline that in the present protocol both the examiner and the examinee were blinded to the current stimulus, thus being judgements about stimulation intensity not affected by prior knowledge or expectations. Therefore, the present finding that perceived stronger intensity was related to unpleasant stimuli could not be ascribed to subjective biases, but might be explained in a physiological perspective, as roughness activates pain receptors in the skin (nociceptors), which are located closer to the skin surface compared to the CT-afferent mechanoreceptors associated with pleasant touch (Pollatos et al., 2012). However, at the moment this speculative interpretation is not supported by empirical data that could be obtained by means of microneurography, not included in our experimental design.

The palm of the hand (particularly the left palm) was the most sensitive area both for pleasantness and intensity ratings. Although recent meta-anlysis did not show a significant difference between pleasant touch perception in palm and hairy skin regions (Cruciani et al., 2021), our finding is consistent with several studies showing that the palm is particularly sensitive to tactile stimulation, despite being a glabrous area (Kida & Shinohara, 2013; Lamm et al., 2015; Mountcastle, 2005; Rolls et al., 2003). Differently from what held in classical studies (e.g., Francis et al., 1999), in recent years CT afferents have been identified in glabrous skin areas (Liu et al., 2022; Watkins et al., 2021). Physiological studies on somatosensory processing have shown that even though the presence of CT fibres is equal to about one-seventh compared to hairy areas, the response in the glabrous areas is generally greater (Watkins et al., 2021). This evidence from somatosensory processing may contribute to understand the increased sensitivity to pleasant touch in the area of the palm in our experimental setting. Finally, the predominant response in the left palm could be explained by a possible effect of handedness (participants were all right-handed in our study). Indeed, several studies showed that right-handed individuals may exhibit greater tactile sensitivity in their non-dominant hand, although this finding has not been consistently confirmed (Hage et al., 1995; Kida & Shinohara, 2013; Van Turnhout et al., 1997). Consequently, further research should be carried out to better understand how lateralization influences tactile perception, including also left-handed participants.

Our behavioural results should be discussed also in the light of personal attitudes toward pleasant touch. To this purpose we assessed how participants experience the touch in daily life (by means of the PTQ) and correlated these measures with behavioural data. Correlation analyses showed that higher scores on the PTQ questionnaire positively correlated with pleasantness ratings about pleasant stimuli, with an overall positive evaluation about the experimental procedure, and with a self-reported greater sense of feeling at ease. Specifically, the more the participants were open to physical contact in daily life, the more positively they rated the pleasant stimuli administered and the less they found the entire experimental procedure to be stressful. Our findings align with the frameworks of Affective Touch and the Social Touch Hypothesis, which emphasize that certain forms of tactile stimulation, particularly those activating CT afferents, play an essential role in emotional and social bonding. The Social Touch Hypothesis (Olausson et al., 2010) suggests that gentle, caress-like touch serves as a fundamental means of social communication, with CT afferents functioning to reinforce emotional closeness and bonding. This is particularly relevant to our results, as the correlation analyses indicate that participants who reported higher pleasantness ratings or greater openness to touch also showed overall positive evaluation of the experimental procedure. This is consistent with the idea that CT-mediated touch is not only perceived as pleasant but has also a broader affective and social value (Morrison et al., 2010; Olausson et al., 2010). Although in our study we considered pleasant touch as the edonic component associated with tactile stimulation, our results support the notion that pleasant sensory stimulation may further serve affective and social functions, underscoring its importance in both everyday social interactions and potential clinical applications. To our knowledge, no studies attempted to integrate an experimental investigation of pleasant touch with an assessment of participants' openness and positive engagement with physical contact experiences in daily life. The significant positive correlation of subjective judgements about tactile stimuli with general psychological disposition toward pleasant touch is in line with the evidence that “top-down” information contributes to pleasant attribution of touch (Kida & Shinohara, 2013; Löken et al., 2011; McGlone et al., 2012). This reinforces the need for a double-blind protocol for assessing pleasant touch, as that adopted here, and suggests using questionnaires such as the PTQ in other research contexts to obtain behavioural reference data that can enhance the understanding of the somatosensory processes under study.

It should be reminded, however, that the PTQ has not been formally validated yet, and this constitutes a limitation of the present study. Nonetheless, we deemed useful using this tool to explore participants' general attitudes toward touch, as no other instrument is available to date for this purpose (Carter & Wrench, 2010; Casetta et al., 2020; Gladney & Barker, 1979; Guest et al., 2011; Larsen and LeRoux, 1984; Longarzo et al., 2015; Mehling et al., 2012; Trotter et al., 2018; Von Mohr et al., 2021).

A further issue to acknowledge is related to the stimulation box used here. A possible disadvantage of our stimulation procedure was the limited adaptability to each participant's hand and arm dimensions, as the box was not customized for individual measurements. This may have introduced slight variations in the exact positioning of the stimulation, although the stimulated regions were consistent across participants, and the sample size was sufficiently large to reduce the weight of individual differences. The choice to use a standardized stimulation box could also have caused mild discomfort for some participants, who were required to keep their arm still within the box, and limited exploration of body regions other than hands and forearms. Despite these potential drawbacks, the stimulation box could reduce variability in stimulus administration, and ensured the double-blind condition that is crucial in assessing pleasant touch.

4.2. *Neural response associated with pleasant stimulation*

fNIRS data revealed that both pleasant and unpleasant stimuli elicited greater hemodynamic response in the PFC. In almost all monitored channels the stimuli resulting in the highest activation were one pleasant stimulus (the Plush, but not the Make-up Brush subjectively perceived as the most pleasant stimulus), and one unpleasant stimulus (the Dishnet, subjectively perceived as the most intense stimulus), whose activation was significantly greater as compared to that elicited by neutral stimuli (i.e., the Rubber). Therefore, hemodynamic data partially paralleled our behavioural findings, and underlined the relevance of employing diverse pleasant tactile stimuli to ensure a concomitant brain activation in experimental and clinical settings. Crucially, the present data would suggest that prefrontal activation to tactile stimulation is not strictly related to pleasantness of stimuli but also to the perceived intensity of the stimulus delivered (by a protocol devised to control for objective intensity of stimulation). Thus our data may shed light on a possible unexplored relationship between the pleasantness and the perceived intensity during somatosensory stimulation. Previous literature showed that PFC is activated by pleasant touch stimulation (Kida & Shinohara, 2013), but also by painful stimuli (Hsieh et al., 1995; Petrovic and Ingvar, 2002; Rainville et al., 1999; Rolls et al., 2003). Indeed, from an anatomical perspective, the CT afferent pathway exhibits similarities with projections related to temperature and pain, akin to all unmyelinated afferents utilising the lamina I pathway in the spinal cord (Basbaum et al., 2009; Davidovic et al., 2019; Kandel et al., 2000). Furthermore, damage to the PFC can result in lack of emotional distress for perception of painful stimuli, although patients remain accurate in detecting them (Rolls et al., 2003). Thus our data confirm the role of PFC in processing emotional aspects of somatosensory stimuli and underline that it is particularly related to appreciation of stimuli's relevance, independently from their valence and the precise subjective judgement related to each stimulus (pleasantness or intensity). Although behavioural data revealed greater sensitivity in the left palm, the lack of differences in patterns of hemodynamic changes as a function of the stimulated body area or side might be consistent with the idea that the activation of the PFC reflected the processing of emotional aspects of tactile stimulation, without specific somatotopic reference to the stimulated body part. However, this finding differs from those reported by Kida and Shinohara (2013), who observed a greater hemodynamic response following stimulation with a pleasant stimulus only (velvet), particularly in the left palm (albeit stimulation in this area was not judged as more pleasant than stimulation on the forearm or in the right hand in that study). The discrepancies between the two studies might be explained by the different stimulation procedures, as in Kida and Shinohara's study only the examinee was blind to the current stimulus, and the three stimuli were not strictly controlled for stimulation parameters. This once again highlights the need to adopt rigorous protocols for investigating the neural responses related to pleasant tactile stimulation.

Our findings regarding pleasant touch on glabrous areas, particularly the palm, may suggest a role for CT afferents in processing tactile pleasantness in these regions. However, without direct microneurography, we cannot definitively confirm CT involvement. It is possible that other neural pathways could account for the pleasantness of touch in glabrous skin, and future studies are required to test this hypothesis directly.

In the present study, the increased brain responses to unpleasant and pleasant stimuli compared to neutral ones allow to confirm the validity of the administered protocol. By assessing a variety of stimuli and body areas by a double-blind procedure, we obtained a deeper understanding of how pleasant tactile stimulation is processed and can influence hemodynamic responses in the PFC.

4.3. *Conclusions*

The protocol developed in this study provides an initial framework for investigating tactile stimulation in controlled experimental settings. While the procedure involved a human component, as stimuli were delivered by the experimenter, the double-blind approach aimed to reduce potential biases due to knowledge or expectations on the stimuli and offered insights into how pleasant touch is perceived and processed at both behavioural and neurophysiological levels on specific body areas in healthy participants. The double-blind approach could serve as a reference for future research in the field of pleasant and affective stimulation. Further research will possibly extend the present findings to other body sites, such as face and mouth which have been suggested as preferential areas for studying the CTs-affective fibers (McGlone et al., 2014; Morrison et al., 2010), and explore the modulating effect of other variables such as the participants age which may play a crucial role in responsiveness to affective stimulation (Sehlstedt et al., 2016). Understanding the subjective and objective dimensions of tactile awareness, as discussed by Cirillo et al. (2024), provides a valuable framework for interpreting our findings on pleasant touch, especially regarding how sensory perception and body ownership interact in shaping tactile experiences. Our findings on behavioural and hemodynamic responses to pleasant touch could have potential clinical applications, as pleasant touch can relief stress and induce measurable changes in heart rate, blood pressure, and cortisol release in various medical conditions (Cazzato et al., 2021; Crucianelli et al., 2021; Craig, 2002; Fairhurst et al., 2014; Feldman et al., 2010; Morrison, 2016a; 2016b; Giacino et al., 2014; Gossrau et al., 2021; Löffler et al., 2022; Nees and Becker, 2018; Norwood et al., 2023; Kass-Iliyya et al., 2017; Weaver et al., 2023; Walker & McGlone, 2013; Whitcher and Fisher, 1979).

CRediT authorship contribution statement

Simona Abagnale: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francesco Panico:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Laura Sagliano:** Writing – review & editing, Resources, Methodology, Funding acquisition, Conceptualization. **Olivia Gosseries:** Writing – review & editing, Supervision. **Luigi Trojano:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

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Conflict of interest

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Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2025.01.003.

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