Modeling affective touch pleasantness across skin types at the individual level reveals a reliable and stable basic function

Laura Crucianelli*+, Marie Chancel+, H. Henrik Ehrsson

Department of Neuroscience, Karolinska Institutet, Stockholm, Sweden

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+Equal contribution

*Corresponding author:
Laura Crucianelli, PhD
Department of Neuroscience
Karolinska Institutet
Solnavägen 9, 171 65 Solna
Stockholm, Sweden
Email: laura.crucianelli@ki.se

Abstract

Touch is perceived most pleasant when delivered at velocities known to optimally activate the C-Tactile afferent system. At the group level, pleasantness ratings of touch delivered at velocities in the range between 0.3 and 30 cm/s follows an inverted-U shape curve, with maximum pleasantness between 1 and 10 cm/s. However, the prevalence, reliability, and stability of this function at the individual level and across skin types based on hair density remains unknown. Here, we tested a range of seven velocities (0.3, 1, 3, 6, 9, 18, 27 cm/s) delivered with a soft brush, on both hairy (forearm and dorsal hand) and non-hairy skin (palm) in 123 participants. Our results suggest that the relationship between pleasantness and velocity of touch is significantly best described by a negative quadratic model at the individual level in the majority of participants both on hairy (67.1%) and non-hairy (62.6%) skin, a larger extent than previously reported. Higher interoceptive accuracy and self-reported depression were related to a better fit of the quadratic model and to the steepness of the curve, respectively. The prevalence of the quadratic model at the individual level was stable across body sites (62.6%, Experiment 1), across two experimental sessions (73-78%, Experiment 2), and regardless of the number of repetitions of each velocity (Experiment 3). Thus, the individual perception of tactile pleasantness follows a characteristic velocity-dependent function across skin types and shows trait characteristics. Future studies can investigate further the possibility to use affective touch as a behavioural biomarker for mental health disorders.

New & Noteworthy

Touch is perceived as most pleasant when delivered at slow, caress-like velocities, known to activate C-Tactile afferents. At the group level, tactile pleasantness and velocity of touch show a reliable pattern of relationship on hairy skin. Here, we found that the perception of tactile pleasantness follows a consistent pattern also at the individual level, across skin types and testing sessions. However, individual differences in interoceptive abilities and self-reported depression do play a role.

Introduction

Research on the sense of touch has identified two distinct modalities; a discriminative and an affective one (see (1), for a review). The sensory-discriminative dimension supports the detection and identification of external stimuli, providing information about physical characteristics and spatial location. In contrast, the motivational-affective dimension is involved in the valence and motivational nature of the stimuli, such as hedonic and emotional relevance (2) (3) (4) (5). The affective dimension of touch can be investigated by means of a low-pressure, slow, caress-like tactile stimulation delivered at velocities between 1 and 10 cm/s (5). This type of touch is perceived as generally more pleasant compared to slower or faster velocities according to subjective ratings. Studies using microneurography, a neurophysiological method allowing the recording of the activity of single peripheral nerves in the skin (6), showed an activation of C-Tactile (CT) afferents when touch presents the aforementioned characteristics (7).

Over the last few decades, research has supported the hypothesis that CT afferents constitute a distinct system, both from the anatomical and functional point of view, which may contribute to responses to slow, caress-like types of touch and provide pleasant sensations (7) (2) (5). These fibers are mainly present in the hairy skin of the body (7) (8), and when these fibers are activated, individuals report a pleasant percept. Löken and colleagues showed that there was a linear correlation between the activation of CT fibers and the subjective report of pleasantness (5). At the group level, the averaged pleasantness ratings of touch delivered at velocities in the range between 0.3 and 30 cm/s follow an inverted-U shape curve, with maximum pleasantness between 1 and 10 cm/s (5). This pattern of relationship between velocity of touch and tactile pleasantness has been replicated at the group level across several studies (see (9) for a recent meta-analysis). However, perception occurs in individuals, not groups, and we do not know how prevalent the inverted-U shape curve is and if it observable in most people as the prevailing CT-hypothesis would predict. One concern is that non-linear effects found at the group level could be driven by a minority of participants or effects that are so small as being psychologically "meaningless" for individuals (i.e., only an aggregated group-level effect).

To the best of our knowledge, only one recent study has investigated the fitting of the inverted U-shape curve at the individual level on hairy skin (10). Croy et al. (2021) pooled data from 5 separate studies and showed that surprisingly only 42% of participants presented the typical inverted U-shape curve, while 44% were better described by a linear model, and the remaining participants showed no significant effect of the velocity of touch on pleasantness ratings. Moreover, from the study of Croy and colleagues we do not know if the shape of the inverted U-function varies across different skin types with different CT innervation within individuals. It has recently been observed that CT afferents are seven times more numerous on hairy (forearm) compared to non-hairy skin (i.e., palm, (8)), although these results are preliminary and need to be replicated. According to a central prediction of the CT-hypothesis, this difference in CTs density should be reflected in more prevalent inverted-U shape pleasantness curves on hairy skin, but this important question has not been examined at the individual level. Noteworthy, a recent meta-analysis at the group level found no significant differences between hairy and non-hairy skin in the perception of tactile pleasantness (9), although the inverted-U shape was not analyzed at the individual subject level. Nevertheless, such evidence questions the traditional distinction between hairy and non-hairy skin in the perception of affective touch and what is known so far of the role that the CT system plays in mediating gentle touch, whereby the palm of the hand has classically been used as a control body site to compare against the forearm. Thus, we believe that now more than ever there is the need of more studies that systematically investigate the differences in tactile pleasantness across hairy and non-hairy skin sites. Accordingly, here we aimed to investigate the relationship between velocity of touch and pleasantness scores at the individual level, characterizing individual differences and prevalence of inverted U-shape functions across hairy and non-hairy skin as well as testing the stability and reliability of such individual pleasure-velocity functions across sessions and trials repetitions.

Importantly, the specialized peripheral and central neurophysiological systems underpinning the perception of affective touch (including the CT-system) seem to take a different pathway than the discriminative, more emotionally neutral touch from the peripheral nerves of the skin to the posterior insular cortex ((2), but see (11)). A recent study has suggested that spinothalamic projections might play only a partial role in the hedonic processing of touch mediated by C-Tactile afferents, thus proposing a more integrated view of tactile pleasantness (12).

However, several functional imaging studies in humans have shown that the posterior insular cortex is activated in response to CT fibers stimulation (2) (13) (14), an area strongly interconnected with regions related to emotional processing such as the amygdala, hypothalamus, and orbital frontal cortex ((15) (16), for reviews). Nevertheless, activations in the insula have also been observed in response to more emotionally neutral tactile stimulation (14), and activity in the right posterior superior temporal sulcus (pSTS) has been specifically linked to perceived tactile pleasantness in response to gentle skin stroking, but not to discriminative touch (i.e., vibration, (17)). In light of these neurophysiological observations as well as the role played in emotional processing (16), affective touch has been reconceptualized as an interoceptive modality providing information about the internal states of the body related to homeostatic functions (18) (19) (20) (21).

In parallel with the growing understanding of the functions, pathways, and characteristics of the affective touch system, there has also been increasing interest in better understanding the implications of dysfunction in such a system. In particular, a few studies have investigated the perception of affective touch in clinical populations, showing significant disruptions in the perception of affective touch in anorexia nervosa (22), autism (23) (24), right-hemisphere stroke (25), and chronic pain (26), among others. Overall, these studies have suggested the existence of a link between mental health and social touch perception (27). Given these conceptualizations, it is important to understand whether the perception of affective touch could be used as a behavioral biomarker for the early identification of people at risk of developing a mental health disorder. For this approach to work, it is essential to clarify the reliability and stability of the affective touch modeling results at the individual level in healthy samples.

The subjective perception of affective touch is the result of a combination of peripheral activation of skin receptors and central processing of such stimulation. Furthermore, personality and psychological traits can also play a role in the way we perceive touch. Although touch is mediated by the skin, its perception is the result of a combination of bottom-up signals (i.e., afferent signals resulting from the activation of the nerve fibers in the skin) and top-down factors, such as previous experiences, the context, the identity and gender of the toucher (28), as well as reward processing (e.g., (29)). Accordingly, an additional aim of this study was to investigate the relationship between individual traits and characteristics (i.e., depression, anxiety, eating disorders symptomatology) and individual differences in the perception of tactile pleasantness. In line with the idea of affective touch as an interoceptive modality (18), we also aimed to investigate whether cardiac interoceptive accuracy, measured by means of a classic heartbeat-counting task (30), would predict the pattern of the relationship between velocity of touch and tactile pleasantness (see (21) for a similar approach).

Here, across three experiments, we aimed to assess 1) whether and to what extent the classic negative quadratic model (i.e., inverted U shape) outperformed a linear model to describe the relationship between velocity and pleasantness of touch at the individual level; 2) which individual difference factors can predict the significance and prevalence of the negative quadratic model (i.e., how common or prevalent the negative quadratic model is); 3) whether the relationship between velocity and pleasantness varies across hairy vs. non-hairy skin within individuals; and 4) whether the individual variability in the perception of tactile pleasantness is temporally stable, both when tested across two identical experimental sessions one week apart and when tested with an increasing number of repetitions at each velocity. We separately describe the specific procedures for each experiment below.

EXPERIMENT 1

The *first aim* of Experiment 1 was to test whether the impact of stroking velocity on subjective pleasantness could be better described by a quadratic or a linear regression. (10) recently showed that the typical inverted U-shape curve described the relationship between the velocity of touch and pleasantness in only 42% of participants. However, these results were obtained by pooling data from 5 separate studies that included a total of 127 participants tested by different experimenters and under different conditions. Indeed, Croy and colleagues (2021) reported a consistent effect of the experimental setting on tactile pleasantness. Here, we aimed to investigate whether the classic negative quadratic model outperformed a linear model in describing the relationship between velocity and pleasantness at the individual level with a set of participants tested under the same conditions and by the same experimenter. We hypothesized that the majority of individual participants should display a better fit with negative quadratic model in line with the CT-hypothesis.

Furthermore, several factors are known to influence the shape of the group-level curve. Thus, the *second aim* of Experiment 1 was to test whether these individual characteristics can also modulate pleasantness ratings at the individual level. We collected data regarding several individual characteristics that could potentially influence the perceived pleasantness of touch based on previous studies. We included the Eating Disorder Examination Questionnaire (EDE-Q) to target potential body dissatisfaction and weight restraint behaviors (see (22) (31)); self-reported measures of depression and anxiety to target potential links with anhedonia and affective disorders symptomatology (27) (32) (33) and cardiac interoceptive accuracy, measured by means of the classic heartbeat-counting task (29), to target interoceptive abilities quantified via a non-tactile modality. In keeping with the aforementioned literature, participants with higher scores on the EDE-Q, depression, and anxiety scales were expected to give lower pleasantness ratings overall and to have difficulties differentiating tactile pleasantness levels based on stroking velocities. In other words, we predicted that higher EDE-Q, depression, and anxiety scores would lead to "flatter curves", i.e., the participants would give lower pleasantness ratings and would rate stroking at different velocities as being more similar. Moreover, because of this expected loss of influence of stroking velocity on pleasantness ratings, the quadratic model should be less relevant in participants with higher scores on these individual characteristics with respect to a random pattern of answers. In contrast, a higher cardiac interoceptive accuracy should be related to an increased perception of pleasantness of CT-optimal velocities (see also (21)). Finally, we explored whether the same individual characteristics could predict not only how well participant's answers would be described by a quadratic model but also how well the estimated coefficients of this quadratic model fit.

The *third aim* of Experiment 1 was to assess the hypothesized differences in velocity-pleasantness functions across hairy and non-hairy body sites (forearm/hairy skin vs. palm/non-hairy skin) based on the well-known differences in CT afferents density and related tactile pleasantness perception between these two skin types (e.g., (7) (33) (8)). The CT-hypothesis predicts a more pronounced inverted U-shape pleasantness-velocity function on hairy skin and that a higher proportion of participants should express this function on hairy skin. To this end, we compared the observed and predicted likelihood for each participant to best fit negative quadratic model or the linear model for both body sites.

Methods and Materials

Participants

A total of 107 healthy, naïve participants (53 females and 54 males, mean age 26.2 ± 5 years) were recruited for Experiment 1 using social media and advertising on the Karolinksa Institutet campus. An a priori power analysis based on previous studies in the field of affective touch (e.g., (10)) suggested that the present sample provided enough power to detect our effects of interest. The inclusion criteria included being 18-40 years old and being right-handed. The exclusion criteria included having a history of any psychiatric or neurological conditions, taking any medications, having sensory or health conditions that might result in a skin condition (e.g., psoriasis), and having any scars or tattoos on their left forearm or hand. The study was approved by the Swedish Ethical Review Authority. All participants provided signed written consent, and they received a cinema ticket as compensation for their time. The study was conducted in accordance with the provisions of the Declaration of Helsinki 1975, as revised in 2008. Part of the data obtained in Experiment 1 was analyzed using a different statistical method for different purposes and has been published as part of another manuscript (34).

Self-reported measures

Participants were asked to provide demographic information, such as age and handedness. Next, the participants were asked to complete the following self-report questionnaires: the Eating Disorders Examination Questionnaire (EDE-Q 6.0), a 28-item questionnaire measuring eating disorders symptomatology that has good consistency and reliability (global score $\alpha = .90$; (35) (36) (37)), and the Depression, Anxiety and Stress Scale–21 Item (DASS), a 21-item, three-scale self-reported measure of depression, anxiety and stress that has an $\alpha > .88$ (38) (39).

Cardiac interoceptive accuracy: heartbeat counting task (HCT)

Participants were asked to silently count their heartbeats between two verbally given signals of 'go' and 'stop' without manually taking their pulse. Both hands were placed on the table to ensure that no body part was touched. Participants completed a practice trial of 15 seconds before proceeding to the three experimental trials lasting 25 s, 45 s and 65 s, which were presented in a randomized order. The task is fully described in Supplementary Materials.

Affective touch task

This task takes advantage of the discovery that affective, hedonic touch on the skin can be reliably elicited by soft, light stroking at specific velocities within the range of 1-10 cm/s that activate a specialized peripheral system of CT afferents (5) (3). Before starting the task, the male experimenter identified two adjacent areas measuring 9x4 cm on the left forearm and two on the left palm with a washable marker (see Procedure for more details). Then, participants were familiarized with the rating scale ranging from 0, not at all pleasant, to 100, extremely pleasant. The touch was delivered using a soft brush (i.e., precision cheek brush No 032, Åhléns, Sweden) on the left forearm (hairy skin that contains CT afferents) and left palm (non-hairy skin, where only limited CT afferents activity has been reported (8), and the task of the participants was always to verbally rate the pleasantness of the touch using the rating scale. Participants were asked to wear a blindfold so that they could better focus on the tactile experience. The touch was delivered at seven velocities (0.3, 1, 3, 6, 9, 18 and 27 cm/s). The two slow velocities of 3 and 6 cm/s are typically perceived as more pleasant (i.e., CT optimal velocities) than the borderline optimal velocities (1 and 9 cm/s) and the CT non-optimal speeds (0.3, 18 and 27 cm/s; (5)). In keeping with previous studies (e.g., (10)), each velocity was presented three times, for a total of 21 stroking trials per location (palm and forearm). The order of velocities as well as the order of the location blocks (block palm/block forearm) were randomized. Post-hoc analysis reveals no significant location block order effect (see section 2.6 in Supplementary Materials).

Experimental Procedure

Participants were welcomed in the experimental room, and they were asked to sit at a table opposite the experimenter. Upon arrival, they were asked to sign the consent form and to complete the questionnaires presented in an online format: demographic questionnaire, EDE-Q and DASS. The questionnaires were always presented at the beginning of the experimental procedure to ensure that participants were given some time to rest before completing the heartbeat counting task, which was the first interoceptive task that all participants completed. Given that previous studies showed that the heartbeat counting task might be influenced by other activities (40) (41), we decided to keep it as the first task. Participants were given the choice to keep their eyes closed or open, allowing them to feel more comfortable and be as accurate as possible (as in (21)). Next, participants were asked to wear a disposable blindfold to complete the affective touch task. Participants were familiarized with the pleasantness rating scale, and the experimenter identified and marked with a washable marker two identical areas of 9x4 cm on the left forearm and palm, as in previous studies (42) (22) (21). This was done to control for the stimulated area and for the pressure applied during the touch by checking that the tactile stimulation was only applied inside the marked areas (more pressure would result in a wider spreading of the brush, that is, the tactile stimulation would be applied outside of the marked borders). Alternating the stimulated areas prevented fatigue of the CT fibers (43).

Design and plan of analysis

To test our *first aim* (i.e., whether the impact of stroking velocity on tactile pleasantness was better described by a negative quadratic or a linear regression), the data acquired from the different body sites were considered separately. Please note that in the rest of the manuscript, we talk about quadratic model for simplicity, but we have always considered a *negative* quadratic function. For each participant, both types of regressions were performed on the mean ratings for each stroking velocity (velocities are considered as a categorical factor as custom is affective touch literature, (5)); the fitting procedures were performed in R. We first considered how many participants showed a significant main effect of velocity on the pleasantness ratings (ANOVA). Those who did not, were categorized as having a ‘random’ profile (i.e., not significantly described by either a quadratic or linear regression). The remaining participants were categorized either as having a ‘quadratic’ or ‘linear’ profile. To do so, we fitted two models: one linear: pleasantness ~ velocity, and one quadratic: pleasantness ~ velocity + velocity^2. This categorization was straightforward when only the quadratic fit or the linear fit were significant. When both fits were significant, a likelihood-ratio test (LRT) was performed: this LRT compares the goodness-of-fit of our two models (quadratic versus linear) while considering the lesser parsimony of the quadratic model, i.e., the quadratic model includes one more parameter than the linear model and thus has an inherent advantage. A significant LRT ($p < 0.05$) meant the participants' profile would be categorized as 'quadratic', otherwise the participant's profile would be categorized as 'linear'. We further quantified the goodness-of-fit of the models using the root mean square error (RMSE). A lower RMSE indicated a better fit.

$$RMSE = \sqrt{\sum \frac{(Rating_{observed} - Rating_{predicted})^2}{n_{number\ of\ data\ points}}}$$

Moreover, to compare the relative relevance of each model at the individual level for our whole sample, we performed a confidence interval analysis (CI analysis) on the residual standard deviation (RSD). Simply put, in addition to knowing which model fits best, we wanted to know how much better one model was compared to the other for each participant and whether this difference in performance between the two models was meaningful at the group level. The RSD reflects how much the observed data spread around the regression curve and takes into account the degree of freedom of each model. The smaller the residual standard deviation was, the better the fit and the more predictive the model was.

$$RSD = \sqrt{\sum \frac{(Rating_{observed} - Rating_{predicted})^2}{n_{number\ of\ data\ points} - k_{number\ of\ free\ parameters}}}$$

To compare the two models, the difference in RSD between the quadratic and linear models was calculated and summed across participants. We estimated a confidence interval using bootstrapping: 107 random RSD differences (quadratic – linear) were drawn with replacement from the actual participant's RSD differences and summed; this procedure was repeated 10000 times to compute the 95% CI. Negative CI bounds would provide evidence of an overall better quadratic fit compared to a linear fit (see also Figure S1 in Supplementary Materials).

To address the *second aim* (i.e., to test whether individual characteristics influenced the pleasantness ratings at the individual level), we tested two correlation hypotheses: first, whether the quadratic RMSE increased with higher EDE-Q, depression, and anxiety scores, i.e., we expected a worst fit by the quadratic model. Second, whether the difference in RSD between the quadratic and the linear model (RSDd) would also increase, i.e., we assessed whether the relative relevance of the quadratic model compared to the linear model was reduced. Inverse correlations were expected with cardiac interoceptive accuracy: the lower the cardiac interoceptive accuracy was, the flatter the curve.

Furthermore, we tested the hypothesis that the same individual characteristics could predict not only how well participants' answers would be described by a quadratic model but also the coefficients of this quadratic fit. Indeed, as mentioned above, the participants with higher EDE-Q, depression, and anxiety scores were expected to show "flatter curves", i.e., to give lower pleasantness ratings and to rate the different stroking velocities as similarly pleasant. For the participants with a significant quadratic fit, the quadratic term coefficient (A2) reflects how different the pleasantness ratings are from one velocity to the other, i.e., the curvature of the curve. The intercept coefficient (A0) reflects the overall pleasantness (see Supplementary Materials and Figure S2 for more details about the influence of each coefficient of the quadratic model on the collected pleasantness ratings). Based on our hypothesis, for participants with higher EDE-Q, depression, and anxiety scores, A2 should get closer to 0 and A0 should decrease. We tested these hypotheses by means of one-sided Spearman correlation tests on our whole population to investigate the relationship between the individual characteristics and the quadratic model RMSE and RSDd values. Then, in the subpopulation for which the quadratic fit was significant, we used one-sided Spearman correlation tests between the individual characteristics and the A2 (quadratic term) and A0 (intercept) coefficients.

The *third and last aim* of Experiment 1 was to assess the stability of the relationship between pleasantness ratings and stroking velocity across body sites (forearm versus palm). We compared the observed and predicted likelihood for a participant to be in the same profile category for both body sites. The predicted likelihood was calculated as the square of the probability of having a given profile for stroking on the forearm. The observed likelihood was calculated as the product of the probability of having a given profile for stroking on the forearm multiplied by the probability of participants with this given profile also having this profile for stroking on the palm. This analysis is similar to the one used by (44) to assess the stability of pleasantness ratings across repetitions on two different days. Finally, the participants who showed the ‘quadratic’ profile in both body sites could still display very different patterns of response (e.g., steep versus flat curves, different maximum and minimum). Thus, we investigated how correlated the coefficients of the quadratic model, A2, A1, and A0 were between the forearm and the palm stroking sites.

Results

Demographic and self-reported data

The mean scores and standard deviations for the EDE-Q and DASS are reported in Table S1. No effect of gender on any of these measures was found, except for the EDE-Q scores. See also Figure S3 in Supplementary Materials for the data distribution of the self-reported scores. Chi-squared tests of independence on the profile repartition did not reveal any significant difference between female and male participants for forearm ($p = 0.362$) nor for palm ($p = 0.328$); hence, gender was not included as a factor in the analyses.

Pleasantness for different stroking velocities on the forearm (hairy skin)

a. Categorization into ‘quadratic’, ‘linear’, or ‘random’ profiles

At the group level, we observed the classic inverted U-shaped curve. These results replicating the classically observed group-level results for tactile pleasantness ratings (see Figures 1 and S4).

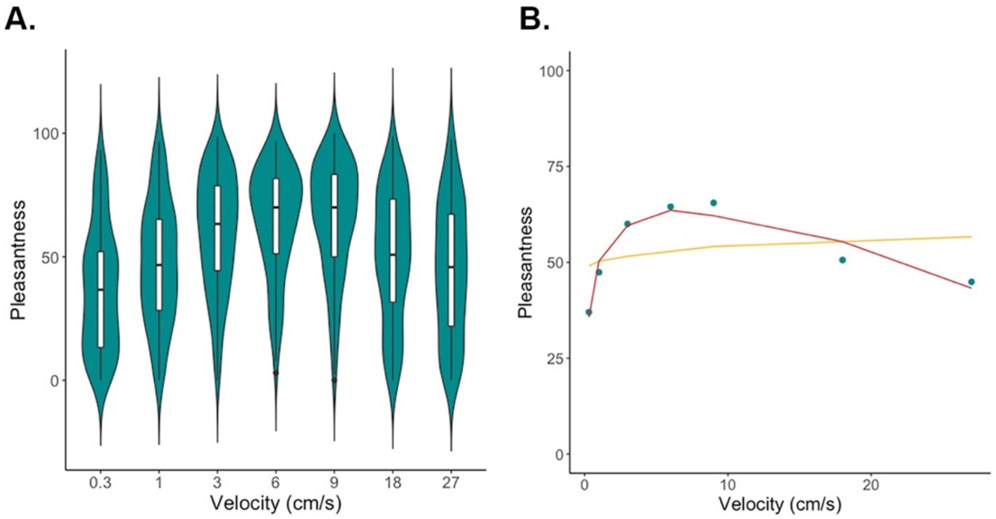
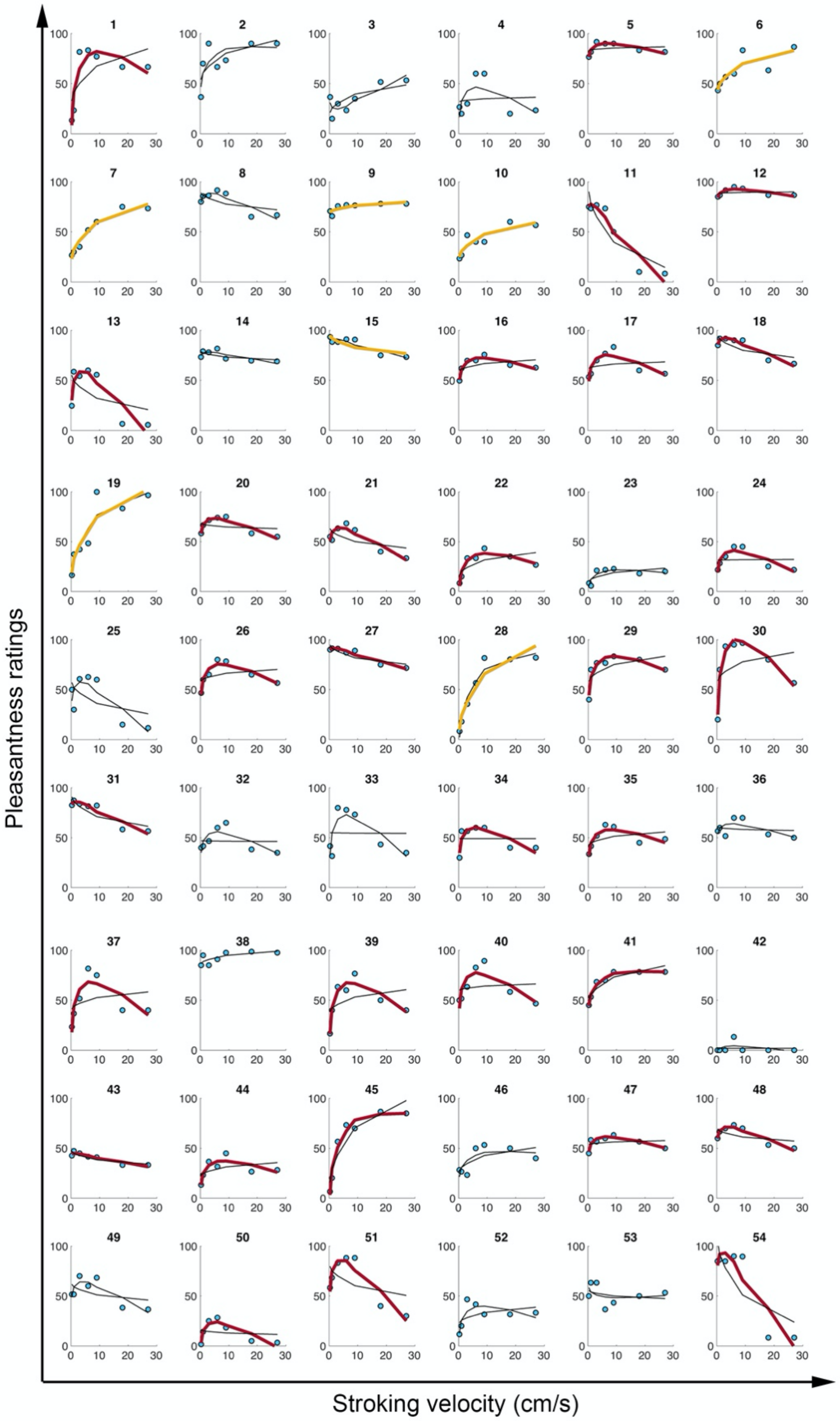


Figure 1: Group level pleasantness ratings in response to strokes applied to the forearm at different velocities. At the group level, we observe the classic inverted U-shaped curve ($F(2, 4) = 26.93$, $p < 0.005$; I(Velocity^2): $t = -7.078$, $p = 0.00210$ **). (A) The plotted colorful shapes reflect the probability densities of the corresponding ratings among the participants. The lower and upper hinges of each box inside the shapes correspond to the first and third quartiles, respectively, with the thick horizontal lines representing the medians. The upper and lower whiskers extending from the boxes indicate the range of maximum to minimum values. (B) Quadratic (red) and linear (yellow) fits of the data (blue dots).

At the individual level, 25 participants (23.4%) did not show a significant effect of velocity on perceived pleasantness and were thus categorized as ‘random’. Out of the 82 remaining participants, 72 (67.1%) showed a ‘quadratic’ profile, and 10 (9.3%) showed a ‘linear’ profile (Figure 2). The raw sum for the RSD differences between the quadratic and linear models was -620, and the 95% CI analysis confirmed that the quadratic regression outperformed the linear regression (lower bound: -727; upper bound: -516). Overall, our results showed that despite individual differences, the influence of stroking velocity on pleasantness ratings was better described by a quadratic regression than by a linear regression at the individual level as it was at the group level.


Pleasantness ratings
Stroking velocity (cm/s)
1
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7
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16
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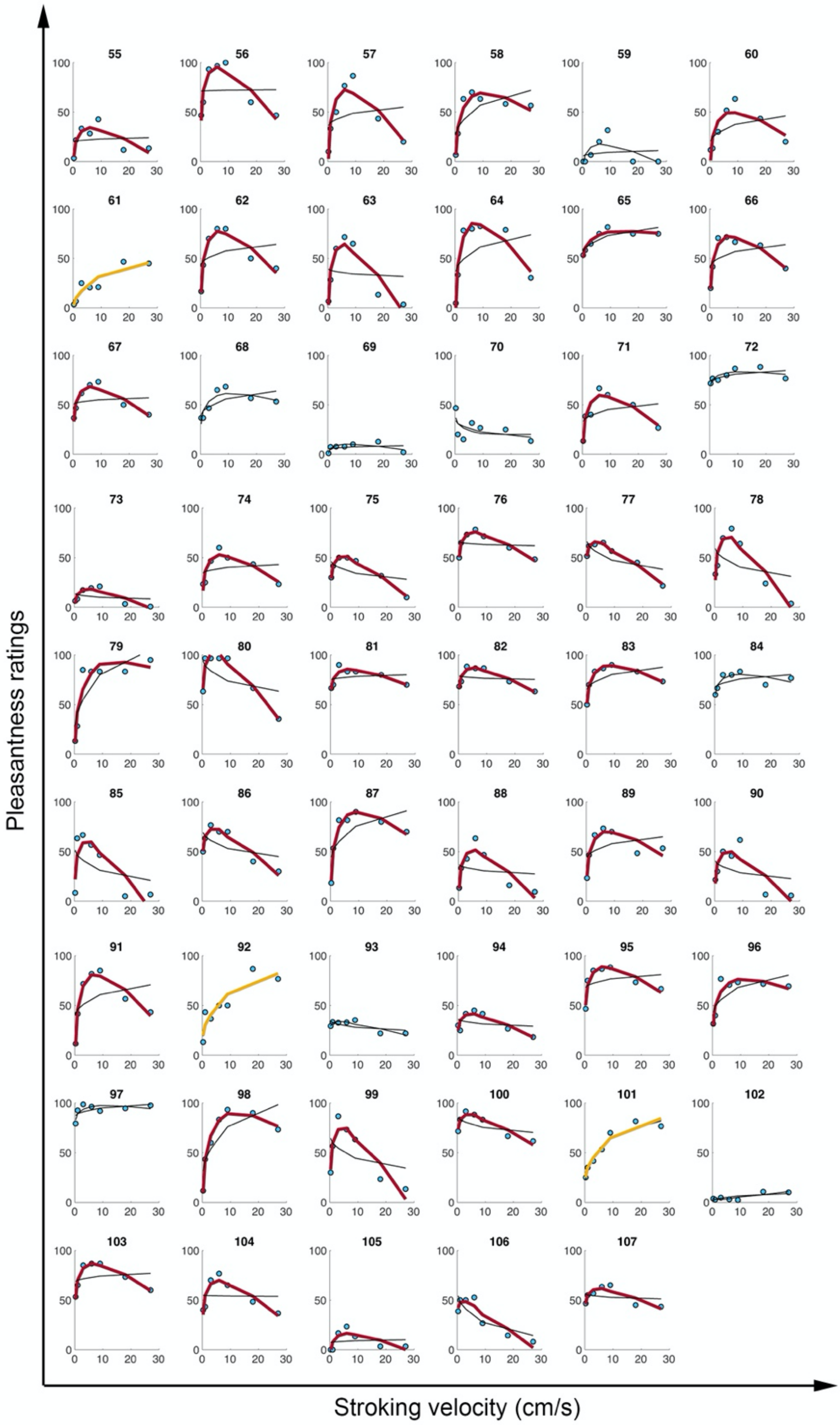


Figure 2: Individual pleasantness ratings in response to strokes applied to the forearm at different velocities (Experiment 1). The figure displays the individual pleasantness ratings at each stroking velocity (blue dots) and the linear and quadratic fit results (curves). A thick red curve indicates that the participant has a 'quadratic' profile (i.e., significant quadratic fit and *p values* (LRT) < .05). A thick yellow curve indicates that the participant has a 'linear' profile (i.e., significant linear fit and *p values* (LRT) > .05). The absence of a bold curve (neither red nor yellow) indicates that the participant has a 'random' profile.

b. Sub-threshold psychopathology scales and cardiac interoceptive accuracy

First, we investigated whether the individual characteristics we collected could predict how well the quadratic model would predict the pleasantness ratings reported by the participants. We observed a small but significant negative correlation between the cardiac interoceptive accuracy score and the RMSE. For the whole population, the better the cardiac interoceptive accuracy was, the better the fit of the quadratic model (Table 2).

Table 2: Correlation results for the stroking delivered to the forearm.

Variable of interest	Spearman correlation	S	*P*	Rho	CI [95%]	
RMSE	EDE-Q	39856	0.37	0.04	-0.20	0.28
	Depression	210404	0.62	-0.03	-0.25	0.17
	Anxiety	202394	0.46	0.01	-0.16	0.20
	Cardiac interoceptive accuracy	**236066**	**0.04**	**-0.16**	**-0.32**	**-0.04**
	Stress	226436	0.26	-0.11	-0.31	0.09
RSDd	EDE-Q	39190	0.68	0.06	-0.19	0.32
	Depression	192923	0.71	0.06	-0.15	0.26
	Anxiety	205676	0.47	-0.01	-0.20	0.18
	Cardiac interoceptive accuracy	212430	0.66	-0.04	-0.22	0.16
	Stress	221298	0.39	-0.08	-0.26	0.09

We then focused on the participants with a ‘quadratic’ profile. We investigated whether the individual characteristics correlated with the shape of the estimated curve, and more precisely, the A2 and A0 coefficients. We found that higher depression scores indicated a flatter curve: higher depression scores were associated with A2 coefficients closer to 0 (Table 3).

Table 3: Correlation results for the stroking delivered to the forearm for the participants with a ‘quadratic’ profile (N = 72).

Variable of interest	Spearman correlation	S	*P*	Rho	CI [95%]	
A2	EDE-Q	8206	0.27	0.10	-0.25	0.43
	Depression	**49024**	**0.04**	**0.21**	**0.06**	**0.42**
	Anxiety	60932	0.43	0.02	-0.20	0.26
	Cardiac interoceptive accuracy	53088	0.89	0.15	-0.09	0.36
	Stress	55333	0.36	0.11	-0.12	0.33
A0	EDE-Q	7406	0.87	0.19	-0.23	0.52
	Depression	55841	0.80	0.10	-0.14	0.33
	Anxiety	54604	0.85	0.12	-0.13	0.33
	Cardiac interoceptive accuracy	52114	0.09	0.16	-0.09	0.38
	Stress	56540	0.45	0.09	-0.17	0.32

Pleasantness for different stroking velocities on the palm (non-hairy skin)

a. Categorization into 'quadratic', 'linear', or 'random' profiles

At the group level, we observed the classic inverted U-shaped curve (see Figures 3 and S5).

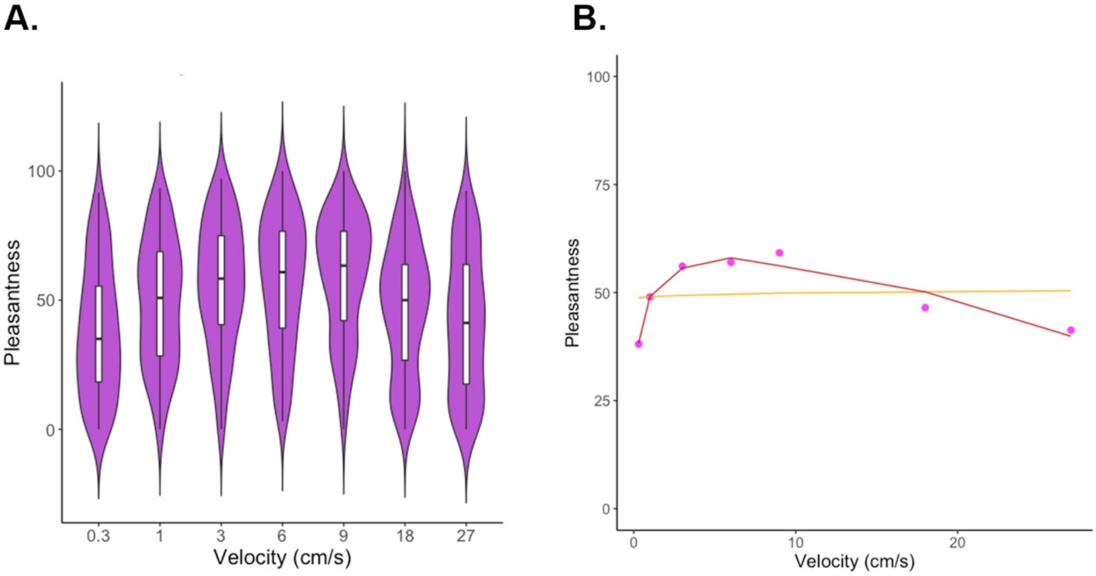
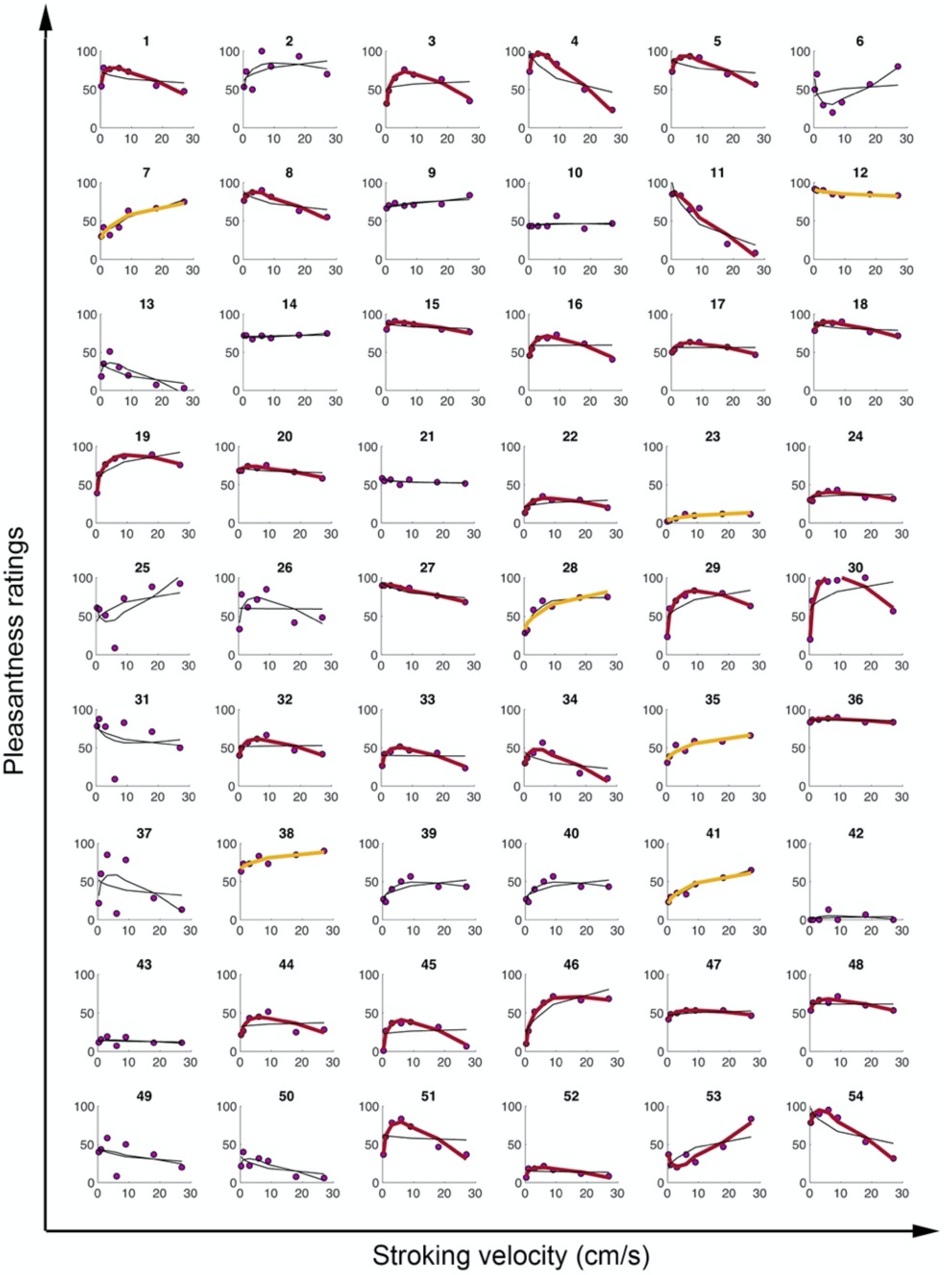


Figure 3: Group level pleasantness ratings in response to strokes applied to the palm at different velocities. At the group level, we observe the classic inverted U-shaped curve ($F(2, 4) = 29.25$, $p < 0.005$, I(Velocity^2): $t = -7.627$, $p = 0.00159$ **). (A) The plotted colorful shapes reflect the probability densities of the corresponding ratings among the participants. The lower and upper hinges of each box inside the shapes correspond to the first and third quartiles, respectively, with the thick horizontal lines representing the medians. The upper and lower whiskers extending from the boxes indicate the range of maximum to minimum values. (B) Quadratic (red) and linear (yellow) fits of the data (purple dots).

At the individual level, 28 participants (26.2%) did not show a significant effect of velocity on perceived pleasantness and were thus categorized as 'random'. Out of the 79 remaining participants, 67 (62.6%) showed a 'quadratic' profile, and 11 (10.3%) showed a 'linear' profile (Figure 4). The raw sum for the RSD differences between the quadratic and linear models was -548, and the CI analysis confirmed that the quadratic regression outperformed the linear regression (lower bound: -642; upper bound: -457). Overall, our results showed once again that despite individual differences, the influence of stroking velocity on pleasantness ratings was better described by a quadratic regression than by a linear regression at the individual level as it was at the group level.


Pleasantness ratings
Stroking velocity (cm/s)
1
2
3
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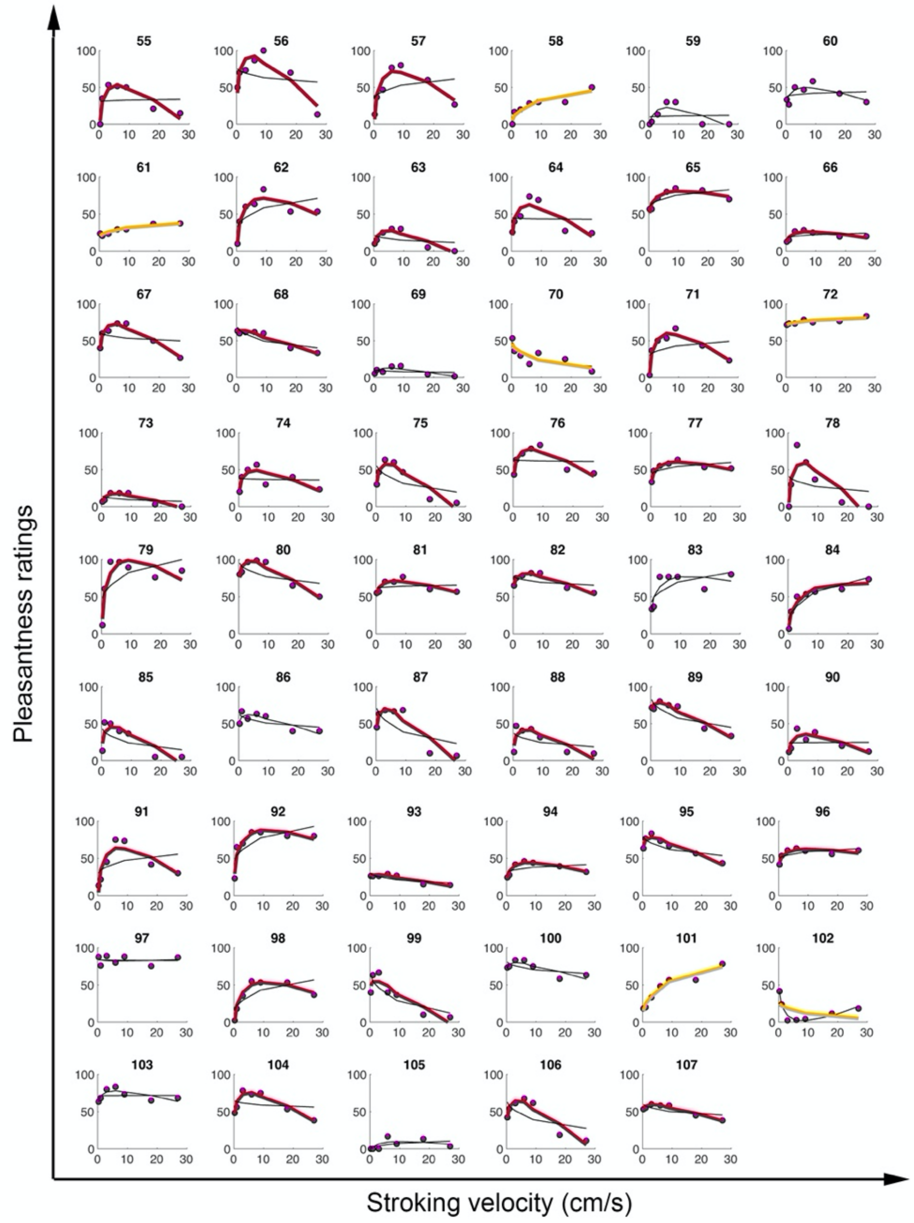


Figure 4: Quadratic and linear fit of individual pleasantness ratings in response to strokes applied to the palm at different velocities (Experiment 1). The figure displays the individual pleasantness ratings at each stroking velocity (purple dots) and the linear and quadratic fit results (curves). A thick red curve indicates that the participant has a 'quadratic' profile (i.e., significant quadratic fit and *p values*(LRT) < .05). A thick yellow curve indicates that the participant has a 'linear' profile (i.e., significant linear fit and *p values*(LRT) > .05). The absence of a bold curve (neither red nor yellow) indicates that the participant has a 'random' profile.

b. Sub-threshold psychopathology scales and cardiac interoceptive accuracy

The following correlation analyses are the same as those reported before: we investigated whether the individual indices we collected could predict the shape of the pleasantness ratings reported by the participants, but this time for stimulation delivered to the palm. For the whole population, no significant correlation was observed. Only trends were identified between interoceptive accuracy and RMSE

(Table 4), while this correlation was significant for the data collected after stroking the forearm (Table 2).

Table 4: Correlation results for the stroking delivered to the palm.

Variable of interest	Spearman correlation	S	*P*	Rho	CI [95%]	
RMSE	EDE-Q	36972	0.19	0.11	-0.13	0.36
	Depression	204788	0.51	0.00	-0.21	0.17
	Anxiety	184781	0.17	0.09	-0.12	0.27
	Cardiac interoceptive accuracy	234346	0.06	-0.15	-0.30	0.09
	Stress	196670	0.71	0.04	-0.15	0.21
RSDd	EDE-Q	45320	0.25	-0.09	-0.35	0.18
	Depression	177493	0.91	0.13	-0.08	0.33
	Anxiety	191446	0.74	0.06	-0.14	0.26
	Cardiac interoceptive accuracy	205820	0.53	-0.01	-0.21	0.18
	Stress	207402	0.87	-0.02	-0.21	0.19

We then performed the same analyses we performed for the forearm ratings, focusing only on the participants with a ‘quadratic’ profile and the A2/A0 coefficients. No significant correlations were observed (Table 5).

Table 5: Correlation results for the stroking delivered to the forearm for the participants with a ‘quadratic’ profile (N = 67).

Variable of interest	Spearman correlation	S	*P*	Rho	CI [95%]	
A2	EDE-Q	6298	0.42	0.04	-0.29	0.38
	Depression	47420	0.33	0.05	-0.18	0.29
	Anxiety	51208	0.57	-0.02	-0.27	0.23
	Cardiac interoceptive accuracy	44645	0.81	0.11	-0.13	0.34
	Stress	56032	0.34	-0.12	-0.34	0.10
A)	EDE-Q	6983	0.35	-0.07	-0.45	0.30
	Depression	54582	0.24	-0.09	-0.32	0.14
	Anxiety	49388	0.55	0.01	-0.22	0.29
	Cardiac interoceptive accuracy	56072	0.83	-0.12	-0.35	0.13
	Stress	56762	0.28	-0.13	-0.35	0.13

Stability of pleasantness ratings across body sites

a. Repartition in profiles

Sixty-seven (62.6%) participants displayed the same profile for forearm and palm stroking. This result is above chance level (33%). The detailed repartition of the participants is shown in Table 6. Furthermore, the observed likelihood for each profile exceeded the predicted likelihood (Table 7). Again, this result suggested that the identified profiles were stable across body sites.

Table 6: Repartition of the participants into profiles for both body sites.

		Palm profiles			
		Quadratic	Linear	Random	*Total*
Forearm profiles	Quadratic	53	4	15	*72*
	Linear	3	4	3	*10*
	Random	11	4	10	*25*
	Total	*67*	*12*	*28*	*107*

Table 7: Predicted and observed likelihoods for each profile to be identical at both body sites.

	Predicted likelihood	Observed likelihood	Difference	Interpretation
Quadratic	0.453	0.495	0.043	The observed likelihood is always higher than the predicted one. This is an argument in favor of stability.
Linear	0.009	0.037	0.029	
Random	0.055	0.093	0.039	

b. Stability of the model's coefficients for participants with a 'quadratic' profile

This section examines the correlations between the model coefficients A2 (quadratic term), A1 (linear term), and A0 (intercept) for the different body sites for the participants who had a 'quadratic' profile at both the forearm and the palm. Each coefficient was significantly correlated with its homolog from the other body site (A2: S = 8571, $p < .001$, rho = 0.65; A1: S = 8604, $p < .001$, rho = 0.65; A0: S = 4970, $p < .001$, rho = 0.80; see Figure S6 in Supplementary Materials). These strong observed correlations argue in favor of a stability in pleasantness judgment across body sites. Too few participants (four) showed a stable "linear" profile for a similar analysis in this subpopulation to be meaningful.

EXPERIMENT 2

The focus of Experiment 2 was to test the stability of the perceived pleasantness across two experimental sessions performed a week apart. We compared the observed and predicted likelihood for a participant to be in the same profile category in both sessions. The predicted likelihood was calculated as the square of the probability of having a given profile in session 1. The observed likelihood was calculated as the product of the probability of having a given profile in session 1 multiplied by the probability of participants with this given profile also having this profile in session 2. This analysis is similar to the one used in Experiment 1 to assess the stability across body sites and by Bendas et al. (2021) to assess the stability of pleasantness ratings across repetitions on two different days. Again, the participants who had a ‘quadratic’ profile in both sessions could still display very different patterns of response (e.g., steep versus flat curves, different maximum and minimum). Thus, we investigated the correlation between the coefficients of the quadratic model, A2, A1, and A0, from one session to the other.

Method

Participants and procedure

Forty-one participants from Experiment 1 took part in this follow-up (20 females and 21 males; 25.1 ± 4 years). These participants underwent the same exact procedure as in Experiment 1 twice in total, with the two sessions being one week apart. This group was also tested at another hairy-skin body site, i.e., the back of their hand (dorsal condition), in both sessions. This body site is less often investigated than the forearm; therefore, we chose to report mainly the comparison between the palm and forearm. However, the results regarding the dorsal condition can be found in Supplementary Materials (Figure S11).

Data analysis

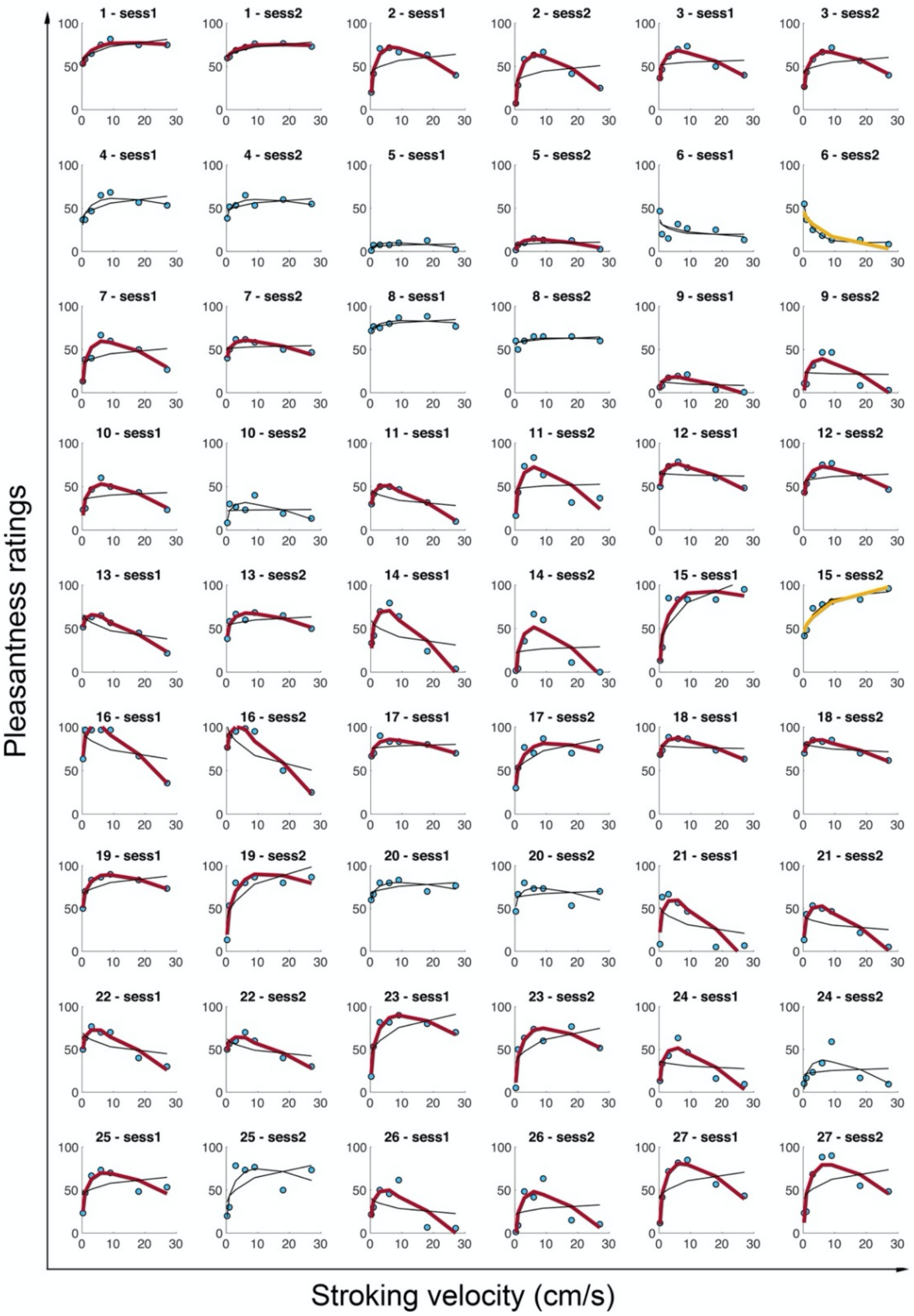
For each body site, the data from the two sessions were analyzed separately. The model fitting and profile categorization were the same as those used in Experiment 1.

Results

Response to forearm (hairy skin) stimulation

a. *Quadratic, linear, and random profile categorization*

At the group level, we observed the classic inverted U-shaped curve. These results replicating the classically observed group-level results for tactile pleasantness ratings can be found in Supplementary Materials (see Figure S7). In response to stimulation applied to the forearm, 8 (19.5%) participants did not show a significant effect of velocity on perceived pleasantness and were thus categorized as ‘random’, 31 (75.6%) participants were categorized as having a ‘quadratic’ profile, and 2 (4.9%) participants were categorized as having a ‘linear’ profile in session 1 (Figure 5). In session 2, 7 (17.1%) participants were categorized as having a ‘random’ profile, 28 (68.3%) participants were categorized as having a ‘quadratic’ profile, and 6 (14.6%) participants were categorized as having a ‘linear’ (Figure 5). As in Experiment 1, the CI analysis showed a clear superiority of the quadratic model for both sessions (session 1: lower bound: -356, raw sum: -291, upper bound: -226; session 2: lower bound: -310, raw sum: -255, upper bound: -202).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26 - sess1
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27 - sess2
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100
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10
20
30
Pleasantness ratings
Stroking velocity (cm/s)

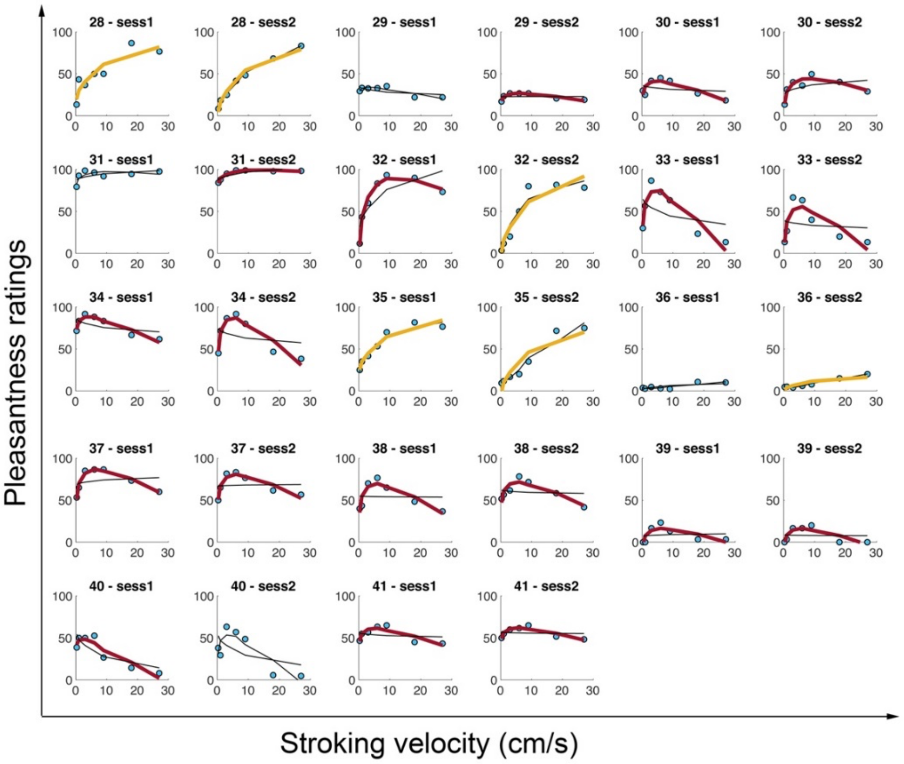


Figure 5: Quadratic and linear fit of individual pleasantness ratings in response to strokes applied to the forearm for both sessions (Experiment 2). The figure displays the individual pleasantness ratings at each stroking velocity (blue dots) and the linear and quadratic fit results (curves). A thick red curve indicates that the participant has a 'quadratic' profile (i.e., significant quadratic fit and *p values*(LRT) < .05). A thick yellow curve indicates that the participant has a 'linear' profile (i.e., significant linear fit and *p values*(LRT) > .05). The absence of a bold curve (neither red nor yellow) indicates that the participant has a 'random' profile. For each participant, the results from the two sessions are plotted side-by-side.

b. *Stability across sessions for forearm stroking*

Twenty-five (73%) participants displayed the same profile in session 1 and session 2. This result was above chance level (33%). The detailed repartition of the participants is shown in Table 8. Furthermore, the observed likelihood for each profile exceeded the predicted likelihood (Table 9). This result suggested that the identified profiles were stable across sessions.

Table 8: Repartition of the participants into profiles for both sessions.

		Session 2 profiles			
		Quadratic	Linear	Random	*Total*
Session 1 profiles	Quadratic	25	2	4	*31*
	Linear	0	2	0	*2*
	Random	3	2	3	*8*
	Total	*28*	*6*	*7*	*41*

Table 9: Predicted and observed likelihoods for each profile to be identical in both sessions.

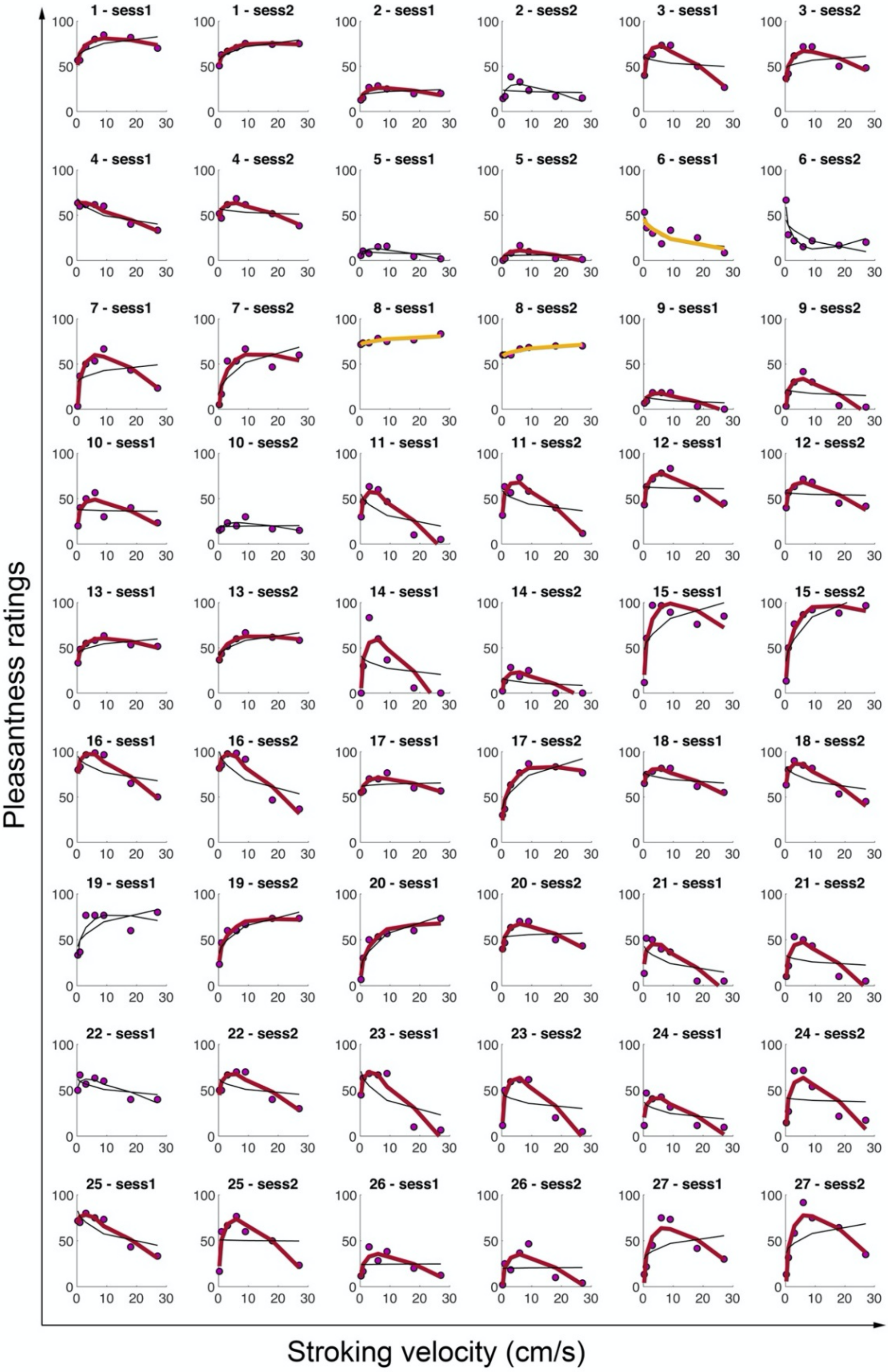
	Predicted likelihood	Observed likelihood	Difference	Interpretation
Quadratic	0.57	0.61	0.04	The observed likelihood is higher than the predicted one. This is an argument in favor of stability
Linear	0.00	0.05	0.05	
Random	0.04	0.07	0.04	

We then examined the correlations between the model coefficients A2 (quadratic term), A1 (linear term), and A0 (intercept) between the two sessions for the 25 participants who had a ‘quadratic’ profile in both sessions. Each coefficient was significantly correlated with its homolog from the other session (A2: S = 886, $p < .001$, rho = 0.66; A1: S = 817, $p < .001$, rho = 0.69; A0: S = 802, $p < .001$, rho = 0.69; see Figure S8 in Supplementary Materials). These strong observed correlations argue in favor of a stability of pleasantness judgment across sessions.

Response to palm (non-hairy skin) stimulation

a. Quadratic, linear, and random profile categorization

At the group level, we observed the classic inverted U-shaped curve. These results replicating the classically observed group-level results for tactile pleasantness ratings can be found in Supplementary Materials (see Figure S9). In response to stimulation applied to the palm, 8 (19.5%) participants did not show a significant effect of velocity on perceived pleasantness and were thus categorized as having a ‘random’ profile, 30 (73.1%) participants were categorized as having a ‘quadratic’ profile, and 3 (7.3%) participants were categorized as having a ‘linear’ profile in session 1 (Figure 6). In session 2, 7 (17.1%) participants were categorized as having a ‘random’ profile, 28 (68.3%) participants were categorized as having a ‘quadratic’ profile, and 6 (14.6%) participants were categorized as having a ‘linear’ profile (Figure 6). As in Experiment 1, the CI analysis showed a clear superiority of the quadratic model for both sessions (session 1: lower bound: - 345, raw sum: - 285, upper bound: -226; session 2: lower bound: - 336, raw sum: - 276, upper bound: -219).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26 - sess1
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27 - sess2
0
50
100
0
10
20
30
Pleasantness ratings
Stroking velocity (cm/s)

576

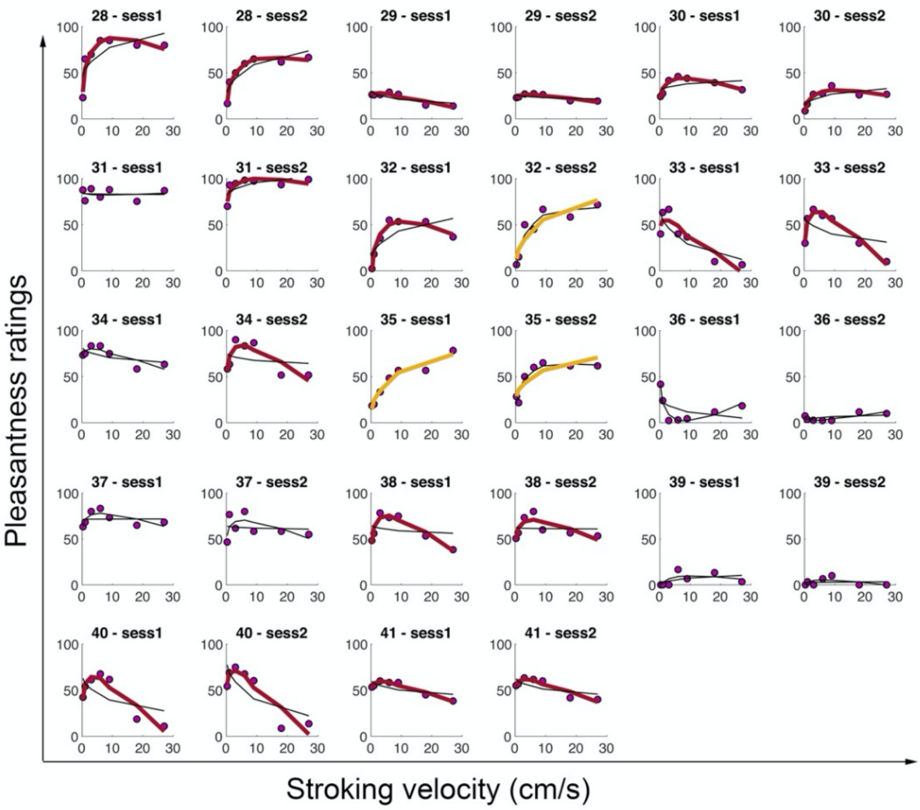

Figure 6: Quadratic and linear fit of individual pleasantness ratings in response to strokes applied to the palm for both sessions (Experiment 2). The figure displays the individual pleasantness ratings at each stroking velocity (purple dots) and the linear and quadratic fit results (curves). A thick red curve indicates that the participant has a 'quadratic' profile (i.e., significant quadratic fit and *p values*(LRT) < .05). A thick yellow curve indicates that the participant has a 'linear' profile (i.e., significant linear fit and *p values*(LRT) > .05). The absence of a bold curve (neither red nor yellow) indicates that the participant has a 'random' profile. For each participant, the results from the two sessions are plotted side-by-side.

b. Stability across sessions for palm stroking

Thirty-two (78%) participants displayed the same profile in session 1 and session 2. This result was above chance level (33%). The detailed repartition of the participants is shown in Table 10. Furthermore, the observed likelihood for each profile exceeded the predicted likelihood (Table 11). This result suggested that the identified profiles were stable across sessions.

Table 10: Repartition of the participants into profiles for both sessions.

		Session 2 profiles			
		Quadratic	Linear	None	*Total*
Session 1 profiles	Quadratic	27	1	2	*30*
	Linear	0	2	1	*3*
	Random	5	0	3	*8*
	Total	*32*	*3*	*6*	*41*

Table 11: Predicted and observed likelihoods for each profile to be identical in both sessions.

	Predicted likelihood	Observed likelihood	Difference	Interpretation
Quadratic	0.54	0.66	0.12	The observed likelihood is always higher than the predicted one. This is an argument in favor of stability
Linear	0.01	0.05	0.04	
Random	0.04	0.07	0.04	

We then examined the correlations between the model coefficients A2 (quadratic term), A1 (linear term), and A0 (intercept) between the two sessions for the 27 participants who had a 'quadratic' profile in both sessions. Each coefficient was significantly correlated with its homolog from the other session (A2: S = 1668, $p < .05$, rho = 0.49; A1: S = 2010, $p < .05$, rho = 0.39; A0: S = 1139, $p < .001$, rho = 0.65; see Figure S10 in Supplementary Materials). These observed correlations argue in favor of a stability of pleasantness judgment across sessions. However, the correlation between A1 in session 1 and session 2 was weaker than the correlations previously reported for forearm stimulation.

EXPERIMENT 3

The focus of Experiment 3 was to test the stability of the perceived pleasantness across several repetitions. Sensory processing is "noisy", and this intrinsic uncertainty in our sensory system may explain differences between individuals and differences between studies (e.g., (10)). In Experiments 1 and 2, we found a higher percentage of individuals for whom the quadratic regression was significant than in a previous study (67.1% vs. 42%; (10)). Most of the studies assessing pleasantness in response to different velocities of stroking assess each condition 3 times. This low number of repetitions is justified by the quick habituation and fatigue of affective touch fibers. (45) showed that tactile pleasantness diminished during 50 minutes of repetitions, particularly when touch was delivered at 3 cm/s, compared to slower (0.3 cm/s) and faster (30 cm/s) velocities. Nevertheless, when interested in individual perception, an optimal approach would be to collect more data per participant to better account for individual variability and sensory uncertainty (46). In Experiment 3, we propose a new protocol that includes more repetitions in each condition to better account for individual variability. By doing so, our aim was to evaluate whether the number of repetitions influenced the categorization of participants into profiles (quadratic, linear, or random). We first compared the profile repartition we obtained with the classic three repetitions of each stroking velocity (as we did in the first two experiments) to the results obtained with ten repetitions. Then, for a more fine-grained evaluation of the impact of the number of repetitions on the shape of the tactile pleasantness ratings, we focused on how the fit of the quadratic model and the corresponding estimated parameters varied with increasing repetitions.

Method

Participants

Sixteen healthy, naïve participants took part in Experiment 3 (6 females; 24.3 ± 5 years). All volunteers provided written informed consent prior to their participation. All participants received a cinema ticket as compensation for each hour spent on the experiment. All experiments were approved by the Swedish Ethics Review Authority.

Affective touch task procedure

We followed the same procedure as in Experiment 1. However, each velocity was presented ten times, for a total of 70 stroking trials per location (palm and forearm, in randomized order).

Data analysis

a. Descriptive modeling: Quadratic, linear, and random profile categorization

The model fitting and profile categorization were the same as in Experiments 1 and 2. We compared the outcomes when the fit was performed on all data or when considering the first 3 repetitions in each condition.

b. Influence of the number of repetitions

As shown in the previous two experiments, the negative quadratic model seemed to be an efficient model to capture the perception of pleasantness in response to touch delivered at different velocities at the individual level. However, are the fitting outcomes significantly impacted by the number of repetitions of each type of tactile stimulation? To answer this question, we fitted the quadratic model to the participants' pleasantness ratings for the first presentation of each velocity only and then repeated the same fitting procedure taking into account one additional presentation of each velocity each time (from 2 to 10 repetitions). Thus, we obtained 10 fitting outcomes per participant. We used linear mixed models to evaluate the impact of the number of repetitions at each stroking velocity on the goodness of fit of the quadratic model (reflected by the RMSE) and on the shape of the fitting curve (reflected by the estimated A2 and A0 coefficients).

Results

a. Quadratic, linear, and random profile categorization

At the group level, we observed the classic inverted U-shaped curve (see Figure S14 in Supplementary Materials). In this experiment, similar to Experiments 1 and 2, the 'quadratic' profile was predominant. Based on (45), we expected that this predominance might be reduced when considering the 10 repetitions for each condition: with more repetitions, the sensory attenuation would probably increase, and the participants might become less sensitive and more "numb" to the pleasantness, which could decrease the relevance of the quadratic model. However, the results actually suggested the opposite: regardless of whether stroking was applied to the forearm or the palm, a clear majority of participants presented a ‘quadratic’ profile after three repetitions at each velocity (forearm = 56%; palm: 75%); this relatively higher prevalence of the ‘quadratic’ profile further increased when each stimulation was repeated 10 times (forearm = 75%; palm: 94%), as the observed likelihood for this profile was higher than the predicted likelihood (Tables 12 and 13 and Figure 7 and 8). This suggested that the quadratic velocity-pleasantness response function was robust over repeated stimulations and that pleasant tactile sensations did not quickly attenuate.

Table 12: Repartition of the participants into profiles when considering 10 or 3 repetitions in each condition.

Forearm profiles						**Palm profiles**					
		3 repetitions						3 repetitions			
		Quadratic	Linear	None	Total			Quadratic	Linear	None	Total
10 rep.	Quadratic	8	0	4	12	10 rep.	Quadratic	12	1	2	15
	Linear	0	1	0	1		Linear	0	0	0	0
	Random	1	1	1	3		Random	0	0	1	1
	Total	9	2	5	16		Total	12	1	3	16

Table 13: Predicted and observed likelihoods for each profile to be identical when considering the first 3 and then 10 repetitions at each stroking velocity.

	Forearm profiles			**Palm profiles**		
	Predicted likelihood	Observed likelihood	Difference	Predicted likelihood	Observed likelihood	Difference
Quadratic	0.32	0.50	0.18	0.56	0.75	0.19
Linear	0.02	0.06	0.05	0.00	0.00	0.00
Random	0.10	0.06	-0.04	0.04	0.06	0.03

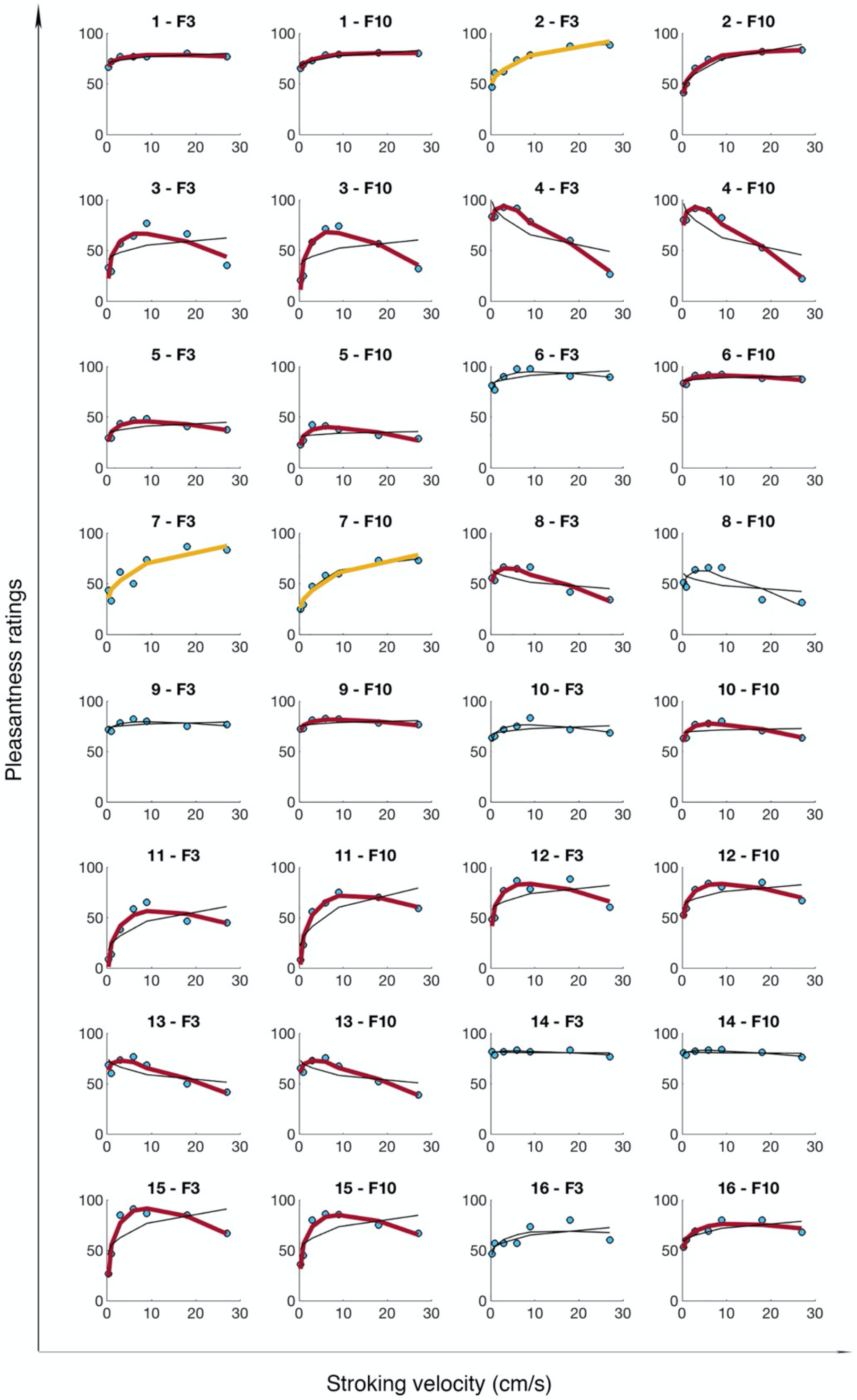

Figure 7: Quadratic and linear fit of individual pleasantness ratings in response to strokes applied to the forearm for 10 and 3 repetitions in each condition (Experiment 3). The figure displays the individual pleasantness ratings at each stroking velocity (blue dots) and the linear and quadratic fit results (curves). A thick red curve indicates that the participant has a 'quadratic' profile (i.e., significant quadratic fit and *p-values*(LRT) < .05). A thick yellow curve indicates that the participant has a 'linear' profile (i.e., significant linear fit and *p values*(LRT) > .05). The absence of a bold curve (neither red nor yellow) indicates that the participant has a 'random' profile. For each participant, the results for 3 repetitions are plotted first, and the results when 10 repetitions are taken into account are plotted side-by-side.

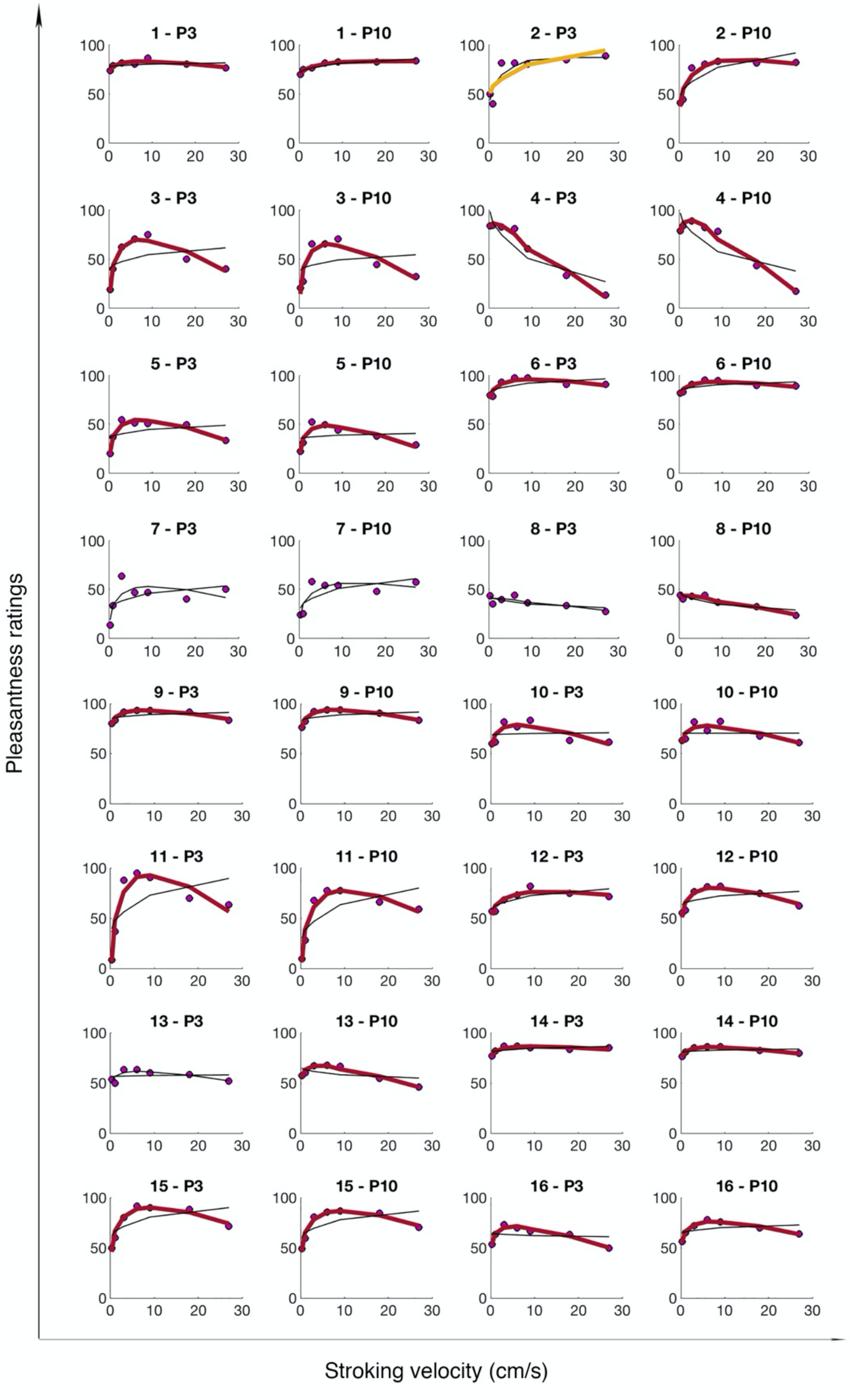

Figure 8: Quadratic and linear fit of individual pleasantness ratings in response to strokes applied to the palm for 10 and 3 repetitions in each condition (Experiment 3). The figure displays the individual pleasantness ratings at each stroking velocity (purple dots) and the linear and quadratic fit results (curves). A thick red curve indicates that the participant has a 'quadratic' profile (i.e., significant quadratic fit and *p values*(LRT) < .05). A thick yellow curve indicates that the participant has a 'linear' profile (i.e., significant linear fit and *p values*(LRT) > .05). The absence of a bold curve (neither red nor yellow) indicates that the participant has a 'random' profile. For each participant, the results for 10 repetitions are plotted first, and the results when only 3 repetitions are taken into account are plotted side-by-side.

b. *Influence of the number of repetitions on fitting outcomes*

By increasing the number of repetitions for each stroking velocity delivered to the forearm, we observed a significant decrease in RMSE values, i.e., the fit of the quadratic model became better with more repetitions (*F*(1,15)=26.8, *p* < .001), although the magnitude of this improvement remained modest (linear coefficient for the fixed effect of the number of repetitions: -0.31). However, the corresponding estimated A2 reflecting the curvature of the quadratic regression did not significantly change when the number of repetitions increased (*F*(1,15)=0.9, *p* = .37). A0, the coefficient representing the overall pleasantness perception did not seem to be significantly influenced by the number of repetitions (*F*(1,15)=1.5, *p* = .24; see Figure S15 in Supplementary Materials).

By increasing the number of repetitions for each stroking velocity delivered to the palm, we observed no significant change in RMSE values, i.e., the fit of the quadratic model remained similar despite more repetitions (*F(*1,15)=0.4, *p* = .52). Once again, the corresponding estimated A2 coefficient reflecting the curvature of the quadratic regression did not significantly change when the number of repetitions increased (*F*(1,15)=1.5, *p* = .24). A0, the coefficient representing the overall pleasantness perception seemed to slightly increase with the number of repetitions (*F*(1,15)=5.6, *p* = .03; linear coefficient for the fixed effect of the number of repetitions: 0.89; see Figure S16 in Supplementary Materials).

Discussion

Summary of key findings

Across three experiments, we 1) tested the hypothesis that the classic negative quadratic model (inverted-U shape function) would outperformed a linear model in describing the relationship between velocity of touch and subjective tactile pleasantness at the individual level in the majority of individuals; 2) explored how individual difference factors predicted the outcome of such individual fit (Experiment 1); 3) tested whether the shape of the quadratic model would be more pronounced and observed in more people on hairy compared to non-hairy skin , and 4) establish whether the individual shape of the tactile pleasantness-velocity functions was temporally stable, both across two identical experimental sessions one week apart (Experiment 2) and when the number of repetitions at each velocity increased (Experiment 3).

Our results showed that at the group level (N = 123), the relationship between the velocity of touch and subjective pleasantness was better described by a negative quadratic model than a linear model in the majority of participants. At the individual level, most participants (67.1% for the hairy skin site and 62.6% for the non-hairy skin site) showed a significant negative quadratic relationship between velocity of touch and pleasantness, which is substantially more frequent than previously reported (10) and thus more in line with the CT-hypothesis and suggesting that the inverted-U-shape function best captures individuals' typical perception of affective touch. Unexpectedly, the frequency of the negative quadratic model fit, and the shape of this model, was similar across hairy (forearm) and non-hairy skin (palm) with 62.6% of participants displayed the same pattern at the forearm and palm. This result does not fit with the CT-hypothesis but is more in line with recent proposals that suggest that affective touch sensations arise from multiple afferent and top-down sources rather than being driven exclusively (or mainly) by afferent CT information. In terms of individual differences, we found that higher cardiac interoceptive accuracy was related to a better fit of the quadratic model of the perception of touch on hairy skin (and with a statistical trend for such relationship on non-hairy skin), and individual differences in self-reported depression influenced the steepness of the curve. Noteworthy, the patterns of the relationship between the velocity of touch and subjective pleasantness were temporally stable across two experimental sessions (73% of participants displayed the same profile across sessions on hairy skin and 78% on non-hairy skin; Experiment 2) and were robust and replicable with an increasing number of trials (Experiment 3), which supports the idea that the current individual subject modeling could be a viable approach for future clinical research into biomarkers for mental health conditions. Collectively, our findings suggest that the relationship between the velocity of tactile stimulation and subjective pleasantness follows a negative quadratic function in most people, that the shape of this function was robust and replicable across trials and sessions and present for both hairy and non-hairy skin, and thus it is likely to represent a universal function for tactile pleasantness experience in humans.

The perception of affective touch at the individual level

We believe that our results provide an important contribution to the affective touch field from the experimental, behavioral, and clinical points of view. Several studies have shown that slow, caress-like touch delivered at velocities between 1 and 10 cm/s might optimally activate the CT afferent system and is perceived as more pleasant than slower or faster velocities based on subjective ratings (e.g., (5) (7)). At the group level, the averaged pleasantness ratings of touch delivered at velocities in the range between 0.3 and 30 cm/s follow an inverted-U shape curve, with maximum pleasantness between 1 and 10 cm/s. Here, we provide novel evidence that this pattern is also valid at the individual level and on both hairy and non-hairy skin. This is an important advance for the field because it is individuals – not groups – that experience pleasant touch, and the relationships observed at the group level (through data averaging) may not be representative of the specific perception of individual participants. One of the reasons accounting for why we might have found that a higher percentage of participants at the individual level followed the inverted-U shaped pattern compared to the results of one previous study (10) is the fact that all our participants were tested under the same conditions with the tactile stimulation always delivered by the same experimenter. In contrast, Croy et al. 2021 pooled data from 5 separate experiments with the common ground that participants were tested on the forearm; this approach might have increased experimental noise and added additional individual variability, over and above that associated with tactile perception per se.

Importantly, by using our modeling approach, we could, for the first time, investigate the relationship between individual traits and characteristics, namely, depression, anxiety, eating disorders symptomatology, and cardiac interoceptive accuracy, and individual differences in the precise shape of the tactile pleasantness-velocity function. We found that individual differences in self-reported depression influenced the steepness of the quadratic curve, at least when touch was delivered on hairy skin. These results are in keeping with recent evidence suggesting that depressive symptomatology can influence how participants perceive and think about tactile social encounters (32). Furthermore, these results can be interpreted in the context of a more general anhedonia, which has traditionally been linked to depression and has been found to affect the perception of tactile pleasantness in people with eating disorders (31).

Consistent with the idea of affective touch as an interoceptive modality, our results showed that higher cardiac interoceptive accuracy as measured by means of a classic heartbeat counting task (30) was related to a better fit of the negative quadratic model for the perception of touch on hairy skin (with a similar but non-significant statistical trend observed for non-hairy skin). In this regard, recent studies have reported non-significant relationships between the perception of affective touch and cardiac interoceptive accuracy (21) (34); however, interoceptive accuracy was a predictor of tactile pleasantness in a multisensory integration paradigm only when touch was delivered at the borderline velocity for CT optimality (9 cm/s, (21)). Taken together, these findings suggest that the link between cardiac interoception and tactile pleasantness is more complex than originally thought, and modeling approaches might be better suited to describe such relationships.

Overall, our findings suggest that the perception of affective touch follows a relatively consistent pattern at the individual level; nevertheless, this finding should be contextualized in a broader picture that takes into account other individual differences, such as depressive symptomatology and interoceptive abilities. As such, the subjective perception of affective touch reflects the complexity of studying social touch where context and person matter (e.g., (28)), and it should not be reduced only to bottom-up processing of the signals triggered by the tactile stimulation of the peripheral receptors in the skin; information regarding social and contextual cues modulates the pleasantness experience at central levels of processing.

Differences in the perception of touch on hairy and non-hairy skin

We found that the pattern of results was similar for touch delivered on hairy (forearm) and non-hairy (palm) skin. These results are surprising in light of classic findings in the field of affective touch (e.g., (43)) but consistent with a recent meta-analysis that pooled data from 18 studies and reported no systematic difference in pleasantness ratings in response to affective touch across hairy and glabrous skin when considered in group-level analyses (see (9)). Notably, here, we demonstrated this finding at the individual level for the first time, which is important because it is only at this level that the precise shape of the velocity-pleasantness functions can be modeled and directly compared across skin types.

As such, our results are timely and in line with an ongoing shift in the field, suggesting that a more holistic approach might allow us to better capture the perception of tactile pleasantness, where both bottom-up and top-down signals play a role. To the extent that the subjective perception of touch is the result of the activation of mechanoreceptive afferents on the skin in combination with central processing ((47) (1), here, we showed that the pattern of relationship between velocity of touch (and presumably CT activation; (5)) and subjective tactile perception follows a similar pattern across hairy and non-hairy skin at the individual level. In the affective touch field, it has long been common practice to select a glabrous skin site (i.e., palm of the hand) as a control condition to compare to the perception of tactile pleasantness on hairy skin. However, our findings might suggest that more careful consideration is needed when selecting control conditions and in interpreting the results when any remarkable difference is found between hairy and non-hairy skin sites because such findings may not relate to tactile pleasantness per se. In fact, our findings indicate that the inverted-U shaped curve could constitute a fundamental function that describes the typical relationship between tactile stimulation velocity and subjective pleasantness across all body parts and skin types (although further studies are needed to confirm this across more body parts than the three sites investigated here).

Nevertheless, we found that interoceptive accuracy and self-reported depression were related to the perception of tactile pleasantness on hairy skin only, thus indirectly suggesting that there are intrinsic differences in the processing and interpretation of touch based on skin site (e.g., (47) (48)). As such, our results further contribute to our understanding of touch perception and, in particular, the relative contribution of the CT system to the perception of tactile pleasantness. A recent study reported sparse CT afferent recordings from glabrous skin for the first time (8); thus, it could be that even a small number of CT fibers is sufficient to contribute to the perception of tactile pleasantness from a physiological point of view. An alternative explanation of our findings could be that the contribution of the CT system to the perception of tactile pleasantness is minimal, and the perception of the hedonic aspects of touch is mainly driven by other afferent tactile information (49), top-down beliefs about touch perception (e.g., (31)), and previous tactile experiences throughout life (50).

Stability of touch perception across testing sessions and repetitions

The results of Experiment 2 suggest that healthy participants present a rather consistent relationship between velocity of touch and tactile pleasantness at the individual level across two testing sessions. Thus, the way in which we perceive tactile pleasantness might represent a trait rather than a state characteristic. This result is in line with previous findings suggesting that the preferred velocity of touch is stable across two testing sessions taking place 21 days apart (51). Taken together, these findings are particular important for clinical research because they can pave the way for further investigation exploring whether the perception of affective touch can be used as a behavioral biomarker for the early identification and diagnosis of psychiatric and neurodevelopmental disorders. Nevertheless, we should point out that the perception of tactile pleasantness is still context-dependent (see (52) for a review), and in this study participants were always blindfolded as to reduce the effect of the visual environment on the sensory experience. Therefore, the present results should be replicated and extended to show that the perception of tactile pleasantness is stable also under different circumstances.

Several studies in the field of affective touch have been criticized for the low number of repetitions used at each velocity. However, it has also been highlighted that several repetitions could reduce the perceived pleasantness of touch (45). In this context, the results of Experiment 3 showed that increasing the number of repetitions at each velocity from 3 to 10 did not significantly deteriorate the fit of the model. That is, participants already showed a strong pattern after 3 trials, and this pattern did not change over subsequent trials. These results provide additional, indirect validity for the findings from previous studies that investigated the perception of affective touch using less than 10 repetitions per velocity (see (53) for a recent review), and they further suggest that the perception of affective touch might represent a trait characteristic, with a strong potential to be used as such in future studies.

In this regard, we believe that our results provide important methodological information to consider when designing future studies. The evidence that it is possible to reliably assess affective touch perception using a low number of trials might be crucial for studies conducted with clinical populations presenting symptoms such as fatigue, cognitive impairment, and difficulties in social interactions, as well as when testing in hospital facilities or at bedsides. In such situations, it is essential to collect reliable data while keeping the testing time as brief as possible to guarantee participants' comfort and safety.

Concluding remarks and future directions

We believe that our findings highlight the translational potential of quantifying the perception of affective touch as a proxy for socially embodied cognition and have important implications for our understanding of the relationship between mental health and affective touch (27). The affective touch system seems to play a role in the development and maintenance of affiliative behaviors and social bonding and for the communication of emotions (see (2) (5) (48) (3) (54)). Thus, it has been suggested that this modality could be important for the development of the social brain (see (55) for a review) and for the way we relate to ourselves and others (42). Furthermore, the integration of interoceptive/affective (including signals derived from affective cutaneous stimulation) and exteroceptive/sensory information plays a critical role in bodily awareness at any given time and the construction of the subjective experience of the self (e.g., (56) (19) (21) (57)). Our findings that healthy participants showed a rather consistent relationship between velocity of touch and tactile pleasantness at the individual level, combined with clinical data suggesting a close link between affective touch and mental health, can pave the way for further investigation exploring the perception of affective touch in people at different stages of mental health conditions, ranging from populations at risk of developing such disorders to people who have successfully recovered from them. For example, it remains unclear whether disruptions in the perception of affective touch can be considered a consequence of other symptoms or whether they are a contributing factor for the development of mental health disorders. Along this line, one study investigated the perception of affective touch in people who had recovered from anorexia nervosa compared to women with anorexia nervosa and matched healthy controls (31). The results suggested that the difficulties in the perception of affective touch might persist even after an otherwise successful recovery. Thus, such deficits might represent a trait rather than a state phenomenon related to the status of malnutrition associated with this clinical condition.

To the best of our knowledge, this is the first study to apply an advanced modeling approach to better characterize the perception of tactile pleasantness at the individual level. We systematically investigated the stability of the profiles across body sites, comparing hairy and non-hairy skin, across two testing sessions one week apart, and across several repetitions (from 3 to 10). Our results provide an important novel contribution to the field and further validate previous findings investigating the perception of affective touch. Future studies could also include a measure of precision of the subjective perception by asking participants to report their confidence in their responses, for example (e.g., (58) (59)). Such metacognitive approaches hold the potential to provide a more complete picture of the way peripheral tactile stimulation can give rise to a subjective pleasantness percept.

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Author contributions

L.C, M.C. and H.H.E. conceived and designed the experiments. L.C. performed and supervised data collection. M.C. and L.C. conducted the statistical analysis. L.C., M.C. and H.H.E. wrote the manuscript.

Competing interests

The authors declare no competing interests.

Materials & Correspondence

Correspondence and material requests should be addressed to laura.crucianelli@ki.se.

Supplementary materials are available here: https://figshare.com/s/3f5e29e7f33c2e710d40

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