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## Individual variability of pleasantness ratings to stroking touch over different velocities

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Many studies have investigated the perception of tactile pleasantness over a range of stroking velocities. On average, pleasantness is low at slow (e.g. 0.3 cm/s) and fast (e.g. 30 cm/s) stroking velocities, but is rated highest at velocities between 1-10 cm/s. On a group level, this results in an inverted-U shape pleasantness ratings curve, which is described statistically by a negative quadratic equation. We reanalyzed the data from 5 earlier studies to investigate whether the inverted-U shape pleasantness curve at the group level is also present at the level of the individual - a precondition for using tactile pleasantness perception as a diagnostic marker. We pooled the data from five studies with a total of 127 participants. Each study included a 'standard condition' of stroking on the dorsal forearm over different velocities (0.3, 1, 3, 10, 30 cm/s) and participants rated the pleasantness. Factors other than stroking velocity were also varied in these studies. On the whole-group level and in each study, pleasantness ratings produced a significant negative quadratic pleasantness curve over the stroking velocities. In individual participants, ratings varied greatly and only 42% of the participants showed a significant negative quadratic curve. The steepness of the inverted-U correlated only moderately across other experimental conditions, showing that the experimental circumstances can influence pleasantness ratings. Our findings have important implications for future work, where differences in the tactile pleasantness curve should not be used to predict or diagnose issues at an individual level.

### Highlights

- We conducted a reanalysis of 5 studies into variability of pleasant touch perception from stroking over the skin.
- We asked whether the inverted-U shape pleasantness curve over slow to fast stroking existed at the level of the individual.
- We pooled the data from 127 healthy participants who rated pleasantness of slow to fast stroking.
- Group data clearly exhibited the inverted-U shaped pleasantness curve, but this was not found in individuals.
- High inter-individual variability exists in tactile pleasantness and this should not be used diagnostically in individuals.

**Keywords:** touch; brushing; pleasant; positive affect; variability

The field of positive affective touch has grown rapidly since the discovery of C-tactile (CT) afferents in human hairy skin (Johansson et al., 1988; Nordin, 1990; Vallbo et al., 1993) that putatively code pleasant tactile sensations (Löken et al., 2009; Ackerley et al., 2014a). This type of gentle touch, hereby specified as pleasant touch, underpins the 'social touch hypothesis' (which extends the 'affective touch hypothesis') that activity from CT afferents has the potential to elicit a pleasant tactile experience and this input complements that from emotional, hormonal, and behavioral mechanisms during contact with conspecifics (Morrison et al., 2010; Olausson et al., 2010; McGlone et al., 2014). The high interest in this field stems from the implications that arise from stimulating the affective touch system, including the possibility to increase social and inter-personal bonds, and in potentially diagnosing and treating conditions that relate to tactile interactions, such as autism.

There is a distinction between the peripheral encoding of gentle touch and its central interpretation. Mechanoreceptive afferents in the skin encode only qualities of the physical touch (e.g. force, speed), whereas the *percept* of tactile pleasantness is a central construct and is prone to inter-individual variability and interpretation. A relationship exists between the firing frequency of CT afferents and pleasantness ratings at a group level. However, if the experimental conditions are changed, the relationship between CT

firing and pleasantness can break down, such as stroking at different temperatures (Ackerley et al., 2014a), showing the complexity of the relationship.

The social touch hypothesis postulates that the properties of CT afferents and their firing are well-suited to convey aspects about pleasant sensations, particularly during inter-personal, skin-to-skin touch. These properties include the low force activation threshold of CTs, their exquisite sensitivity to a gentle skin stroke, and optimal responses during stroking around skin temperature (for a review, see Ackerley and Watkins, 2018). Further, the reception of touch appears to be important, as CTs have only been found in hairy (non-glabrous) skin, which is implicated less in discriminative touch and more in affective touch (Ackerley et al., 2014c), and that inter-personal skin stroking is optimized for activating CTs (Croy et al., 2016b; Tricoli et al., 2017; Van Puyvelde et al., 2019). Therefore, the CT system is well-equipped for signaling positive emotional bodily information and it is believed that CTs project primarily to the insula (Olausson et al., 2002), which is involved in processing interoceptive signals (Craig, 2002).

The original finding that the speed of stroking over the skin correlated with the perception of pleasantness was made by Essick et al. (1999) and this was then linked to the firing frequency of CTs by Löken et al. (2009). In brief, when hairy skin is stroked over a range of velocities, intermediate velocities (1-10 cm/s) are rated as more pleasant than slower or faster speeds, which produces an 'inverted U-shaped pleasantness curve'. These two studies, as well as many subsequent studies (Essick et al., 2010; Löken et al., 2011; Morrison et al., 2011; Tricoli et al., 2013; Ackerley et al., 2014a, 2014b; Gentsch et al., 2015; Jönsson et al., 2015, 2017; Sehlstedt et al., 2016; Croy et al., 2016a; Luong et al., 2017; Bendas et al., 2017; Hielscher and Mahar, 2017; Kass-Iliyya et al., 2017; Krahé et al., 2018; Sailer and Ackerley, 2019) have systematically shown such a pleasantness curve. These studies typically analyze the inverted-U pleasantness curve using parametric analyses (e.g. analysis of variance, multi-level mixed model) with curve fitting (e.g. to a negative quadratic equation).

On a group level, the inverted U-shape for tactile pleasantness seems to be robust and reproducible. For example, one study investigated whether pleasantness ratings differed using robotically-applied or manually-applied brush strokes, but found no difference (Tricoli et al., 2013). Similarly, the pleasantness curves, as well as the firing frequency of CTs, appear equivalent during stroking with a brush or a metal plate (cf. Löken et al., 2009; Ackerley et al., 2014a). Pleasantness in stroking also seems to be analogous across hairy skin sites (Essick et al., 1999, 2010; Ackerley et al., 2014b; Jönsson et al., 2015). Further, such pleasantness perceptions are present across the lifespan (Sehlstedt et al., 2016; Croy et al., 2019), where tactile pleasantness may even increase with age (Sehlstedt et al., 2016). Little has been published regarding sex differences in pleasant touch; however, a recent meta-analysis has shown that females generally rate stroking touch as more pleasant than males (Russo et al., 2019).

Recent studies have investigated the possibility that changes in CT afferents and/or their central integration may be involved in various conditions. Patients with autism (Cascio et al., 2008, 2012; Kaiser et al., 2016) and Parkinson's disease (Kass-Iliyya et al., 2017), as well as older healthy people (Sehlstedt et al., 2016), may actually rate gentle touch as equal to or *more* pleasant than controls, which is noteworthy considering the loss of afferent density with age and in Parkinson's disease. Conversely, Morrison et al. (2011) found that patients with reduced CT density, due to a rare hereditary sensory neuropathy, led to a general decrease in the perception of

Pleasantness ratings study	Conditions	No. participants
(1) Odor (Croy, Sailer et al., unpublished; see supplementary material for experimental procedures) Stability over different olfactory conditions. Guided brush stroking performed manually on the arm. Conducted at Technical University of Dresden, Dresden, Germany.	No odor	27 (0 males)
	Hedione	
	PEA	
(2): Body sites 1 (Ackerley et al., 2014b) Stability over body site stroked. Four hairy skin sites (with CTs present) were included and one glabrous skin site (palm, believed to lack CTs). Brush stroking performed by a robot. Conducted at Sahlgrenska Hospital, Gothenburg, Sweden.	Forearm	30 (15 males)
	Forehead	
	Palm	
	Shin	
	Thigh	
(3) Temperature (Ackerley et al., 2014a) Stability over different stroking temperature conditions. Stroking using a metal plate performed by a robot on the arm. Conducted at University of Gothenburg, Sweden.	18°C	30 (15 males)
	32°C	
	42°C	
(4) Test-Retest (Croy, Hausmann et al., unpublished; see supplementary material for experimental procedures) Retest-reliability of the inverted-U pleasantness curve. Brush stroking performed by robot on the arm. Conducted at Technical University of Dresden, Dresden, Germany.	Test	20 (8 males)
	Re-test	
(5) Body sites 2 (Jönsson et al., 2015) Stroking on the forearm and thigh with ratings of eroticism, intensity, and pleasantness. Brush stroking performed by a robot. Conducted at Sahlgrenska Hospital, Gothenburg, Sweden.	Forearm	20 (10 males)
	Thigh	

**Table 1:** The five studies in the reanalysis, including their specific conditions and participant details.

pleasantness over stroking velocities and both Crucianelli et al. (2016) and Davidovic et al. (2018) independently found that pleasantness decreased in anorexics during intermediate velocity, ‘CT-optimal’ stroking, as compared to controls. Further, small decreases in affective touch perception have been found for people who seldom received inter-personal touch (Hielscher and Mahar, 2017; Sailer and Ackerley, 2019) and for those undergoing psychotherapy (Croy et al., 2016a). The latter result generated the hypothesis that the presence of the inverted-U pleasantness curve could be used as a diagnostic marker for mental health conditions. However, in order to allow such a statement about potential symptom markers, it must first be clarified how stable the inverted-U pleasantness curve is in the healthy individual.

The present work aimed to investigate the variability of this pleasantness curve at the individual level. A recent study showed that intra-individual pleasant touch is rated in a relatively reproducible way (Luong et al., 2017), but little is known about the variability of the curve between individuals. We hypothesized that the majority of individuals would show typical inverted U-shaped curves, with a significant negative quadratic fit; however, there would be a number of individuals where this is not present, due to variation in the population and the perception of pleasantness.

### Experimental procedures

Five studies were identified and included in the present reanalysis (Table 1), which were conducted over three different laboratories, by different experimenters. All of these studies gained formal local ethical committee approval (available on request) and conformed to the guidelines set out in the Declaration of Helsinki. All procedures were carried out with the adequate understanding of the participants, who gave written, informed consent and were paid for their participation. The studies were chosen as they had a high level of similarity (e.g. experimental design, comparable conditions) and we had access to all the details of each experiment and the full data sets. For the study to be included, it was a requirement that pleasantness ratings were obtained in healthy humans from stroking over at least one hairy skin site, including the ‘full range’ of velocities that typically make up the pleasantness curve (0.3, 1, 3, 10, and 30 cm/s). In these studies, stroking was performed using a robot that delivered brush strokes of precise velocity and force, apart from Croy, Sailer et al. (unpublished; see supplementary information), where the stimuli were delivered by hand. In all of the present studies, each of the 5 stroking velocities was pseudo-randomly repeated three times and after each stroke, pleasantness was rated on a visual analogue scale (VAS; with the anchors at ‘unpleasant’ to ‘pleasant’).

This repetition of ratings (3 strokes x 5 velocities) is standard in such studies, as it increases confidence in the data and it enabled us to examine individual variation in our present reanalysis. A minimum number of 20 participants was required per study to be included in the analysis.

The five studies included in our reanalysis covered different manipulations of stroking stimulation: stroking under the influence of odors (Sailer et al. unpublished; see supplementary information), stroking on different body sites (Ackerley et al., 2014b; Jönsson et al., 2015), stroking with different temperatures (Ackerley et al., 2014a), and stroking in a test-retest paradigm (Croy et al. unpublished, see supplementary information) (see Table 1 for details). Importantly, all studies included the condition where the dorsal forearm of the participant was stroked without any additional experimental stimulation. We refer to this as the ‘standard’ stroking condition, as it was common throughout to

allow for direct comparisons. For the temperature study (Ackerley et al., 2014a), we choose 32°C temperature stroking as the standard condition, as this matched participants’ typical skin temperature. In order to facilitate comparability between studies (reliability) and to maximize generalizability over studies (validity), we analyzed the rating patterns separately for the standard condition only and then investigated the effect of different conditions.

### Reanalysis of pleasantness studies

Data were analyzed using SPSS (version 23; IBM statistics). As participants of Studies 1 and 4 rated pleasantness on a 0-100 VAS (with an accuracy of 1) and participants of Studies 2, 3, and 5 used a 0-10 VAS (with an accuracy of 0.1), all ratings were changed using a linear transformation to match the standard end-points of -10 (unpleasant) to 10 (pleasant) for each of visualization (Löken et al., 2009). The two typical approaches for analyzing pleasantness ratings are to use ANOVA or a multi-level mixed model. Repeated-measures ANOVA can be used when there are no missing data and when the data are normally distributed. ANOVA is an accepted way to analyze the differences among group means, as well as providing estimates of effect size and power. Hence, the present data were analyzed this way, as our data did not violate these assumptions and all ANOVA were performed using ratings from the individual trials, not the average for each velocity, per participant.

*Analysis of the pleasantness curve at a group level:* The data were first analyzed over the five studies and we created a dataset with all the individual pleasantness ratings in the standard condition (stroking over all velocities on the dorsal forearm). The data were explored using descriptive statistics and information about the variability and deviation in the whole dataset were collected. We conducted a repeated-measures ANOVA with the pleasantness ratings as the dependent variable and with the within-subject factors of stroking velocity (5 levels: 0.3, 1, 3, 10, 30 cm/s) and stroking trial (3 levels: trial repeat 1, 2, 3) and the between subject factor study (i.e. experimental setting, 5 levels: Odor, Body sites 1, Temperature, Test-Retest, Body sites 2). In a next step, we analyzed each study separately using repeated measures ANOVA, with the same within-subject factors. Greenhouse-Geisser correction was used for violations of sphericity, if present.

We used polynomial contrasts to explore whether there was a significant linear or quadratic trend in the stroking velocity curve. Pre-planned, Bonferroni-corrected post-hoc t-tests between the middle stroking velocity (3 cm/s) and the (i) slowest (0.3 cm/s) and (ii) fastest (30 cm/s) were performed (corrected by a factor of 2). We additionally tested the effect of repetition of stroking velocity (trial) using Bonferroni-corrected post-hoc t-tests, to investigate whether the participant’s ratings changed consistently

over time. To follow up the potential effect of differences between studies, we carried out Bonferroni-corrected post-hoc t-tests between the overall average ratings of pleasantness in each study. In all cases, we calculated the effect size (partial  $\eta^2$ ) and show all our results to 2 decimal places (apart from the significance, which was presented to 3 significant figures).

**Analysis of the pleasantness curve on an individual level:** We wanted to test whether there were significant U-shaped pleasantness curves present in individual participants. For each participant, in the standard condition of each study, quadratic and linear curves were fit to their pleasantness ratings using the 3 trial repeats at each of the 5 stroking velocities. The analysis gave standardized beta values (i.e. strength of fit) for both the quadratic and linear curve fits, as well as a corresponding ANOVA output (i.e. main effect of stroking velocity), per participant. We counted the number of participants per study whose ratings followed a significant quadratic or a linear term ( $p < 0.05$ ) or whose ratings showed a significant main effect of velocity (ANOVA). Note that multiple assignments of significance were possible, as both the linear and quadratic fits, as well as the ANOVA, could be significant within one participant's pleasantness curve.

**Analysis of similarity of rating patterns over different conditions:** In order to estimate the similarity of the individual rating patterns over experimental modulations, we tested whether the individual standardized beta values extracted from the quadratic curve fit were normally distributed within each condition per study, which was ensured by Kolmogorov-Smirnov-Tests. Thereafter, we correlated those beta values of the standard conditions to the beta values of each other condition within the same study using Pearson's correlation. To further estimate the similarity of the individual rating patterns over experimental modulations, we examined the correlation of ratings, per velocity and study, across the different conditions.

**Results**

**Analysis of the pleasantness curve at a group level**

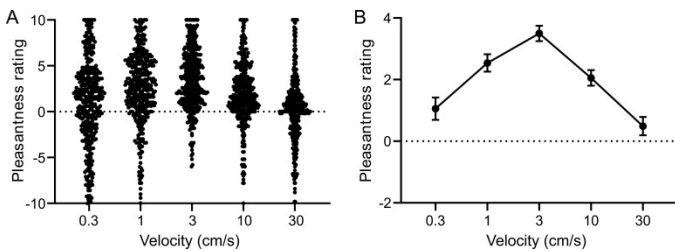


Figure 1: Overview of all the pleasantness ratings from all the participants. (A) Pleasantness ratings are shown from all 127 participants over each stroking velocity and trial repeat. (B) The mean of all these participants' ratings is shown with standard error bars ( $\pm$ SEM).

We analyzed the standard condition (stroking over all velocities on the dorsal forearm) over the five studies and for each study. Figure 1 shows the whole reanalysis pleasantness ratings plotted with all the individual data points on the left and as the mean ( $\pm$ SEM) on the right. The variability and deviation in these data are detailed in Table 2. It can be seen that there was a large spread of

**Table 3:** Group analysis of velocity dependent pleasantness ratings over different conditions in the standard condition.

All five studies revealed a significant effect of velocity on pleasantness ratings, which followed a quadratic term. Post hoc tests (over all conditions) showed the medium stroking velocity of 3cm/s was rated higher than the fastest and slowest velocity. Significant results are displayed in bold font and post hoc tests are presented Bonferroni corrected by factor 2.

Velocity	Mean Rating	Minimum rating	Maximum rating	Variance	SD	SEM
0.3	1.1	-9.8	10.00	21.4	4.6	0.24
1	2.5	-10.0	10.00	14.9	3.9	0.20
3	3.5	-6.0	10.00	10.8	3.3	0.17
10	2.1	-7.8	10.00	11.7	3.4	0.18
30	0.5	-9.8	10.00	13.4	3.7	0.19

**Table 2:** Overview of the mean pleasantness ratings and the deviation statistics for the full reanalysis dataset. For 127 participants, rating each velocity three times, the table details the mean pleasantness data that are shown in Figure 1. SD = standard deviation, SEM = standard error of the mean.

ratings over all the velocities, where for each velocity, there were always some unpleasant (negative) ratings regarding the stroking, but this was far more frequent for the slowest (0.3 cm/s) and fastest (30 cm/s) velocities. The middle stroking velocity of 3 cm/s gave the least variable ratings (Figure 1, Table 2), although this was due to fewer ratings being made in the unpleasant range. The main effect of stroking velocity was highly significant over the full dataset of five studies (ANOVA  $F(2.5,216.5) = 33.57$ ,  $p < 0.001$ , partial  $\eta^2 = 0.22$ ) and followed a negative quadratic pattern (ANOVA  $F(1,122) = 104.37$ ,  $p < 0.001$ , partial  $\eta^2 = 0.46$ ).

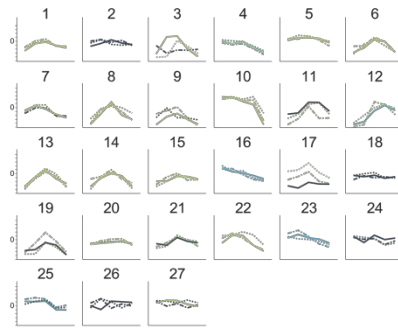
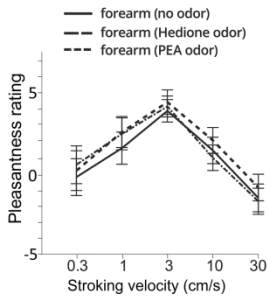
The group data per study is shown in Figure 2, with each participant's pleasantness ratings plotted to the side, demonstrating the variability in the shape of the individual curves. Table 3 shows these results in detail per study, where all the comparisons showed significant main effects in the each study's group ANOVA (apart from Study 4, Test-Retest). The pleasantness curves generated per study all showed a significant negative quadratic fit (i.e. they all showed an inverted U-shape), whereas no linear fit was significant at the group level. The quadratic fit explained a variance of 27-62% per study, whereas the linear term explained a variance of 0.3-17% only.

Post-hoc comparisons were used to explore whether the slowest (0.3 cm/s) and fastest (30 cm/s) stroking velocities differed in perceived tactile pleasantness, compared to the medium velocity of 3 cm/s. These post-hoc tests showed a consistent significant difference in pleasantness ratings between stroking at 3 and 30 cm/s (apart from Study 4, Test-Retest where  $p = 0.066$ ) and between stroking at 0.3 and 3 cm/s (apart from Study 1, Body sites 1 and Study 4, Test-Retest; although these were nearing significance, both  $p < 0.06$ ). Therefore, the medium stroking velocity of 3 cm/s was, in general, rated higher than the fastest or slowest velocity of stroking.

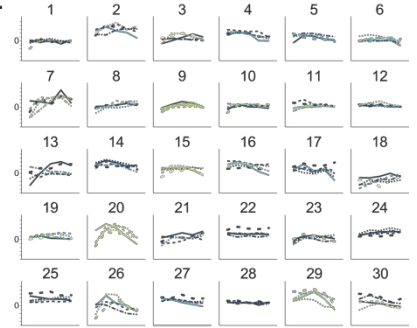
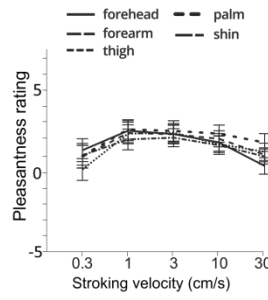
We investigated whether the repetition of stroking velocity (trial) could have an influence on the pleasantness ratings, but we found no significant main effect of stroking velocity repetition, nor any significant post-hoc comparisons, indicating no differences in the pleasantness ratings per velocity over the course of each experiment. We additionally looked at

	ANOVA Stroking velocity	Comparison stroking velocities		Test of velocity curve	
		0.3 to 3 cm/s	3 to 30 cm/s	Linear	Quadratic
<b>All studies</b>	$F(2.5,216.5) = 33.57$ <b><math>p &lt; 0.001</math></b> partial $\eta^2 = 0.22$	<b><math>p &lt; 0.001</math></b> mean diff = 2.4 $\pm 0.3$	<b><math>p &lt; 0.001</math></b> mean diff = 3.0 $\pm 0.3$	$F(1,122) = 3.22$ $p = 0.075$ partial $\eta^2 = 0.03$	$F(1,122) = 104.37$ <b><math>p &lt; 0.001</math></b> partial $\eta^2 = 0.46$
<b>Study 1 Odor</b>	$F(2.4,63.3) = 14.13$ <b><math>p &lt; 0.001</math></b> partial $\eta^2 = 0.35$	<b><math>p &lt; 0.001</math></b> mean diff = 4.2 $\pm 0.9$	<b><math>p &lt; 0.001</math></b> mean diff = 5.5 $\pm 0.8$	$F(1,26) = 1.21$ $p = 0.281$ partial $\eta^2 = 0.05$	$F(1,26) = 41.50$ <b><math>p &lt; 0.001</math></b> partial $\eta^2 = 0.62$
<b>Study 2 Body sites 1</b>	$F(2.2,62.6) = 4.06$ <b><math>p = 0.019</math></b> partial $\eta^2 = 0.12$	$p = 0.060$ mean diff = 1.1 $\pm 0.5$	<b><math>p = 0.002</math></b> mean diff = 1.2 $\pm 0.3$	$F(1,29) = 0.12$ $p = 0.677$ partial $\eta^2 = 0.01$	$F(1,29) = 10.82$ <b><math>p = 0.003</math></b> partial $\eta^2 = 0.27$
<b>Study 3 Temperature</b>	$F(2.4,68.6) = 10.67$ <b><math>p &lt; 0.001</math></b> partial $\eta^2 = 0.27$	<b><math>p &lt; 0.001</math></b> mean diff = 2.5 $\pm 0.6$	<b><math>p &lt; 0.001</math></b> mean diff = 2.8 $\pm 0.6$	$F(1,29) = 0.22$ $p = 0.640$ partial $\eta^2 = 0.01$	$F(1,29) = 32.50$ <b><math>p &lt; 0.001</math></b> partial $\eta^2 = 0.53$
<b>Study 4 Test-Retest</b>	$F(2.1,40.1) = 2.26$ $p = 0.115$ partial $\eta^2 = 0.11$	$p = 0.054$ mean diff = 2.5 $\pm 1.0$	$p = 0.066$ mean diff = 2.4 $\pm 1.0$	$F(1,19) = 0.06$ $p = 0.807$ partial $\eta^2 < 0.01$	$F(1,19) = 7.3$ <b><math>p = 0.014</math></b> partial $\eta^2 = 0.28$
<b>Study 5 Body sites 2</b>	$F(2.6,28.5) = 9.42$ <b><math>p &lt; 0.001</math></b> partial $\eta^2 = 0.33$	<b><math>p = 0.02</math></b> mean diff = 2.0 $\pm 0.7$	<b><math>p &lt; 0.001</math></b> mean diff = 3.4 $\pm 0.6$	$F(1,19) = 3.80$ $p = 0.066$ partial $\eta^2 = 0.17$	$F(1,19) = 27.74$ <b><math>p &lt; 0.001</math></b> partial $\eta^2 = 0.59$

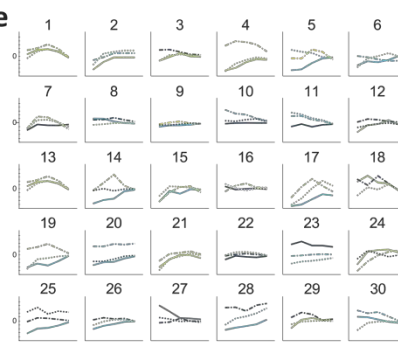
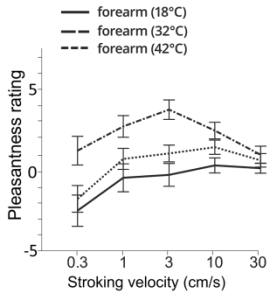
**A Study 1 Odor**



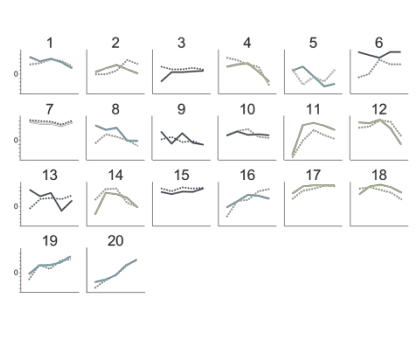
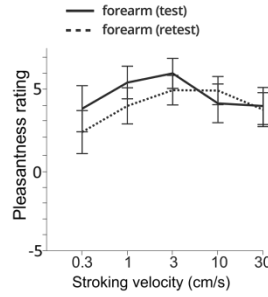
**B Study 2 Body sites 1**



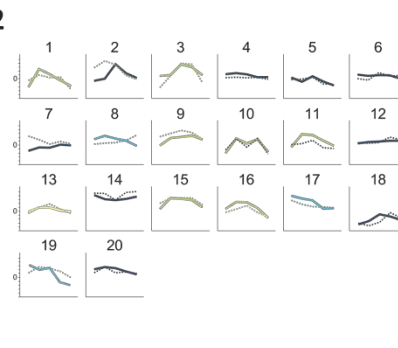
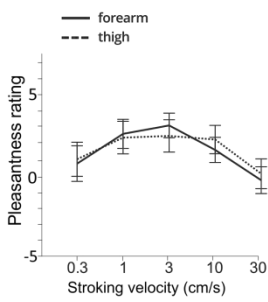
**C Study 3 Temperature**



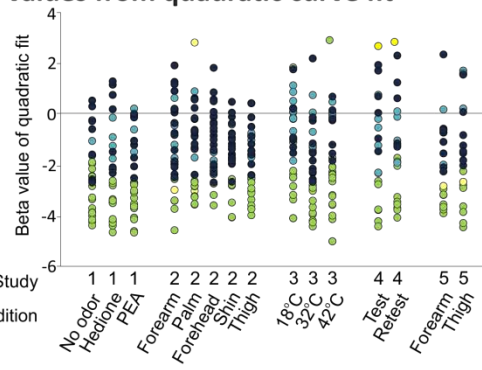
**D Study 4 Test-Retest**



**E Study 5: Body sites 2**



**F Beta values from quadratic curve fit**



Legend for Figure 2F:   
■ Significant quadratic fit and significant main effect of velocity   
■ Significant quadratic fit and no significant main effect of velocity   
■ No significant quadratic fit and significant main effect of velocity   
■ No significant quadratic fit and no significant main effect of velocity

**Figure 2:** Plots of the separate studies in the reanalysis showing pleasantness ratings over the stroking velocities for group data and in individual participants.

The graphs show pleasantness ratings in the reanalysis on the group and individual level, where individual data are coded for their significance of fit to a negative quadratic equation and in the ANOVA, over the different stroking velocities. In (A)-(E), the plots for the average and individual pleasantness curves can be seen over all the conditions in each study included in our reanalysis. For each study, on a group level (large plot), a significant negative quadratic interaction was found. On the individual level (small plots to the right of each large plot), the pleasantness ratings data from each participant can be seen over all the conditions, per study. Individual participants were rather consistent in their ratings over different velocities (i.e. intra-participant consistency); however, a significant negative quadratic fit to stroking velocity was only found in around half of the participants (i.e. there was high inter-participant variability). (F) Individual participant standardized beta coefficients for the fit to the negative quadratic equation are shown for each condition in each study. The spread and variation in the curve fit for individual participants can also be seen in these data.

whether the experimental setting had an influence on the pleasantness ratings. We found a significant effect of study (ANOVA  $F(4,122) = 6.27, p < 0.001$ , partial  $\eta^2 = 0.171$ ). Here, ratings in Study 4 (Test-Retest) were significantly higher as compared to all the other studies (mean 2.1 units on the rating scale; all  $p < 0.05$ ). However, 17.1% of the variance was explained by the experimental setting, which was substantially lower than the variance explained by the quadratic fit of velocity (46.1%).

*Analysis of the pleasantness curve on an individual level*

The clear quadratic fit of the pleasantness curve observed at the group level in the standard condition was not replicated at the individual level. Depending on the study, 43-70% (mean: 57%) of participants had a significant main effect of stroking velocity for their pleasantness ratings in

their individual ANOVAs (Table 4). This means that, on average, 43% of the participants did not show any significant pleasantness trend across the stroking velocities, which can be seen by the shapes of the individual curves in Figure 2. The distribution of the beta values extracted from the negative quadratic curve fit is shown in Figure 2F, where many participants' individual curves did not show a significant quadratic fit, nor a significant main effect of velocity (i.e. that their pleasantness ratings significantly differed in any way with the velocity of stroking). Further, nearly an equal percentage of participants showed significant linear or quadratic fits to their pleasantness curves (mean 44% for linear fit, as compared to 42% quadratic fit; Table 4), meaning that, individually, neither curve shape fit the data better.

*Relationship between pleasantness rating patterns over different conditions*

On a group level, the beta values extracted from the quadratic curve fits per study showed various strengths of correlation between the standard

	No. participants (%) with a significant effect for stroking velocity		
	ANOVA main effect velocity	Linear fit	Quadratic fit
Study1 Odor (n = 27)	19 (70%)	8 (30 %)	18 (67%)
Study 2 Body sites 1 (n = 30)	13 (43%)	11 (37%)	6 (20%)
Study 3 Temperature (n = 30)	17 (57%)	12 (40%)	13 (43%)
Study 4 Test-Retest (n = 20)	13 (65%)	9 (45%)	8 (40%)
Study 5 Body sites 2 (n = 20)	10 (50%)	5 (25%)	8 (40%)
<b>Mean</b>	<b>57%</b>	<b>44%</b>	<b>42%</b>

condition and the various other conditions, such as the modulation of olfactory context, stroking temperature, or body site tested ( $R = 0.221-0.684$  with a median  $R$  of 0.40). This quadratic beta value was significant in 6/10 comparisons (first line of each Study section in Table 5, see end). On inspection of the pleasantness ratings per velocity, the correlations reached a large effect size, with little difference across the stroking velocities (medians: 0.3cm/s  $R = 0.622$ ; 1cm/s  $R = 0.556$ ; 3cm/s  $R = 0.554$ ; 10cm/s  $R = 0.552$ ; 30cm/s  $R = 0.560$ ). Overall, the majority of correlations between the standard condition and each other condition per study were significant. However, this was not the case for Study 3 (Temperature), where only one significant correlation was found (Table 5, see end). Further, Study 4 (Test-Retest) allowed us to inspect the correlation between quadratic curve fits and individual velocities across time, as a repeat of the paradigm was carried out under the standard condition approximately a week later. When we directly compared the pleasantness ratings, the Study 4 quadratic beta value correlation was  $R = 0.49$  and the individual stroking velocities showed large correlations ( $R=0.535-0.792$ ), although the spread of these values was similar to that found in other studies (cf. Study 5 (Body sites 2)) (Table 5, see end).

## Discussion

As we predicted, on a group level, our analysis of a large, combined dataset showed the previously reported velocity-dependent pleasantness ratings that follow an inverted U-shaped pattern (Essick et al., 1999, 2010; Löken et al., 2009, 2011; Morrison et al., 2011; Tricoli et al., 2013; Ackerley et al., 2014a, 2014b; Gentsch et al., 2015; Jönsson et al., 2015, 2017; Sehlstedt et al., 2016; Croy et al., 2016a; Kass-Iliyya et al., 2017; Luong et al., 2017; Bendas et al., 2017; Hielscher and Mahar, 2017; Krahé et al., 2018; Sailer and Ackerley, 2019). We found the same group-level result for each of the individual studies we reanalyzed, confirming the findings from three previously published studies (Ackerley et al., 2014b, 2014a; Jönsson et al., 2015) and in two unpublished ones. Thus, on a large group level ( $n = 127$  participants giving a combined total of 1905 pleasantness ratings in the standard condition) and at the typical-size study level (20-30 participants), significant inverted U-shaped curves, with a peak in pleasantness around the stroking velocity of 3 cm/s, were found. Moreover, in none of these cases did we find a significant linear fit over the different stroking velocities on a group level. However, on an individual participant level, the results were more complex and there was great variation between pleasantness curves.

The analysis of individual ratings on a single participant level showed that the derived pleasantness through stroking was highly variable, especially at slower and faster stroking velocities, and that the pleasantness curve did not typically resemble the inverted-U shape seen at a group level (cf. Figure 2). Only 42% of the participants had a pleasantness rating pattern that significantly fit an inverted U-shaped curve and a similar number showed a linear rating pattern, although note that both quadratic and linear fits could be significant in the same participant. Further, 60% of the participants had a rating pattern that significantly differed with the velocity of stroking (i.e. through the ANOVA), whereas those without a significant effect of stroking velocity either showed too much variability in their ratings or did not differentiate in pleasantness over the velocities (i.e. their curve was flat).

We compared whether repetition of each stroking velocity would give differences in pleasantness ratings, but in no case did we find an effect of trial repetition. This gives us confidence that the perception of pleasantness does not change substantially over the course of the experiment, as there could have been practice or fatigue effects (cf. physiological fatigue in CTs (Vallbo et al., 1999) and the satiety for pleasant touch over time (Tricoli et al., 2014; Sailer et al., 2016)). Further, we investigated whether the experimental setting influenced the pleasantness ratings, where we found that Study 4 (Test-Retest) produced significantly higher pleasantness ratings overall. Taking into account the high variability of individual rating patterns,

**Table 4:** Individual analysis of velocity dependent pleasantness ratings over different studies.

The individual rating patterns were tested for a main effect of stroking velocity over each participant's ratings using ANOVA and whether this pattern was best fit by a linear or quadratic fit. Note that multiple assignments were possible; hence the ANOVA, linear fit and/or quadratic fit could be significant within one participant.

we can speculate that it was the composition of this group of participants and/or certain experimental conditions (e.g. different experimenter) that gave this result by chance, as studies at the same place (Study 1) and using the same number of participants (Study 5) were not significantly different. Thus, care in interpretation must be taken when applying the results of a specific study to a population, as the experimental conditions and/or participant pool may produce different effects.

It has been previously shown that the experimental condition can change the shape of the pleasantness curve, such as for order effects in pleasantness ratings across skin sites (Löken et al., 2011), that the same stroking velocity is evaluated differently when presented alongside other velocities or on its own (Tricoli et al., 2014), and when stroking is delivered at different temperatures (Ackerley et al., 2014a; Study 3 presently). This effect can also be seen in the present reanalysis in that Study 3 (Temperature) showed almost no inter-correlations with the standard condition, neither in the form of the curve, nor at different stroking velocities. Hence, when experimental conditions are manipulated, there is the possibility that the pleasantness curve will change. The variability in pleasantness ratings can also be seen in the analysis of Study 4 (Test-Retest), where the same stroking paradigm in the standard condition was repeated around a week later in the same participants. The correlations between the quadratic term and individual velocities between the initial Test and later Retest show moderately large correlations, but these are not particular higher than other studies (e.g. Study 5, Body sites 2). Thus, there is inherent variability in the way the same participants rate the same stroking touch, although it seems that individual participants do have a stable and preferred velocity of touch (Luong et al., 2017).

It is expected that perceptual rating data are noisy and influenced by various factors, such as the experimental setting and by mood, boredom, or motivation. Our observation that individual behavior did not necessarily resemble the average of a given population is known as ecological fallacy or aggregation bias (Thorndike, 1939; Robinson, 1950). This illustrates the risk of over-interpretation of the pleasantness curve, which is thought to reflect the activity of CT afferents in hairy skin. The two studies investigating CT firing frequency over the same range of stroking velocities have found correlations with perceived pleasantness (Löken et al., 2009; Ackerley et al., 2014a); however, this correlation did not hold true when the conditions were varied (cf. no significant correlation between CT firing and pleasantness at cooler or warmer stroking temperatures in Ackerley et al., 2014a). In these microneurography studies, CT firing also appears to be variable, where individual unit responses do not necessarily resemble the average curve. Further, inverted U-shaped pleasantness curves have been found when stroking human glabrous skin, where CTs are thought not to be present (Löken et al., 2011; Ackerley et al., 2014b), implying that CTs are not required for this pleasantness curve to be found, which argues for a more central mechanism in the interpretation of tactile pleasantness. We confirm this result in our correlation analysis, where we find high correlations between hairy forearm skin stroking and stroking over the glabrous palm. Presently, we cannot say whether this is driven by the possible presence of CTs in glabrous skin (cf. in the rat, Djouhri, 2016) or whether the previous experience of CT touch shapes all pleasant tactile perception. However, it is clear that for the conscious perception of pleasant touch, A $\beta$  mechanoreceptive afferent input is required, as rare neuropathy patients who lack such fibers feel little in the way of actual touch (Olausson et al., 2002). Hence, it may that the inverted U-shaped pleasantness curve relates to CT firing under certain conditions, but that tactile pleasantness is a complex and centrally-mediated phenomenon that includes input from many different mechanoreceptors (Eriksson Hagberg et al., 2019).

The consistent inverted U-shaped pleasantness curve over different stroking velocities has been found in many studies (Essick et al., 1999, 2010; Löken et al., 2009, 2011; Morrison et al., 2011; Tricoli et al., 2013; Ackerley et al., 2014a, 2014b; Gentsch et al., 2015; Jönsson et al., 2015, 2017; Sehlstedt et

al., 2016; Croy et al., 2016a; Kass-Iliyya et al., 2017; Luong et al., 2017; Bendas et al., 2017; Hielscher and Mahar, 2017; Krahé et al., 2018; Sailer and Ackerley, 2019), which may tempt experimenters to over-interpret such results, in the assumption that the group results relate to the individual. Thus, findings on different pleasantness curves in certain populations may be misinterpreted in their potential to be markers for disorders such as autistic traits (Cascio et al., 2008, 2012; Croy et al., 2016a; Kaiser et al., 2016), anorexia (Crucianelli et al., 2016; Davidovic et al., 2018), Parkinson's disease (Kass-Iliyya et al., 2017), or sensory neuropathy (Morrison et al., 2011). However, this would require that the group data are generalizable to the individual and that there norm data are available and reliable. This is the case for other clinical methods to assess somatosensory function, such as quantitative sensory testing (Dyck, 1993), used to assess a sensory detection threshold in touch, temperature, or pain. With this method, a pain threshold, for example, can be measured in an individual and compared to normative data, based on a large population. In contrast, when interpreting the pleasantness curve to stroking at different velocities, it is important to keep in mind that the quadratic curve does not offer an equivalent metric in terms of CT afferent function and we show presently that there may be too much variability at the level of the individual to do so.

Our current results show that the group-to-individual projection must be questioned, as it may be erroneous to make assumptions based on small statistical differences in groups with low numbers of participants and/or showing highly variable data. An increase in the variability of tactile pleasantness in patient groups has been reported (Morrison et al., 2011; Cascio et al., 2012), but it is not known if this stems from limited sample size or a true reflection of the disorder. In any case, interpretations about the shape on an individual's pleasantness curve may lead to an erroneous diagnosis, which could have serious medical consequences.

Future studies investigating tactile pleasantness during stroking must exercise great care in designing, analyzing, and interpreting experiments. We propose that authors show individual participant curves and/or actual ratings, rather than only relying on the average, which we show gives rise to results that may not represent the real spread of individuals. To guide future studies, we have calculated the minimum sample size required for significant effects from our large dataset. This aims to overcome the large individual variability and see how individuals contribute to gaining the whole group effect. We used an online sample size calculator (clinical.com), with an alpha of 0.05 and power of 80%, and used the average difference between 3 vs. 0.3/30 cm/s stroking ratings in our current reanalysis. For a difference of 2.7

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in pleasantness ratings (on a 20-point scale, +10 to -10) with a standard deviation of 3.8, a minimum sample size of 16 participants is recommended. However, this minimum number relates to the typical stroking pleasantness paradigm presented and may not be applicable if the effect size changes due to other parameters.

Overall, there are many individual and top-down factors that can influence pleasantness and the typically-presented mean ratings curve may give a misleading view of tactile pleasantness perception. In comparing the actual individual values, it is clear to see the great variation in pleasantness ratings, especially at the slower and faster velocities, where participants may rate a stroke at either extreme of the pleasantness scale. Further, individual pleasantness curves on the whole do not resemble the averaged group inverted U-shaped curve. We conclude that it is not advisable to use individual pleasantness curve results in explaining perceptual phenomena, nor for the diagnoses of disorders. This does not nullify the results from previous studies investigating differences in tactile velocity preferences between healthy and target groups, rather, we recommend that the emphasis on findings on a group level cannot necessarily be applied to an individual.

#### CRedit author statement

**Iлона Croy:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Antonie Bierling:** Methodology, Validation, Formal analysis, Writing - Original Draft, Visualization. **Uta Sailer:** Conceptualization, Methodology, Validation, Writing - Original Draft, Writing - Review & Editing. **Rochelle Ackerley:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization.

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## Supplementary material

### Supplementary experimental procedures

#### Odor study (Study 1)

A total of 27 women, aged between 20 and 48 years (mean = 27.8, SD = 5.9), were recruited and participants received a financial compensation of €10. The study was approved by the ethics committee of Dresden University of Technology. Written, informed consent was obtained from all participants. Before beginning the experiment, a Sniffin' Sticks identification test (Hummel et al., 1997) was performed with all participants to ascertain the participant had normal function of smelling. Each of 16 Sniffin' Sticks contained a different odor, and participants were asked to smell and identify the odor by choosing from 4 different pictures. If at least 10 of the 16 odors were identified correctly, the participant was considered to have normal olfactory ability. Participants were told that the study was about testing how odors affect mood and the experience of touch. They were seated with their right arm resting comfortably on a table, to the right of which the experimenter sat. View of the experimenter was prevented by a curtain.

Three different odor conditions were administered in an order randomized across participants. Odor administration was done via three different transparent nose clips (Aspira®) containing either odorless air, hedione (0.3 ml), or phenylethylalcohol (PEA) (0.05ml of PEA diluted in propyleneglycole at 10%) in concentrations that were deemed as equal in intensity. After putting the nose clips into their nose, participants were asked to close their eyes and concentrate on the odor for 30 seconds. Immediately after administration of the odor, participants rated its pleasantness, intensity, and eroticism on three consecutively presented VAS-scales. These scales had the endpoints: 'pleasant–unpleasant', 'strong–weak', and 'erotic–not erotic', which were later coded from +10 (when maximally pleasant, strong, or erotic) to -10.

To determine whether the odor induced any mood changes, participants filled in the Positive and Negative Affect Schedule (Watson et al., 1988) both prior to each odor administration and after having rated the odor on the three VAS-scales. Subsequently, during each of the three odor conditions (PEA, hedione, air), the participants' right forearm was stroked in the direction toward their hand by the hand of the experimenter at 5 different velocities (0.3, 3, 1, 10, 30 cm/s) in a randomized order. The experimenter was trained to deliver this stimulation at the given velocity with a pressure of around 0.4 N by stroking on a balance. During the execution of the stroking movements, the experimenter was guided by a visual meter. Participants were asked to close their eyes and concentrate on the touch during the stroking. Following each stroke, participants rated touch pleasantness, intensity, and eroticism on the same three VAS-scales as used for the odor. Each velocity was repeated two more times in randomized order, for a total of three repetitions per velocity.

#### Test-Retest study (Study 4)

A total of 20 healthy participants (12 women), aged between 21 and 28 years (mean = 22.9, SD = 1.7) were recruited and participants received a financial compensation of €10. The study was approved by the ethics committee of

Dresden University of Technology. Written, informed consent was obtained from all participants.

The study was part of a larger investigation, in which we analyzed the influence of C-tactile targeted stroking on several rating scales, one of them being pleasantness-unpleasantness. The participants were seated with their right arm resting comfortably on a table, to the right of where an experimenter sat. The participant's arm was stroked by a 7 cm wide soft goat hair brush, delivered by a robot (Dancer Design, UK) in order to ensure constant force and precise velocity. Each of the 5 different velocities (0.3, 3, 1, 10, 30 cm/s) was presented three times in a randomized order, with an inter-stimulus interval of 10 s. Immediately after stroking, participants rated the pleasantness of the stroke on a visual analog scale with the endpoints 'pleasant' and 'unpleasant' (coded from +10 to -10). In six other sessions, executed in randomized order on the same day, the participants rated their perception of the stroking perception on other perceptual measures. The experiment was repeated after 4-15 days (mean: 8 days).

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Study	Velocity	Comparison experimental conditions							
Study 1: Odor (N=27)		PEA odor		Hedione					
		R	Sig	R	Sig				
Standard condition: No odor	Quadratic beta	<b>0.570</b>	<b>0.002</b>	<b>0.399</b>	<b>0.039</b>				
	0.3 cm/s	<b>0.841</b>	<b>0.000</b>	<b>0.812</b>	<b>0.000</b>				
	1 cm/s	<b>0.459</b>	<b>0.016</b>	<b>0.607</b>	<b>0.001</b>				
	3 cm/s	0.355	0.069	-0.024	0.907				
	10 cm/s	<b>0.529</b>	<b>0.005</b>	<b>0.552</b>	<b>0.003</b>				
	30 cm/s	<b>0.758</b>	<b>0.000</b>	<b>0.827</b>	<b>0.000</b>				
Study 2: Body sites 1 (N=30)		Forehead		Palm		Thigh		Shin	
		R	Sig	R	Sig	R	Sig	R	Sig
Standard condition: Forearm	Quadratic beta	<b>0.488</b>	<b>0.006</b>	0.338	0.068	0.261	0.164	<b>0.444</b>	<b>0.014</b>
	0.3 cm/s	<b>0.725</b>	<b>0.000</b>	<b>0.480</b>	<b>0.007</b>	<b>0.622</b>	<b>0.000</b>	<b>0.706</b>	<b>0.000</b>
	1 cm/s	<b>0.661</b>	<b>0.000</b>	<b>0.798</b>	<b>0.000</b>	<b>0.599</b>	<b>0.000</b>	<b>0.504</b>	<b>0.005</b>
	3 cm/s	<b>0.869</b>	<b>0.000</b>	<b>0.683</b>	<b>0.000</b>	<b>0.598</b>	<b>0.000</b>	<b>0.554</b>	<b>0.001</b>
	10 cm/s	<b>0.792</b>	<b>0.000</b>	<b>0.482</b>	<b>0.007</b>	<b>0.750</b>	<b>0.000</b>	<b>0.631</b>	<b>0.000</b>
	30 cm/s	<b>0.542</b>	<b>0.002</b>	0.302	0.105	<b>0.483</b>	<b>0.007</b>	<b>0.691</b>	<b>0.000</b>
Study 3: Temperature (N=30)		18°C		42°C					
		R	Sig	R	Sig				
Standard condition: 32°C	Quadratic beta	0.221	0.240	0.252	0.180				
	0.3 cm/s	0.289	0.121	0.075	0.695				
	1 cm/s	-0.145	0.444	-0.102	0.591				
	3 cm/s	-0.125	0.511	0.020	0.918				
	10 cm/s	-0.074	0.697	0.189	0.317				
	30 cm/s	0.148	0.436	<b>0.560</b>	<b>0.001</b>				
Study 4: Test-Retest (N=20)		Re-test							
		R	Sig						
Standard condition: Test	Quadratic beta	<b>0.490</b>	<b>0.028</b>						
	0.3 cm/s	<b>0.535</b>	<b>0.015</b>						
	1 cm/s	<b>0.554</b>	<b>0.011</b>						
	3 cm/s	<b>0.792</b>	<b>0.000</b>						
	10 cm/s	<b>0.719</b>	<b>0.000</b>						
	30 cm/s	<b>0.732</b>	<b>0.000</b>						
Study 5: Body sites 2 (N=20)		Thigh							
		R	Sig						
Standard condition: Forearm	Quadratic beta	<b>0.684</b>	<b>0.001</b>						
	0.3 cm/s	<b>0.581</b>	<b>0.007</b>						
	1 cm/s	<b>0.556</b>	<b>0.011</b>						
	3 cm/s	<b>0.821</b>	<b>0.000</b>						
	10 cm/s	<b>0.766</b>	<b>0.000</b>						
	30 cm/s	<b>0.820</b>	<b>0.000</b>						

**Table 5:** Correlations between beta values extracted from each quadratic curve fit per study and between velocity specific ratings and over experimental manipulations. Significant values are displayed in bold.