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Stroking Trajectory Shapes Velocity Effects on Pleasantness and Other Touch Percepts

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Research has identified an inverted u-shaped relationship between stroking velocity and perceived pleasantness. However, the generalizability of this relationship is questionable as much of the work relied on the rotary tactile stimulator (RTS), which strokes skin with force varying along an arc, but confounds stimulus velocity with duration. We explored how these parameters shape the subjective evaluation of touch. In Study 1, one group of participants was stroked by the RTS, while two other groups were stroked by a new robot capable of different types of skin stroking. Participants were stroked at five velocities and rated pleasantness, humanness, intensity, and roughness. In Study 2, participants were stroked by the new robot imitating the movement of the RTS exactly, imitating it while controlling stimulus duration, or moving linearly or ovally with both constant force and duration. Participants rated pleasantness and humanness. Although stroke velocity was related to both pleasantness and humanness in an inverted u-shaped manner, stimulus motion modulated this relationship and the association between velocity and the other ratings. Together, our results clearly link stroking velocity to the perception of touch, but highlight that this relationship is shaped by other parameters such as the duration and spatial trajectory of touch.

Public Significance Statement

Psychophysical research has identified an inverted u-shaped relationship between a touch's velocity and subjective pleasantness, which has guided current thinking about the processing and benefits of a gentle caress. Here, we show that this relationship depends on aspects of the tactile stimulus that, so far, have been overlooked, including the duration of skin contact and the trajectory of the touch. We find that stroking duration and trajectory shape how stroke velocity modulates subjective pleasantness, humanness, intensity, and roughness. Thus, we identify a need for research to go beyond velocity and to consider other motion features of touch, especially those that approximate human social touch outside the laboratory.

Key words: affective touch, C-tactile, stroking, Aβ mechanoreceptors

Feelings of love or friendship often induce an urge to touch which, if gratified, elicits positive affect or pleasure. Thus, how touch changes the way we feel has excited much interest and stimulated research on relevant somatosensory and higher-order psychological processes (McGlone et al., 2014). Yet many questions remain, as both peripheral and central processes are highly complex and current study paradigms rely on a simple tactile stimulus with limited generalizability. Here, we sought to tackle this problem by comparing a dominant mode of presenting gentle touch with more recent alternative stimulations. Specifically, we wished to determine whether and how physical differences in how touch moves across a person's skin modulate perceived pleasantness as well as other related psychological constructs. To appreciate the importance of this endeavor, it is crucial to understand the motivation behind the multitude of studies that used this simple tactile stimulus and the manner in which they have shaped current thinking about the psychological and neurophysiological processing of touch.

Touch pleasantness and stroking velocity

It has long been noted that humans and many other animals engage in friendly physical contact with each other (Darwin, 1872). Thus, research into the mechanisms prompting such contact and underpinning its pleasurable sensation has a longstanding history within psychological science. Yet, it is only in the last two decades that this research took on a significant role and attracted substantial contributions from other related disciplines including anthropology (Blake, 2011), engineering (Flagg & MacLean, 2013; MacLean, in press) and neuroscience (Choi et al., 2020; Vrontou et al., 2013). Largely responsible for this surge in interest was the discovery of an unmyelinated mechanosensensory fiber referred to as C-tactile (CT) afferent. First proposed in cats (Zotterman, 1939), CTs have since been demonstrated in other mammals including humans (Nordin, 1990; Vallbo et al., 1993), where their firing characteristics have been examined using microneurography, a technique that involves the insertion of a thin electrode into a peripheral nerve and recording from a single afferent fiber. Past attempts to quantify and describe CT activity have highlighted their sensitivity to low-force stimulation, a preference for slow, dynamically moving touch, and specific thermosensory properties (Ackerley, 2022). Moreover, their average firing rate seems maximal for gentle stroking between 1 to 10 cm/s at skin temperature (Ackerley, Backlund Wasling, et al., 2014; Löken et al., 2009). As such, the optimal activity of CTs seems tuned to friendly physical contact between conspecifics.

Whereas non-human animals cannot report to us the way gentle stroking makes them feel, such reports can be obtained from humans and have been the primary means for linking CT activity to tactile pleasure. Early evidence combining microneurography with a psychophysical approach indicated that the inverted u-shaped relation found between stroking velocity and average CT firing is correlated with a similar inverted u-shaped relation between stroking velocity and pleasantness ratings (Ackerley, Backlund Wasling, et al., 2014; Löken et al., 2009). This correlation and the finding that CT stimulation in the absence of Aß mechanoreceptor activity contributes little to conscious tactile perception and discrimination (Olausson et al., 2002), informed current perspectives that see CTs as functionally relevant for tactile pleasantness and that refer to touch which optimally stimulates CTs as pleasant or affective touch (McGlone et al., 2014; Olausson et al., 2010).

More than pleasantness

Although affective touch research has centered on pleasantness, recent evidence highlights a potential relevance of other psychological constructs. A study by Jönsson and colleagues (2015), for example, required individuals in romantic couples to stroke each other at different velocities and found that both pleasantness and eroticism ratings related to velocity in an inverted u-shaped manner. Work by Sailer and colleagues (2020) addressed, apart from pleasantness, how arousing, burdensome, rough, hard, or intense being stroked by a soft brush felt. They found evidence for an inverted u-shaped relation between stroking velocity and pleasantness, roughness, and burdensomeness. Along similar lines, work by Wijaya and colleagues (2020) compared the velocity dependence of pleasantness and humanness ratings and found that like pleasantness, humanness was rated higher for stroking at a CT optimal velocity when compared with a non-optimal velocity. Moreover, across a range of stroking materials (e.g., paper, velvet, and denim), pleasantness ratings linearly predicted humanness ratings and both variables were similarly related to sensory percepts, including moisture, softness, warmth, grip and roughness. Thus, pleasantness is not a uniquely defining feature of CT-optimal touch and the functional role of CTs may entail other processes such as the detection and reinforcement of physical contact with conspecifics.

Traditional touch stimulation—advantages and limitations

To date, research examining CT activity and/or the velocity tuning of touch relevant psychological constructs has relied largely on a specific robot that rotates a brush or other materials across the forearm (Ackerley, Backlund Wasling, et al., 2014; Ackerley, Carlsson, et al., 2014; Croy et al., 2016, 2020; Essick et al., 2010; Löken et al., 2009; Luong et al., 2017; Sailer et al., 2020). This robot called the Rotary Tactile Stimulator (RTS, Dancer Design, St. Helens, UK) allows precise control of stroking force and velocity. As such, it affords a level of experimental control not possible with natural touch, delivered by a human. However, the RTS has two significant technical limitations that constrain the type of laboratory touch that can be examined, which may be central in defining affective touch in relation to pleasantness and other tactile percepts.

One RTS limitation concerns its fixed trajectory (i.e. the path of the stimulus) that moves linearly and across the skin with force varying along its motion arc. This kind of rotary touch poorly matches the manner in which humans naturally stroke another. A recent study by Lo and colleagues (2021) demonstrated this by asking participants to stroke the arm of their romantic partner, a dog's back, a foam arm, or their own arm with the intention to maximize a touchee's perceived pleasantness. Although stroking moved along a linear axis, strictly linear motion was less likely during social as compared with non-social touch. Moreover, partner-stroking in particular took varying oval

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trajectories, whereby hand surfaces moved perpendicularly rather than with an arc on and off the skin.

A second RTS limitation concerns the control of stimulus duration. This duration depends on the velocity with which a brush moves across the skin. For fast velocities, stimulus duration is extremely short, whereas for slow velocities it is long. For the fastest typically tested velocity of 30 cm/s, skin contact may last for only 0.2 s, whereas for the slowest typically tested velocity of 0.3 cm/s, skin contact may last for 20 s. Thus, prior research confounds velocity and stimulus duration. Note, however, that any manipulation of velocity is necessarily confounded. When comparing different speeds, one can either control the traveled distance, as done by the RTS, or the time on skin. Ideally, though, one would test both as to see whether the results compare or differ.

Taken together, many studies have identified an inverted u-shaped relation between stroking velocity and pleasantness and this relation has become a proxy for studying CTs. This is because the activity of CTs themselves can only be measured using microneurography, a rare and challenging technique. Yet, to what extent perceived pleasantness is tied to CT firing has come under debate as other psychological constructs show similar velocity-dependent response patterns (Jönsson et al., 2015; Sailer et al., 2020; Wijaya et al., 2020). Moreover, limitations with the stimulus used to study CTs, touch pleasantness and other constructs raise concerns about whether their relation may be specific to a fairly artificial touch or shows robustly for more natural touch patterns.

The present study

To address the above concerns, the present study collected ratings of touch pleasantness and other psychological constructs for stimuli presented with the RTS and a new cable-driven robot with more degrees of freedom (i.e. the brush was suspended and driven via cables; see Figure 1). Specifically, the cable robot could move a brush either along an arc or with a constant perpendicular force, it could trace either a linear or an oval pattern on skin, and it could control either stroking distance or duration. This allowed us to explore the relevance of these motion features, henceforth captured under the term trajectory, for the classical relation between velocity and pleasantness. Additionally, we could examine whether and how a touch's trajectory modulates the relationship between velocity and other constructs and how it is relevant for the manner in which pleasantness and these other constructs relate to each other. We addressed these points in two investigations conducted in two different countries.

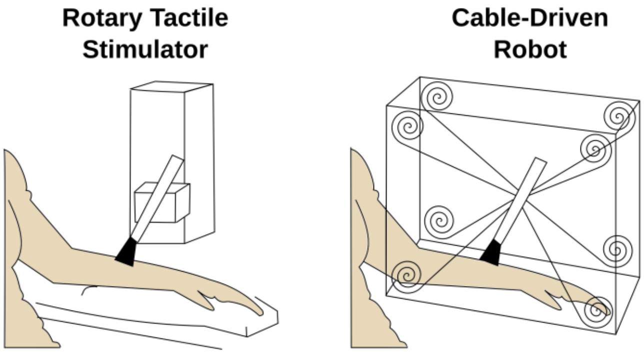

Figure 1. Touch stimulation devices.
Illustrated on the left is the RTS, which has been frequently used in past touch research. Illustrated on the right is a new cable-driven touch robot that offers more degrees of freedom in stroking trajectory.

A first investigation used a between-subjects design comparing a data set collected with the RTS in France with two data sets collected in Hong Kong with the cable-driven robot producing a linear or oval trajectory with constant contact-force and duration (Schirmer et al., 2021; Wijaya et al., 2020). In this study, participants rated the pleasantness, humanness, intensity, and roughness of stroking. A second study, conducted in Hong Kong, used a within-subjects design and compared the effect of four different trajectories on ratings of pleasantness and humanness only. Trajectories were delivered using the cable-driven robot and entailed a direct imitation of the RTS, a duration-controlled adaptation of the RTS, a duration and force-controlled linear trajectory, and a duration and force-controlled oval trajectory. Note that the RTS trajectory and its cable-driven counterparts differed from the linear and oval trajectories in that the former approached and depressed the skin along its motion arc, with maximal normal force in the middle of the stroke, whereas the latter moved a brush perpendicularly onto the skin before moving linearly/ovally at the same normal force. Figure 2 illustrates the different trajectories.

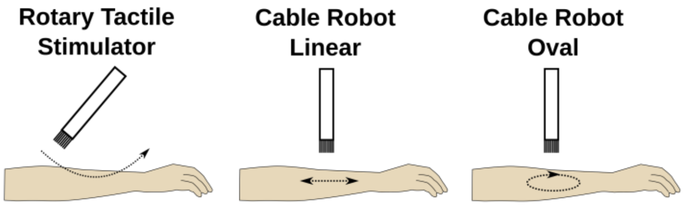

Figure 2. Tactile Stimulation Trajectories.
Across two studies, this research contrasted three stroking trajectories. In Study 1, we contrasted the RTS (left) with two cable robot conditions in which a brush moved back and forth (middle) or in an oval (right) manner across a participant's arm. In Study 2, we implemented the RTS trajectory exactly and as a duration-controlled adaptation with the cable-driven robot and compared this again with linear and oval trajectories.

Based on previous studies using the RTS, we predicted an inverted u-shaped relationship between stroking velocity and pleasantness. As prior research has found that touch with a CT optimal velocity feels more human than other touch (Wijaya et al., 2020), we also predicted stroking velocity to relate to humanness in an inverted u-shaped manner such that pleasantness ratings would correlate positively with humanness ratings. Additionally, we expected to replicate previous data showing that stroking with faster velocities is perceived as more intense (Jönsson et al., 2015; Sehlstedt et al., 2016), yet formulated no predictions for roughness as existing findings are somewhat inconsistent (for further details please see General Discussion). If stroking velocity shapes pleasantness and other tactile percepts independently of the trajectory of a stroke, velocity effects should show consistency across the various trajectory conditions (i.e., RTS & cable robot). Otherwise, we should see different velocity effects for the different trajectories.

Study 1

Methods

This research was approved by the national ethical committee (committee Est-III for the protection of persons in France) in France and the survey and behavioral research ethics committee at The Chinese University of Hong Kong. All participants received information prior to the study and signed informed consent forms. The data were collected in the first half of 2021, thus during the COVID-19 pandemic. At the time, experimental procedures were permitted, but it is noteworthy that the participants from both countries were experiencing similar restrictions in social contact.

Transparency and Openness

We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study, and we follow JARS (Kazak, 2018). All data, analysis code, and research materials are available upon reasonable request directed at the corresponding author. This study's design and its analysis were not pre-registered.

Participants

We recruited 26 participants in France who were stroked using the RTS (Dancer Design, St. Helens, UK). These participants had a mean age of 25.3 years (SD 5.1) and comprised 13 women and 13 men. All participants described themselves as right-handed, apart from one participant who was predominantly left-handed. In addition, we recruited two groups of participants in Hong Kong that were stimulated using a cable-driven robot. One group of 34 participants with a mean age of 22 years (SD 3.8) was stroked with a linear trajectory, whereas another group of 34 participants with a mean age of 21.2 years (SD 2.7) was stroked with an oval trajectory. Both Hong Kong groups had a balanced number of women and men and were right-handed. No participants were excluded from the data analysis.

Please note that power estimates in the context of the present mixed effect modeling approach are not straightforward and could have been done only on simulated data with estimated condition differences (Green & MacLeod, 2016; Kumle et al., 2021; Lakens & Caldwell, 2021). As we had no means of reasonably estimating these differences (Cohen, 1992), we aligned our sample size with previous studies in the area (Jönsson et al., 2015; Sailer et al., 2020; Wijaya et al., 2020). Moreover, we aimed at replicating key results in

Study 2. In France, participation was reimbursed with 10 Euros per hour. In Hong Kong participation was reimbursed with 50 HKD per hour.

Apparatus

Tactile stimuli were presented using either the RTS or a cable-driven robot (Figure 2). The RTS is the current tactile stimulator of choice in research on affective touch. It moves a stimulus, typically a soft goat's hair artist brush (width 5 cm), as used presently, in a circular manner, such that the brush strokes the skin during one such movement. The cable-driven robot was constructed in-house at The Chinese University of Hong Kong (https://drive.google.com/file/d/1JclE_8DQvEef9NtKM6Xu0cYx72aF6J3F/view). Eight motors, each driving one spool, were attached to a rectangular cuboid frame and controlled cables that could move a touch effector in any direction with high spatial and temporal precision. The touch effector held a soft cosmetic brush with a tip size of ~0.5 cm, which was notably smaller than that used with the RTS. While the RTS had a calibrated normal stroking force of 0.4N, for the cable-driven robot, the normal stroking force was approximately 0.3 N.

Procedure

In France, the RTS delivered strokes in a single direction, proximal to distal, on the left forearm. A vacuum cushion was used to hold the arm in a steady and comfortable position. The RTS brush was positioned 1 cm above the middle of the participants' forearm, as measured from the wrist to the elbow, on the dorsal side. The stroked distance across the skin (proximodistal) was approximately 6 cm. Participants were seated comfortably with their head turned towards a computer monitor that displayed the visual analog scales (VASs). A cardboard screen blocked view of the RTS and noise-canceling headphones (Bose, Framington, MA) masked any extraneous noise. In the test session, stroking was done at 0.3, 1, 3, 10, and 30 cm/s in pseudorandomized order with trials divided into three short blocks. Respective stimulus durations were 20, 6, 2, 0.6, and 0.2 s. Each velocity was presented 3 times, giving a total of 15 strokes. This protocol was performed four times, once for each rating task as described below.

In different tasks, participants rated the pleasantness, humanness, intensity, and roughness of the brush strokes. Task-order was counter-balanced across participants. Each trial started with a stroke of the RTS, then a VAS appeared in front of the participant, who made a rating about the tactile percept. The pleasantness scale ranged from unpleasant to pleasant; the roughness scale from smooth to rough; the intensity scale from mild to intense; the humanness scale from not human to human. This was translated into French for the study in France (i.e. deplaisant to plaisant, lisse to rugueux, faible to fort, pas humain to humain, respectively), which matched well with the English equivalent and was found to be similar in meaning. Each scale was presented using a horizontal line on the screen that had aforementioned anchor points at each end. Using a sliding bar device held in the right hand, the subject moved a cursor along the scale and pressed a button to record a response, which saved a numeric rating between -100 to 100. For comparison with the Hong Kong data, score ranges were converted to match those reported below. The next trial started after the rating and there was a delay of at least 10 s between each stroke.

In Hong Kong, the cable-driven robot delivered either linear or oval strokes. Similar to the set-up in France, the mid-point of the forearm (from wrist to elbow) was marked for calibration to ensure that the same area was stroked across blocks. Participants placed their left arm on a cushioned, molded arm rest. Linear strokes moved across a 7.5 cm distance back and forth across the skin. Oval strokes were programmed to move along a 15 cm trajectory with a minor radius of 1 cm and a major radius of 3.22 cm. Small deviations from these set points were necessary due to variation in skin area curvature across participants. Across trials within a condition, we shifted the onset of stroking along the oval circumference such that each section along that oval was stroked equally often. The touch device and the target arm were blocked from the participant's view using a curtain. Noise canceling headphones that presented a soft white noise masked sounds associated with the touch stimulation.

A trial started with a central fixation cross. After 0.4 to 0.55 s, a stroke was delivered at one of five velocities (0.5, 1, 3, 10 and 20 cm/s) for a duration of 2.5 s. Thus, rather than stroking continuously in the oval condition, durations were held constant across the two trajectories because this facilitated condition comparisons and was in fact necessary to achieve comparable trial numbers. Note that due to technical constraints, the slowest velocity was a bit faster and the fastest velocity a bit slower than that of the RTS. Nevertheless, both extreme values were outside the optimal CT/pleasantness range of 1-10 cm/s, therefore the lower and higher speeds are believed to be perceptually similar. One second after stimulus offset, participants were shown a VAS. In four separate blocks, they rated either pleasantness, humanness, intensity, or roughness with similar endpoints as described above and recordings being made on a -50 to 50 continuum for pleasantness and on a 0 to 100 continuum for the other concepts. Ratings were collected in English, the university's language of instruction. The block order was counter-balanced. Participants had a total of three 5-minute compulsory breaks in-between each block while having a self-paced break every thirty trials.

Participants used their right hand to operate a mouse and to mark their rating on the screen. As a participant's arm was not even and the touch trajectory was calibrated based on the participant's arm position small changes in that position could affect touch stimulation such that a stroke could no longer be felt. To alert experimenters to this, participants were shown a response button on each trial next to the rating scale. After participants submitted their rating, there was a brief interval lasting 1, 1.5 or 2 seconds (uniformly distributed) before the next trial began. For each rating task, participants were presented with 12 trials per velocity and thus 60 trials in total.

Note that small procedural differences between France and Hong Kong arose from what was typically done in each lab and were not adjusted for the present purpose as to enable comparisons with previous studies. Instead, these small procedural differences were formally addressed in Study 2.

Data analysis

The different scales were shifted so as to all fall within a 0 to 100 range and subjected to a mixed modeling approach. This enabled us to account for missing values arising from the different velocities tested with the RTS in France and the cable robot in Hong Kong and to model a polynomial regression within subjects. Analyses were conducted in R (R Core Team, 2015) with the afex package (Singmann et al., 2019).

Our dependent variable was the rating score averaged for each condition and participant. We normalized rating averages across conditions, but separately for each task, to a mean of 0 and a standard deviation of 1. Apart from removing potential differences in how participants used the 100-point scale across tasks, this normalization had no impact on the statistical results but facilitated the interpretation of beta coefficients returned by the models. A beta of 1 thus reflected an increase of one standard deviation with a one unit change in the independent variable. Prior to analysis, the velocity variable was subjected to the common logarithm (base 10) in line with previous work (Löken et al., 2009) and entered each model as a second order polynomial to account for its predicted inverted u-shaped function.

We began our analysis with a comprehensive model including Velocity (0.3 to 30 cm/s), Trajectory (RTS, oval, linear), and Task (pleasantness, humanness, intensity, roughness) as well as their interactions as fixed effects and the participants' intercepts as the random effects. Significance testing and the estimation of degrees of freedom was done using the Kenward-Roger method as implemented with the mixed function of the afex package. This method yields both F and p values for main and interaction effects. Associated effect sizes were estimated using the effectsize package (Ben-Shachar et al., 2020). Inclusion of the polynomial velocity effect meant that the Velocity effect comprised both a linear and a quadratic term that were each tested for significance. While a positive quadratic term indexed a convex relation, a negative quadratic term indexed a concave (potentially like an inverted u) relation between velocity and the rated sensory experience. The examination of linear and quadratic terms in follow-up analyses was done using FDR correction for multiple comparisons.

In an effort to explore the relationship between pleasantness and the other rating constructs, we tested three additional models, one for each of these constructs. Respective models had pleasantness as the dependent variable. The fixed effects included Velocity, Trajectory, and either humanness, intensity or roughness with all interactions. Again, the participants' intercepts served as the random effect. All other aspects of this analysis compared to what was reported above. Of interest were only main and interaction effects for the construct of interest (i.e., humanness, intensity or roughness). Other effects were not pursued/reported.

Results

An initial comprehensive model including Velocity, Trajectory and Task returned a significant effect of Velocity (F[2,1677]=39.29, p<.001, ηp2=.04) and significant interactions between Velocity and Task (F[6,1677]=30.93, p<.001, ηp2=.1), Velocity and Trajectory (F[4,1677]=9.53, p<.001, ηp2=.02), Task and

Trajectory (F[6,1677]=13.33, p<.001, ηp2=.05), and Velocity, Task and Trajectory (F[12,1677]=10.77, p<.001, ηp2=.07). We pursued these results separately for each task, by probing a model with Velocity and Trajectory as fixed effects. Please refer to Figure 3 for an illustration of experimental effects and to Table 1 for a summary of follow-up analyses.

Pleasantness

For pleasantness ratings, we observed a significant effect of Velocity (F[2,354]=19.51, p<.001, ηp2=.56), Trajectory (F[2,114]=11.11, p<.001, ηp2=.89) and an interaction between Velocity and Trajectory (F[4,354]=6.37, p=.007, ηp2=.84). Thus, we examined the Velocity effect for each level of Trajectory.

For the RTS stimuli, we observed a positive linear term (pFDR=.0007; for statistical details see Table 1) and a negative quadratic term (pFDR<.0001). For the linear trajectory, we observed a negative linear term (pFDR=.007) and a negative quadratic term (pFDR<.0001). For the oval trajectory, we found both linear and quadratic term were non-significant (psFDR>=.141).

In light of the Trajectory main effect obtained with the full model, we also probed how this effect differs for different velocities. As the velocity endpoints differed slightly between the trajectories, those endpoints were excluded from analysis. The main effect of Trajectory for the shared velocities was established using a likelihood ratio test comparing a null model with a model that included the effect. The result was significant for 1 cm/s (X[2]=4.82, p=.01), 3 (X[2]=12.02, p<.0001), and 10 cm/s (X[2]=10.2, p<.001) stroking. At 1 cm/s, the RTS group rated stimuli as more pleasant than the oval group (beta=-.69, SE=0.22, t[87]=-3.07, pFDR=.009). The linear group failed to differ from both the RTS (p=.205) and the oval group (beta=0.4, SE=0.21, t[87]=-1.89, pFDR=.093). At 3 cm/s, ratings were more positive in the RTS group when compared with the oval group (beta=-.91, SE=.19, t[87]=-4.83, pFDR<.0001) and, but marginally, when compared with the linear group (beta=-.37, SE=.19, t[87]=-1.97, pFDR=.052). Ratings were more positive for the linear group when compared with the oval group (beta=.54, SE=0.18, t[87]=3.02, pFDR=.005). Last, at 10 cm/s, the RTS group had more positive ratings than both the oval (beta=.76, SE=.19, t[87]=-4.01, pFDR<.001) and the linear group (beta=.75, SE=.19, t[87]=-3.95, pFDR<.001), which failed to differ (p=.948).

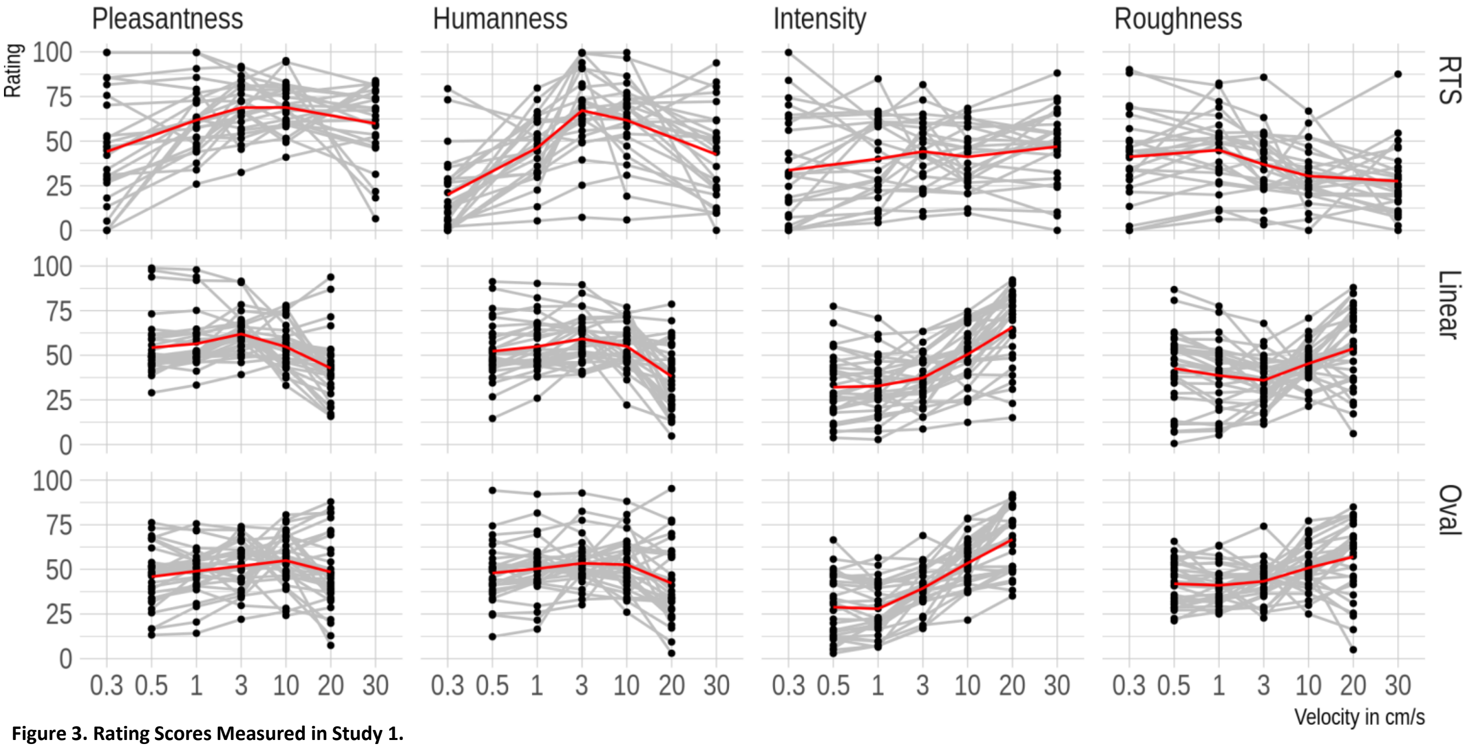

Figure 3. Rating Scores Measured in Study 1.

This figure illustrates the participant-wise mean ratings as a function of velocity, trajectory, and task. Each dot represents one participant. The red line represents the mean obtained when averaging across participants.

Together, these results imply that pleasantness increased with increasing velocity for the RTS, that it decreased with increasing velocity for the linear trajectory, and that it failed to change linearly with the oval stimulus. While both the RTS and the linear trajectory also showed a concave response, such a response did not reach significance for the oval stimulus.

Humanness

Analysis of humanness ratings revealed an effect of Velocity (F[2,354]=40.97, p<.001, ηp2=.73) and an interaction of Velocity and Trajectory (F[4,354]=13.22, p<.001, ηp2=.92). The trajectory main effect was non-significant (p=.664).

Again, we pursued the effect of Velocity for each level of Trajectory. Analysis of the RTS condition revealed a positive linear (pFDR<.0001; for statistical details see Table 1) and a negative quadratic term (pFDR<.0001). For the linear trajectory, we found a negative linear (pFDR=.0002) and a negative quadratic term (pFDR<.0001). Last, for the oval trajectory, the linear term was non-significant (p=.288), while the quadratic term showed the expected effect (pFDR=.005).

Together these results largely compare to the velocity effects observed for pleasantness.

Intensity

Analysis of intensity ratings returned a significant effect of Velocity (F[2,354]=131.53, p<.001, ηp2=.9) and a significant interaction of Velocity with Trajectory (F[4,354]=19.23, p<.001, ηp2=.94). The Trajectory main effect was non-significant (p=.686).

For the RTS, the linear term was significantly positive (pFDR=.023; for statistical details see Table 1), while the quadratic term was non-significant (pFDR=.5). For the linear trajectory, both the linear (pFDR<.0001) and the quadratic term (pFDR<.0001) were significantly positive. Similarly, both linear (pFDR<.0001) and quadratic terms (pFDR=.0006) were significantly positive for the oval trajectory.

Together these effects show that all trajectories felt more intense with increasing velocity. Additionally, linear and oval trajectories showed a convex relation between velocity and subjective stimulus intensity.

Roughness

Examination of roughness ratings identified a significant effect of Velocity (F[2,354]=7.13, p<.001, ηp2=.32), Trajectory (F[2,90.6]=8.93, p<.001, ηp2=.86) and a significant interaction between both factors (F[4,354]=15.13, p<.001, ηp2=.93).

For the RTS, we found the linear term was significantly negative (pFDR<.0001; for statistical details see Table 1), while the quadratic term was non-significant (pFDR=.298). The linear stimulus produced a positive linear (pFDR=.002) and a positive quadratic term (pFDR=.001). Likewise, the oval stimulus produced a positive linear (pFDR<.0001) and a positive quadratic term (pFDR=.035).

Again, in light of the significant Trajectory main effect, we probed trajectory differences as a function of shared velocities. The Trajectory main effect was non-significant at 1 (p=.358) and 3 cm/s (X[2]=2.55, p=.084) but reached significance at 10 cm/s (X[2]=17.84, p<.0001). At 10 cm/s, the RTS group rated touch as less rough than both the linear (beta=.81, SE=.19, t[87]=4.26, pFDR<.001) and the oval groups (beta=1.11, SE=.19, t[87]=5.84, pFDR<.0001), which failed to differ (beta=-.3, SE=.18, t[87]=-1.67, pFDR=.098).

Together, these effects show that perceived roughness decreased linearly with increasing velocity for the RTS condition, whereas it increased linearly with increasing velocity for the two cable robot conditions. Only for the cable robot, the relation between roughness and velocity was characterized by a convex pattern.

		Linear term				Quadratic term			
Task	Trajectory	B	SE	t	Sig	B	SE	t	Sig
Pleasantness	RTS	3.38	.97	3.49	**	-4.4	.97	-4.53	***
	Linear	-2.36	.68	-3.48	**	-3.41	.68	-5.04	***
	Oval	1.15	.81	1.41	ns.	-1.48	.81	-1.82	ns.
Humanness	RTS	4.84	.97	4.98	***	-7.78	.97	-8.01	***
	Linear	-2.38	.64	-3.74	**	-3.49	.64	-5.48	***
	Oval	-.74	.69	-1.07	ns.	-2.15	.69	-3.1	**
Intensity	RTS	2.06	.8	2.57	*	-.54	.8	-.68	ns.
	Linear	7.08	.59	12	***	2.59	.59	4.39	***
	Oval	8.51	.58	3.5	***	2.03	.58	3.5	**
Roughness	RTS	-3.65	.89	-3.24	***	-.94	.89	-1.05	ns.
	Linear	2.86	.9	3.45	**	3.09	.9	3.45	**
	Oval	3.93	.74	5.29	***	1.58	.74	2.13	*

Table 1. Summary of Results Obtained from Study 1.

Significance codes (Sig): p_{FDR}< 0.001 ***, p_{FDR}< 0.01 **, p_{FDR}< 0.05 *, p_{FDR}< 0.1 #. Rotary refers to the RTS-duration controlled trajectory.

Perceptual predictors of pleasantness

Finally, we examined whether pleasantness ratings could be predicted by perceived humanness, intensity, and/or roughness (Figure 4). With humanness as the predictor, our analysis returned a significant predictor effect (F[1,423]=64.83, p<.0001, ηp2=.69), while interactions between the predictor and other factors were non-significant (ps>.316). Across levels of Velocity and Trajectory, humanness positively predicted pleasantness (beta=.41, SE=.05, t[431]=8.1, p<.0001).

With intensity as the predictor, we observed an interaction between the predictor and Trajectory (F[2,400]=3.01, p=.05, ηp2=.36), while other effects were non-significant (ps>.185). For the linear trajectory only, a predictor main effect (F[1,144]=8.9, p=.003, ηp2=.001) indicated that pleasantness increased as perceived stimulus intensity decreased (beta=-.27, SE=.09, t[143]=-3.05, p=.003). Effects were non-significant for the RTS and the oval trajectory (ps>.336).

Finally, with roughness as the predictor, our model returned a significant predictor effect (F[1,431]=22.09, p<.001, ηp2=.21) and a significant interaction of predictor with Trajectory (F[2,430]=10.67, p<.001, ηp2=.6). The predictor main effect was significant for the RTS (F[1,123]=12.73, p<.001, ηp2=.01) and the linear (F[1,149]=66.3, p<.001, ηp2=.01) but not the oval trajectory (p=.348). For the RTS (beta=-.33, SE=.09, t[123]=-3.63, p=.0004) as well as for the linear trajectory (beta=-.46, SE=.06, t[149]=-8.21, p<.0001), an increased perceived roughness predicted a reduction in perceived pleasantness.

Interim Discussion

Study 1 showed that the three trajectory conditions produced different velocity effects on pleasantness, as well as on the other ratings. Additionally, stroking trajectory qualified the manner in which pleasantness related to humanness, intensity and roughness. Nevertheless, interpreting these findings as trajectory effects is difficult. For one, prior research has highlighted large interindividual variability in touch ratings (Croy et al., 2020) that might produce spurious differences in a between-subjects design. Moreover, differences in velocity range, trial numbers, and other methodological parameters between the France and Hong Kong data could have influenced our results. Indeed, due to basic differences in the lab set-up between the two countries, many parameters varied and we made no attempt to control them simply because that would not have been completely possible and because we were interested in how robust rating results would be. Thus, we planned to replicate the Study 1 results using a within-subjects design.

In a second study, we employed the cable robot with one group of participants only. We implemented an exact replication of the RTS trajectory and added an RTS like condition that maintained the arc and thus changes in force but controlled stimulus duration. This addition, henceforth referred to as rotatory trajectory, was important because it could help elucidate rating differences between the RTS and the other conditions. Specifically, differences between the RTS and the rotatory trajectory would point to the importance of controlling duration vs distance, whereas if both the RTS and the rotatory trajectory differed from the other force-controlled conditions (i.e., linear and oval), this would point to a role of force. To keep experimental time within an acceptable limit, we were forced reconsider the number of rating conditions. As pleasantness and humanness were of the greatest interest, their ratings were retained, while intensity and roughness ratings were dropped.

We expected to replicate Study 1 results. If the trajectory differences observed in Study 1 were due to how touch traveled across the skin rather than to extraneous differences between groups, they should also show in Study 2. Specifically, the RTS data obtained in France should map onto the exact and,

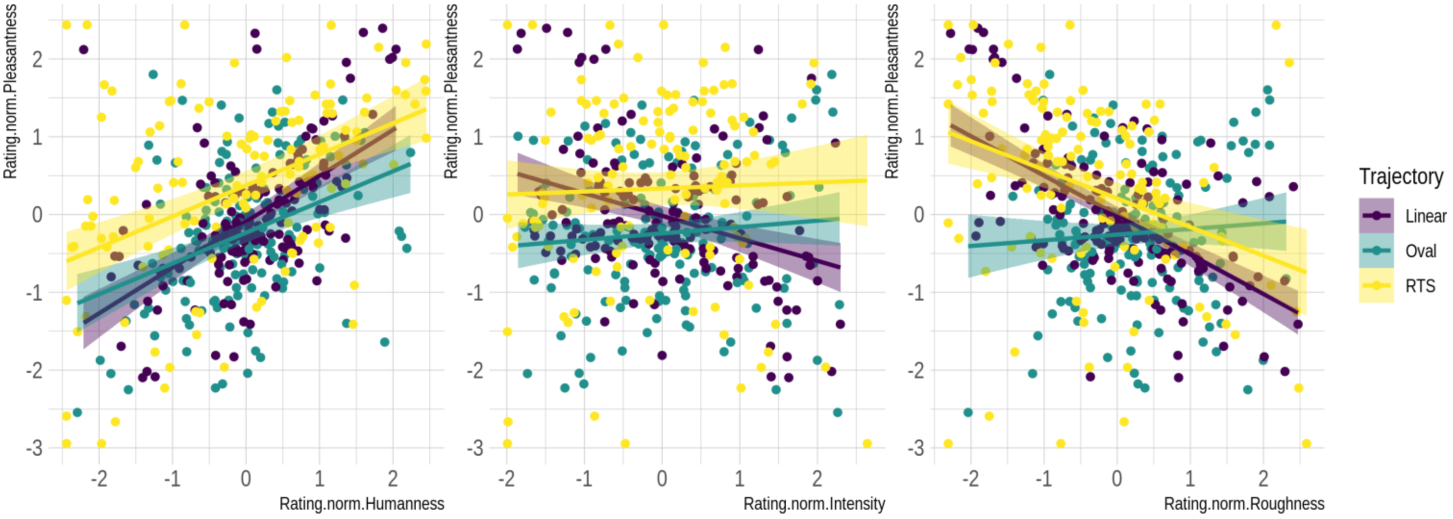

Figure 4. Correlations between pleasantness and other rating constructs measured in Study 1.

Dots represent the mean ratings for each participant (one mean for each velocity) and trajectory.

perhaps, the duration-controlled RTS data obtained in Study 2. In other words, velocity should be related to both pleasantness and humanness in a positively linear and negatively quadratic manner. By contrast the linear trajectory should show negatively linear and negatively quadratic effects and the oval trajectory may yield non-significant effects. Note, however, that due to technical constraints, we had a more restricted velocity range for the RTS conditions in Study 2 when compared with Study 1. Hence, we reasoned that the linear term may be more pronounced and the quadratic term less pronounced for both perceived touch pleasantness and humanness ratings.

Study 2

Methods

This research was approved by the Survey and Behavioral Research Ethics committee of The Chinese University of Hong Kong. All participants received information prior to the study and signed informed consent forms.

Participants

We recruited 61 participants in Hong Kong who were stimulated with the cable-driven robot. One participant was excluded from analysis because he frequently indicated not feeling strokes despite several calibration attempts and visual confirmation that the brush touched the skin. The remaining participants included 30 women and 30 men. They were on average 23.1 years old (SD 5.8) and all right-handed. Participants were reimbursed at a rate of 50 HKD per hour.

Apparatus

We used the same cable-driven robot as described for Study 1.

Procedure

The procedural details were similar to the cable-driven robot groups in Study 1. However, this time, each participant was presented with all four trajectories. This included the cable robot delivering the equivalent RTS trajectory, as described for the RTS in Study 1, the linear trajectory, and the oval trajectory. Additionally, participants were presented with an RTS-like trajectory that was modified to keep the touch duration at 2.5 s across trials and thus comparable to both linear and oval conditions. Moreover, like the linear condition, the brush moved back and forth. Below we refer to this RTS like trajectory as rotatory.

To accommodate this additional trajectory and to make sure trajectories were comparable, one velocity needed adjusting such that the tested velocities were 0.5, 1, 2.5, 10, 20 cm/s. Additionally, we had to adjust distances as follows. For the oval trajectory, strokes traveled along a 12.5 cm perimeter with a minor and major radius of 1 cm and 2.77 cm, respectively. For the linear trajectory, strokes traveled 6.25 cm in length. The arc lengths of RTS and rotatory conditions were also 6.25 cm.

Trials began with a fixation cross. After 0.5 to 1.5 s (uniformly distributed in steps of 0.5), the same brush as before made contact with the skin and stroked for 12.5, 6.25, 2.5, 0.625, and 0.3125 s for the five velocities (respectively slowest to fastest) in the RTS condition and for 2.5 s in rotatory, linear and oval conditions. With stroke offset, a rating scale appeared. After participants submitted their rating response, the next trial started after 1.5 s. Again, an alternative response option accompanied the rating scale in case participants did not feel the touch.

Unlike in Study 1, participants rated pleasantness and humanness only. Intensity and roughness were dropped so as to keep experimental time approximately within an hour and twenty minutes. The continuous ratings were scored between -100 to +100. The two rating tasks were presented as separate blocks. The block order was counter-balanced. Participants had a total of three 5-minute compulsory breaks at the middle and in-between each block while having a self-paced break every thirty trials. Each block comprised 10 trials per velocity and per trajectory condition, presented in pseudorandom order without consecutively repeating the same conditions. This resulted in a total of 200 trials in each block.

All other aspects of the design and analysis compared to what was reported for Study 1.

Results

Mean ratings for each condition and participant were subjected to a linear mixed effect model with Task (pleasantness, humanness), Trajectory (RTS, rotatory, oval, linear), and Velocity (0.5 to 20 cm/s) as well as all interactions between these factors served as the fixed effects. The participants' intercepts served as the random effect.

The model returned a significant effect of Velocity (F[2,2317]=29.54, p<.001, ηp2=.02) and Trajectory (F[3,2317]=13.13, p<.001, ηp2=.02) as well as interactions between Velocity and Trajectory (F[6,2317]=20.5, p<.001, ηp2=.05), Velocity and Task (F[2,2317]=3.5, p=.03, ηp2=.003), and Velocity, Trajectory and Task (F[6,2317]=2.44, p=.023, ηp2=.01). As for Study 1, we pursued the three-way interaction by examining each task separately. Please refer to Figure 5 for a graphical illustration of the results and to Table 2 for a summary of follow-up analyses.

Pleasantness

We probed the role of Trajectory in the relation between pleasantness and Velocity using a model with Velocity and Trajectory as fixed effects. The model returned significant main effects for Velocity (F[2,1129]=20.7, p<.001, ηp2=.37) and Trajectory (F[3,1129]=5.66, p<.001, ηp2=.47) as well as their interaction (F[2,1129]=5.67, p<.001, ηp2=.73).

For the RTS trajectory, velocity predicted pleasantness in a linearly positive manner (p_{FDR}<.0001; for statistical details please see Table 2). The quadratic effect approached significance (p_{FDR}=.064). For the rotatory trajectory, which controlled for stroking duration, both the linear (p_{FDR}=.076) and the quadratic effects (p_{FDR}=.076) merely approached significance. For the linear trajectory, the linear term was non-significant (p_{FDR}=.329) and there was again a significant quadratic term (p_{FDR}=.003). Last, for the oval trajectory, the linear term approached significance (p_{FDR}=.072) and the quadratic term was non-significant (p_{FDR}=.225).

In light of the significant Trajectory effect, we pursued this effect for each level of Velocity and found it significant for 0.5 (F[3,177]=3.07, p=.029), 10 (F[3,177]=7.5, p<.001) and 20 cm/s (F[3,177]=11.39, p<.001; other ps>.337). At the slowest velocity, both rotatory (beta=-.31, SE=.12, t[177]=-2.7, p_{FDR}=.034) and oval trajectory (beta=-.3, SE=.12, t[177]=-2.55, p_{FDR}=.034) were rated as more pleasant than the RTS trajectory with all other effects being non-significant (ps_{FDR}>.165). At 10 cm/s, RTS (beta=.51, SE=.11, t[177]=4.59, p_{FDR}<.001), rotatory (beta=.31, SE=.11, t[177]=2.81, p_{FDR}=.011) and oval trajectories (beta=-.37, SE=.11, t[177]=-3.31, p_{FDR}=.003) were more pleasant than the linear trajectory (other ps_{FDR}>.115). Last with the fastest velocity, the RTS was more pleasant than all other trajectories (betas>.35, SEs=.14, ts[177]>2.51, ps_{FDR}<.015) and both rotatory (beta=.46, SE=.14, t[177]=3.31, p_{FDR}=.003) and oval trajectory (beta=-.43, SE=.14, t[177]=-3.1, p_{FDR}=.004) were more pleasant than the linear trajectory. The rotatory and oval trajectory did not differ (p=.829).

In sum, these results corroborate some but not all effects observed in Study 1. Again, only the RTS trajectory produced a significantly positive linear relationship between stroking speed and pleasantness. However, the concave relation was less robust reaching significance for the linear trajectory only.

Humanness

The humanness model returned significant main effects of Velocity (F[2,1129]=16.25, p<.001, ηp2=.32) and Trajectory (F[3,1129]=9.16, p<.001, ηp2=.57) as well as an interaction of both factors (F[2,1129]=18.73, p<.001, ηp2=.9).

For the RTS trajectory, we observed a positive linear (p_{FDR}<.0001) and a non-significant quadratic term (p_{FDR}=.172). For the rotatory (i.e., RTS duration controlled) trajectory, we observed a non-significant linear (p=.413) and a negative quadratic term (p_{FDR}=.0002). For the linear trajectory, the linear term was significantly negative (p_{FDR}<.0001) and the quadratic term was significantly negative (p_{FDR}=.0002). Last, for the oval trajectory, the linear term was non-significant (p_{FDR}=.609) and the quadratic term was marginally negative (p_{FDR}=.055).

Again, we also examined the Trajectory effect for each level of Velocity with significant results in all cases (Fs[3,177]>3.54, ps<.016), with the exception of 1 cm/s (F[3,177]=2.41, ps=.069). At the slowest velocity, the RTS felt less human than all other trajectories (betas<-.5, SE=.11, ts[177]>-4.4, p_{FDR}<.0001), which did not differ (ps>.787). At 2.5 cm/s, the RTS felt less human than the rotatory trajectory only (beta=-.5, SE=.08, t[177]=-2.44, p_{FDR}=.047). The rotatory trajectory felt more human than the linear trajectory (beta=.25, SE=.08, t[177]=3.09, p_{FDR}=.014, other ps>.166). At 10 cm/s, the RTS felt more human than all other trajectories (betas>.35, SEs=.14, ts[177]>2.53, ps_{FDR}<.014). Additionally, the rotatory (beta=.43, SE=.08, t[177]=3.02, p_{FDR}=.006) and the oval trajectories (beta=-.45, SE=.08, t[177]=-3.2, p_{FDR}=.005) felt more human than the linear trajectory. Rotatory and oval trajectory did not differ (p=.86).

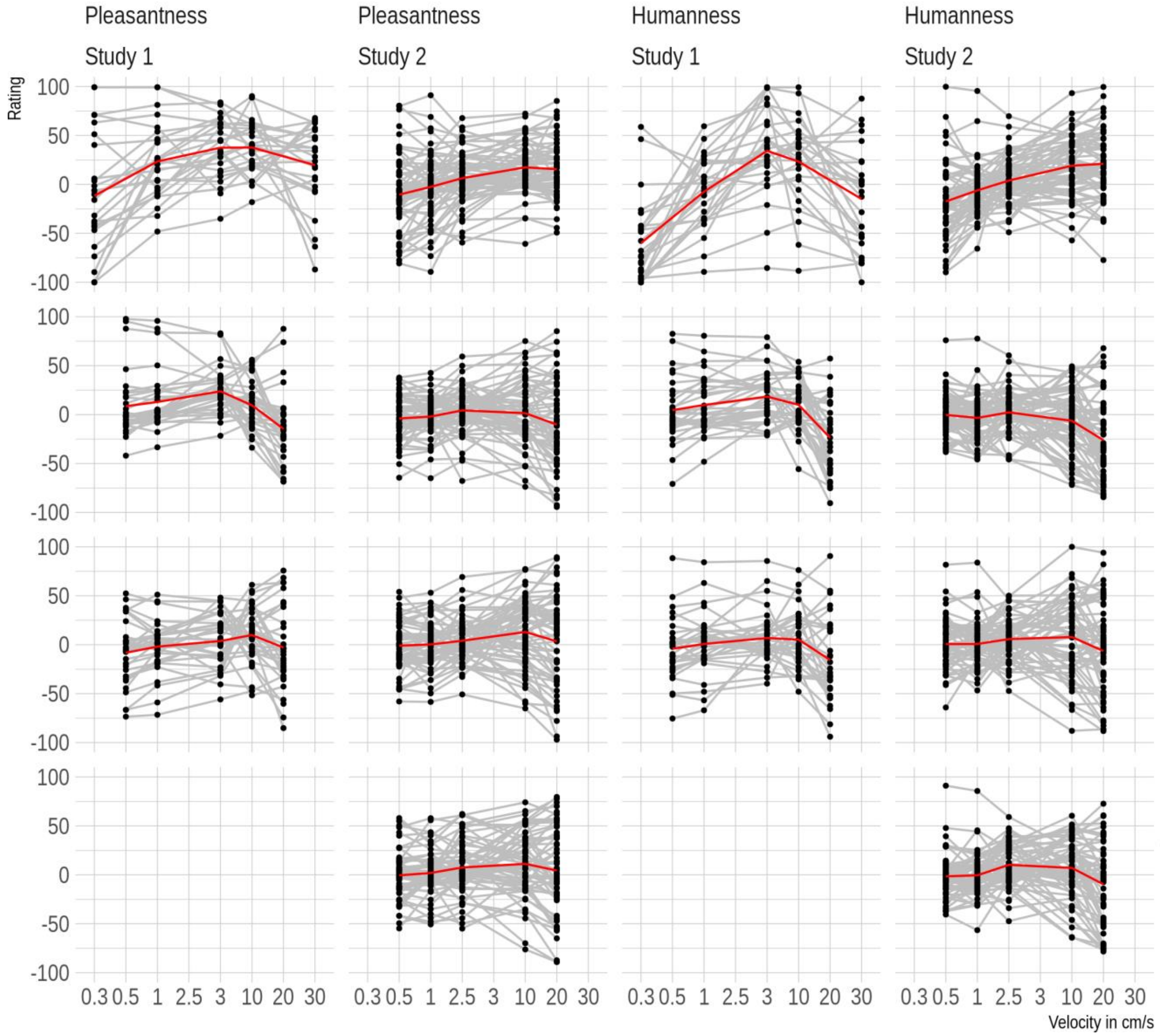

Figure 5. Rating Scores as Measured in Study 1 and Study 2.
This figure shows participant-wise mean ratings as a function of velocity, trajectory, and task. Each dot represents one participant. The red line represents the mean obtained when averaging across participants. When comparing the RTS results between Studies 1 and 2, please take note of the different velocity ranges.

These results replicated at 20 cm/s where again the RTS felt more human than all other trajectories (betas>.87, SEs=.17, ts[177]>5.26, ps$_{FDR}$<.0001) and both the rotatory (beta=.52, SE=.08, t[177]=3.15, p_{FDR}=.002) and the oval trajectories (beta=-.62, SE=.08, t[177]=-3.76, p_{FDR}=.0003; other p=.54) felt more human than the linear trajectory.

In sum, we found that Trajectory modified the relationship between velocity and perceived humanness. As in Study 1, this relationship was positively linear only for the RTS condition. Indeed, for the linear condition, perceived humanness decreased rather than increased with increasing stroking velocity. The expected inverted u-shaped relation showed most convincingly for the rotatory and linear stimuli.

Humanness predicts pleasantness

Again, we probed whether pleasantness could be predicted by the perceived humanness of touch. As was done for Study 1, pleasantness served as the dependent variable, while humanness ratings, Velocity and Trajectory as well as their interactions served as the fixed effects. Corroborating our previous results, we found a significant effect of humanness (F[1,1161]=353.9, p<.001, ηp2=.81), but also an interaction between humanness and Velocity (F[2,1148]=3.33, p=.036, ηp2=.09), and between humanness, Velocity and Trajectory (F[6,1121]=2.54, p=.019, ηp2=.69). Hence, we examined each trajectory separately.

This revealed that only the RTS trajectory elicited an interaction between humanness and Velocity (F[2,257]=4.17, p=.016). Visual inspection of the RTS model (Figure 6) suggested that while there was a positive relation between humanness and pleasantness for each stroking speed, this relation was stronger for slower as compared to faster speeds.

		Linear term				Quadratic term			
Task	Trajectory	B	SE	t	Sig	B	SE	t	Sig
Pleasantness	RTS	5.61	.72	7.8	***	-1.34	.72	-1.86	#
	Rotatory	1.52	.78	1.95	#	-1.38	.78	-1.78	#
	Linear	-.72	.74	-.98	ns.	-2.39	.74	-3.24	**
	Oval	1.82	.86	2.11	#	-1.05	.86	-1.22	ns.
Humanness	RTS	7.99	.85	9.39	***	-1.17	.85	1.69	ns.
	Rotatory	-.68	.83	-.82	ns.	-3.29	.83	-3.94	**
	Linear	-3.02	.8	-5.3	***	-3.02	.8	-3.77	**
	Oval	-.47	.91	-.51	ns.	-2.02	.91	-2.2	#

Table 2. Summary of Results Obtained from Study 2.
Significance codes (Sig): p_{FDR}< 0.001 ***, p_{FDR}< 0.01 **, p_{FDR}< 0.05 *, p_{FDR}< 0.1 #. Rotatory refers to the RTS-duration controlled trajectory.

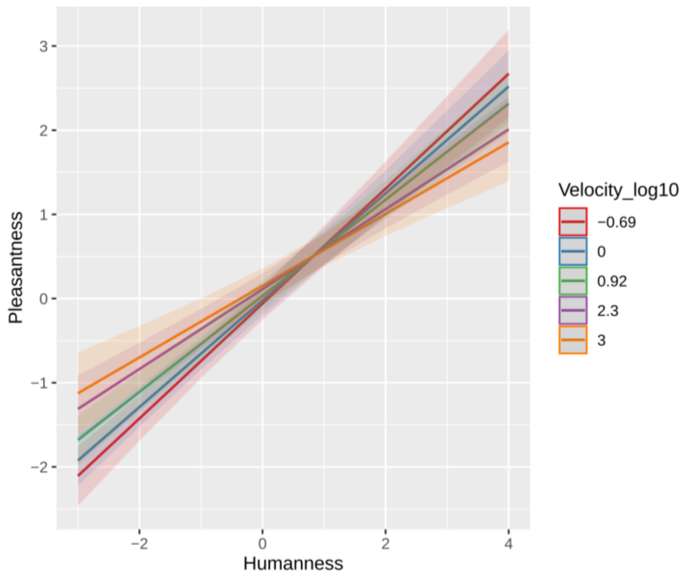

Figure 6. Association Between Pleasantness and Humanness for Different Velocities Presented With the RTS.

Illustrated is the model fit obtained from the analysis reported in the main text.

For the rotatory trajectory, the linear trajectory, and the oval trajectory, the interaction between humanness and Velocity was non-significant ($ps>.172$). These conditions all showed a significant humanness main effect ($Fs[1,279]>59.85$, $ps<.001$) that was driven by a positive linear relationship with pleasantness ($betas>2.03$, $SEs<.77$, $ts[283]>7.7$, $ps_{FDR}<.002$). The results are illustrated in Figure 7.

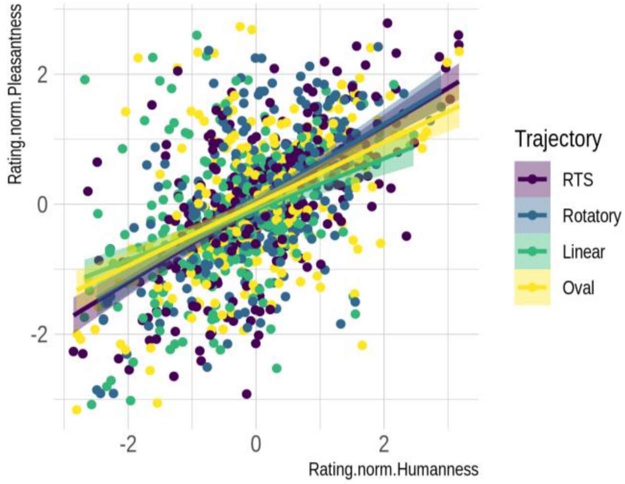

Figure 7. Correlations Between Normalized Pleasantness and Humanness as Measured in Study 2.

Dots represent the mean ratings for each participant (one mean for each velocity) and trajectory.

General Discussion

There is significant variation in the manner in which gentle stroking moves across the skin during natural social interactions (Lo et al., 2021). Yet, past lab-based research has relied largely on a single and somewhat artificial stroking stimulus raising concerns about the generalizability of findings. Here, we compared this stimulus with three other touch stimuli and examined their velocity response function on pleasantness and other rating constructs. Moreover, we probed whether and how stroking trajectory was relevant for the relationship of perceived pleasantness to these other constructs. The following paragraphs address these points in turn.

How does stroking trajectory influence a touch's pleasantness?

To the best of our knowledge, only one prior study compared affective responses to different stroking trajectories (Shirato et al., 2018). In this study, an experimenter rubbed a participant's hand at a speed of 6 to 10 cm/s with either a linear or a circular trajectory for 32 s. Each stimulation was presented four times and followed by nine rating scales on which participants marked the extent to which the previous tactile stimulus made them feel "gentle", "safe", "warm", "comfortable", "preferable", "calm", "unnatural", "nervous", or "unpleasant". Participants also rated the "intensity" of each stimulation. Participants felt less "gentle", "safe", "warm", "comfortable", "preferable", and "calm" but more "unnatural" and "nervous" with the linear when compared with the circular touch. No trajectory differences were observed for "unpleasant" and "intensity".

Although an important first step, this previous study had a number of methodological limitations that may have affected its results. These limitations included (i) its small and sex-biased sample of only 12 women, (ii) that the experimenter's touch was not monitored, for example, to verify its velocity or to describe force and the extent of motion across the skin, and (iii) that participants were presented with many ratings after each stimulus, which they may have conflated and which may have suffered from order effects. A likely significance of one or more of these issues may be inferred from the somewhat counter-intuitive finding that trajectories failed to differ on "unpleasant".

With the present study, we sought to go beyond this work using a psychophysical approach. With a larger and sex-balanced sample, we pursued different perceptual aspects of touch in separate tasks using well controlled tactile stimuli. Moreover, rather than simply contrasting different stroking trajectories, we examined their velocity response functions as a potential index of CT signaling that could be explored in the future.

In line with earlier research, we found that the RTS in Study 1 elicited pleasantness ratings that related to stroking velocity in a concave manner that approximated an inverted "u". Additionally, we observed a positive linear relationship indicating that faster velocities were generally more pleasant than slower velocities. Although rarely reported, this finding converges with prior data that delivered touch stimuli with the RTS (Ackerley, Backlund Wasling, et al., 2014; Croy et al., 2020; Löken et al., 2009; Sehlstedt et al., 2016). It also replicated with the RTS imitation in Study 2 albeit the concave, inverted u-shaped pattern merely approached significance ($p=.064$). Likely, differences in the range of velocities examined in Studies 1 and 2 account for this. The fastest velocity was faster and the slowest velocity was slower for the RTS when compared with the cable-driven robot. As such, Study 1 assessed the typical rating arc more comprehensively than Study 2 and was more sensitive to the underlying quadratic relation.

Interestingly, the RTS results obtained in Studies 1 and 2 differed from those produced with a linear and an oval trajectory. Although the linear condition also showed a concave response, this was accompanied by a non-significant or negative rather than a positive linear trend. Thus, faster velocities tended to be associated with decreased rather than increased perceived pleasantness and were overall less pleasant when compared with the RTS. Moreover, no significant velocity effect emerged with the oval trajectory.

Together, these findings underscore the importance of motion trajectory parameters, besides velocity, in defining perceived tactile pleasure. Based on the present results, we reason that the trade-off between duration and distance as well as the trajectory taken by touch across the skin are both important.

Specifically, changes in duration may contribute to the positive linear term observed with the typical RTS stimulation. In support of this, the strong positive association between velocity and pleasantness observed for the RTS failed to reach significance in the duration controlled RTS, linear, and oval conditions. Moreover, participants tested with the RTS reported informally that they found slower stroking more boring than faster stroking as the former took a much longer time to complete.

Insights into the role of the spatial motion patterns may be derived when comparing linear with oval trajectories. Across two studies, the linear condition showed significant velocity effects on pleasantness, whereas the oval condition did not and this was reflected in the velocity-wise differences between both trajectories. In Study 1, linear stroking was more pleasant than oval stroking at 3 cm/s, whereas in Study 2, linear stroking was less pleasant than oval stroking at 10 and 20 cm/s. That for oval stroking, pleasantness failed to vary as a function of velocity is both interesting and somewhat puzzling because such variation has been reported previously (Schirmer, Lai, et al., 2022). One possible explanation for the present null result is that the perceived pleasantness of oval stroking is only weakly sensitive to velocity perhaps because mechanosensory receptors are differently activated. Unlike linear stroking, oval stroking includes circular forces that may differently indent or pull the skin. In line with this, pleasantness correlated with roughness for all trajectories except the oval one. Alternatively, it is possible that pleasantness ratings are influenced by motion markers that accompany stroking. For linear trajectories that move back and forth, such markers may be more salient than for oval trajectories without sharp turning points. Indeed, one might speculate that many such turning points for very fast stroking reduce tactile pleasure. More research is needed to probe these and other possibilities.

How does stroking trajectory influence other aspects of touch perception?

Apart from pleasantness, we were interested in how different modes of stroking shape perceived humanness, intensity, and roughness. Humanness was of interest because past research has linked CT signaling and tactile pleasure to typical human skin temperature (Ackerley, Backlund Wasling, et al., 2014; Ackerley et al., 2018) and identified overlap with the typical human touch velocity (Croy et al., 2016; Lo et al., 2021). It also established a role of CTs for stress regulation (Coan et al., 2006; Jakubiak & Feeney, 2019) and for reinforcing important social interactions (Croy et al., 2022; Jakubiak & Feeney, 2017). Thus, if humans evolved a tactile sense that represents affectionate physical contact with other humans, then this sense should also be relevant for identifying the humanness of a touch.

This idea received support from an earlier study comparing humanness ratings for slow, CT optimal stroking with fast, CT non-optimal stroking (Wijaya et al., 2020). Here, we extend this evidence to a wider velocity range and show that, similar to CT activity, perceived humanness depends on stroking velocity in a concave manner that approximates an inverted "u". This pattern showed for all trajectories including the oval one raising the possibility that humanness ratings are more closely tied to CT firing than pleasantness ratings perhaps because CTs evolved to signal benign or comfortable skin-to-skin contact.

Like pleasantness, humanness was characterized by a positive linear effect with the RTS and a negative linear effect with the linear trajectory. Again, the RTS effect disappeared when stimulus duration was controlled implying that longer RTS stimuli may be perceived as less human than shorter ones. Possibly, the longer stimuli felt unnatural because of their duration combined with their constant linear motion and unchanging velocity. Indeed, research measuring natural stroking motion shows that spatial trajectory and velocity vary throughout longer periods of touch (Lo et al., 2021).

Importantly, the negative linear effect with duration-controlled stimuli suggests that slower stroking feels more human than faster stroking. This resonates with earlier findings that individuals stroke social partners more slowly whom they perceive as more attractive, likable, and emotionally close (Strauss et al., 2020) and when touching is intended to make a social partner feel pleasant (Lo et al., 2021). Note, however, that although the velocity range of naturalistic stroking and that preferred by CTs overlaps, the former is somewhat faster than the latter (Lo et al., 2021; Strauss et al., 2020).

Ratings of intensity and roughness were of interest because they tapped on more basic sensory aspects of touch previously linked to Aβ mechanoreceptor signaling. Unlike CTs, Aβ fibers enable fast tactile processing and their signals more readily create conscious percepts. Thus, they are thought to underpin discriminative touch perception as is relevant for tactile object recognition and manipulation (McGlone et al., 2014). Aβ firing rate increases monotonically, albeit not necessarily linearly, with the perceived intensity of a touch (Ackerley, Backlund Wasling, et al., 2014; Löken et al., 2009), while variation in the timing and type of Aβ mechanoreceptor fiber activation is relevant for representing texture and roughness (Connor et al., 1990; Phillips et al., 1992; Yoshioka et al., 2001).

Previous psychophysical work using the RTS found a linear positive association between stroking velocity and perceived stimulus intensity (Jönsson et al., 2015; Sehlstedt et al., 2016) albeit one study reported a null finding (Sailer et al., 2020). Additionally, an EEG study revealed that Rolandic rhythms, an index of idle somatosensory processes, decreased with increasing stroking velocity (Schirmer, Lai, et al., 2022). In line with these results, we observed that across stroking trajectories, faster velocities were associated with greater perceived stimulus intensity in a linear manner. Additionally, the duration controlled linear and oval trajectories showed a positive quadratic term, which may have been obscured for earlier and the present RTS data because faster stimuli were also shorter. In support of this possibility, microneurography showed that for some Aβ mechanoreceptors (e.g., hair follicle afferents) firing increases with increasing velocity in a positive quadratic manner, where firing frequency increases exponentially with stroking velocity (Ackerley, Backlund Wasling, et al., 2014; Löken et al., 2009), and thus could highly influence subjectively felt stimulus intensity.

Although several studies have tackled the perception of roughness (e.g., Cascio et al., 2012), to the best of our knowledge only two of them examined roughness as a function of stroking velocity. Whereas Sailer and colleagues identified an inverted u-shaped effect with velocity (Sailer et al., 2020), Wijaya and colleagues found the opposite and showed that roughness negatively predicted both a stimulus' perceived pleasantness and humanness (Wijaya et al., 2020). These observations largely converge with the present results. Stroking with the RTS, as was done by Sailer's group, returned a negatively linear relation between velocity and roughness. Faster and thus shorter strokes were perceived as less rough than slower and thus longer strokes. Stroking with the cable-driven robot, as was done by Wijaya and colleagues, elicited a positive relationship accompanied by a u-shaped velocity effect. Here, faster stroking felt rougher. Thus, differences in the stimulation device and, perhaps, the timing of touch delivery, may account for existing result discrepancies. Notably, for both the RTS and the cable-driven robot, mean participant ratings of roughness negatively predicted pleasantness underscoring that these two perceptual constructs are inversely related as reported previously (Essick et al., 2010; Guest et al., 2011; Wijaya et al., 2020).

Does the relation between tactile pleasantness and other rating constructs differ for different touch trajectories?

Previous research has highlighted that apart from pleasantness other tactile percepts are shaped by stroking velocity and may predict pleasantness ratings (Sailer et al., 2020; Sehlstedt et al., 2016; Wijaya et al., 2020). This is indeed unsurprising as how a somatosensory stimulus makes us feel depends on the bottom-up input from a range of skin receptor types as well as how this input maps onto a person's tactile disposition and previous experience (Sailer & Leknes, 2022).

As mentioned above, one variable of interest has been humanness, due to its potential evolutionary relevance in CT response tuning. Prior evidence for a strong positive correlation between the perceived pleasantness and humanness of touch (Wijaya et al., 2020) could be replicated here. A robust effect was found across three samples in Study 1 and was again demonstrated in Study 2. Note that, additionally, an interaction with trajectory was significant in Study 2, which was better powered and included trajectory as a within-subjects variable. Examination of the interaction identified differences between the RTS and all other conditions. Only for the RTS stimulation did the pleasantness-humanness link vary as a function of velocity. This link was stronger the slower the velocity. The fact that this effect was absent for the duration-controlled RTS stimulation implies a role for the duration/distance trade-off. We speculate that with a longer exposure to a particular touch stimulus, a touchee may form more accurate affective and social touch percepts allowing these percepts to correlate more strongly with each other.

For the sensory features, intensity and roughness, we observed a negative association with pleasantness. The intensity effect was small and showed for the linear trajectory only, whereas the roughness effect was moderate and showed for both the linear trajectory and the RTS. This suggests that, compared to intensity, roughness is more relevant for the affective value of touch at least for touch with a straight trajectory. Indeed, the increased pleasantness of faster RTS velocities was accompanied by a reduction in perceived roughness suggesting that roughness could be relevant for the strongly positively linear relation between velocity and pleasantness that characterizes the RTS data. Note, however, that we did not expressly manipulate stimulus roughness or intensity. Hence, future research introducing changes in touch material (e.g., velvet vs felt) or force (e.g., 0.3 vs 2 N) needs to follow-up on the present results.

Methodological considerations and future directions

The present comparison between different touch robots and stroking stimuli highlights a number of issues that should be considered in the study of affective touch. Apart from emphasizing the role stroking trajectory has in shaping tactile percepts, it identified the tested velocity range as important. This range was smaller for the cable-driven robot than it was for the RTS, which could have affected significance testing of quadratic relationships between velocity and subjective ratings and further studies should explore this possibility, testing more stroking velocities. Indeed, going forward it will be necessary to combine the velocity range advantage of the RTS with the trajectory advantage of the cable-driven robot and to develop a tactile stimulation solution that can stroke naturally in a controlled manner.

Such a solution must include the ability to set both the duration and the distance of strokes traveling across the skin. As we have shown here, ratings differ when slower stroking is confounded with longer durations as compared to shorter distances. As slow, long touches without spatio-temporal variation feel both less pleasant and less human than do fast, short touches, controlling duration may be more critical than distance in research on affective touch. Duration-controlled stimulation also facilitates the interpretation of concurrent neuroimaging data, which are sensitive to stimulus on and offset effects (Schirmer, Lai, et al., 2022). Importantly, however, distance clearly also matters as it determines how many and/or how often mechanoreceptors in the skin are stimulated and potentially fatigued. Thus, future research must address both factors instead of simply one. Moreover, it should accomplish this not only in the context of psychological ratings but combine those with measures of peripheral and central nervous system responses. This would allow unprecedented insights into how mechanoreceptor firing, especially that of C-tactile afferents, is represented in the brain and shapes the complexity of affective touch.

We tested our participants at the same time, during the COVID-19 pandemic, but in different countries. Thus, subtle differences in how the pandemic was handled nationally as well as other inter-individual variables could be relevant in modulating psychophysical responses to touch. Although, the present and previous research, in various cultures, has shown that the inverted-u shaped pleasantness is relatively stable on a group level (Croy et al., 2020; Cruciani et al., 2021; Schirmer et al., 2019), variables such as touch frequency, touch manners, or current ideology have been linked to the feelings elicited by touch (Sailer & Ackerley, 2019; Schirmer, Cham, et al., 2022; Sorokowska et al., 2021). Whether and how they moderate the effect of velocity and other motion properties on the subjective evaluation of stroking touch requires further research.

Last, we wish to raise that although interested in understanding the kind of affective touch that characterizes friendly human interactions, the present like most previous research employed artificial stimuli delivered by a robot. The motivation for this is that robotic touch offers a level of control that is simply impossible to observe with a human experimenter. Future research may tackle this issue in two ways. First, it will be important to record and quantify natural human touch as it unfolds in social interactions. Non-invasive solutions relying on 3D video recordings are currently being developed (Xu et al., 2021) and could be used to link pleasantness and other ratings as well as psychophysiological and brain measures to natural variation in touch. Second, it will be important to translate natural touch recordings into a robotic application. This would enable us to explore causal effects of specific touch parameters on the subjective and biological responses to touch. It would also pave the way to use insights into affective touch towards the development of service robots that offer users socio-emotional support (MacLean, in press).

Conclusions

The present data offer compelling evidence that the effects of velocity on tactile pleasantness depend on how touch moves across a person's skin. For one, they suggest that the RTS results documented in the literature are confounded by the fact that slower stimuli delivered by the RTS last longer. Contrary to stroking by the RTS, duration-controlled stroking may be less pleasant the faster it is. Additionally, pleasantness responses differ for duration-controlled linear and oval stroking pointing to a role of the spatial pattern that touch draws on the skin. Besides pleasantness, other tactile percepts depend on velocity and trajectory. While the effect of a touch's perceived humanness compares to that of pleasantness, more sensory features like intensity and roughness diverge in line with a stronger dependence on Aβ mechanoreceptor signaling. Yet, how pleasantness correlates with humanness, intensity, and roughness is fairly consistent across touch velocities and trajectories.

Together, these results provide compelling evidence for the multi-causality of tactile pleasantness. Apart from velocity, other physical properties including stimulus trajectory and duration are relevant. Additionally, tactile pleasantness appears tied to other tactile percepts, most notably humanness. This raises important issues for future research on affective touch and CTs. Moreover, it highlights the need to study peripheral nerve fibers and their psychological correlates with more diverse and naturalistic touch stimuli.

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