Predictability in Affective Touch

Stroking Trajectory Shapes Pleasantness and Affective Responses

by

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Abstract—
Affective touch is a well-established regulator of emotional well-being, and there is growing interest in designing robotic devices that can replicate its benefits. Yet, most affective touch systems developed so far rely on simple linear stroking patterns, even though natural human touch is rarely so uniform. Specifically, the role of stroking trajectory in shaping affective experience has remained unexplored. This study investigated how the predictability of stroking touch influences pleasantness, subjective affect, and physiological arousal when delivered by a robot to the forearm. 22 healthy adults experienced three stroking trajectories (straight, sine, and sawtooth) at a constant CT-optimal velocity for two minutes each. The trajectories were each administered twice in randomized order. Perceived pleasantness, subjective valence and arousal, and heart rate variability (HRV) were measured for each trial. Statistical analyses showed that the straight trajectory was more pleasant than the sawtooth, while both the straight and sine trajectories resulted in lower subjective arousal than the sawtooth. No significant differences were found for valence or physiological arousal. These findings suggest that stroking predictability modulates subjective arousal, though the subtle trajectory differences were insufficient to produce measurable HRV changes under low-arousal conditions. In addition, a strong positive correlation between perceived pleasantness and valence was observed, raising the theoretical question of whether pleasantness in affective touch studies may be functionally equivalent to valence. The present study argues that stroking trajectory is a meaningful design parameter for robotic affective touch systems, with practical implications for the development of wearable haptic devices and companion robots seeking to modulate human affect.

Index Terms—Affective touch, Arousal, Valence, Heart rate variability (HRV), C-tactile (CT) afferents, Human-robot interaction (HRI)

1 Introduction

Our emotions, moods, and feelings, collectively referred to as affect [1, 2], are a central part of day-to-day life, and our ability to regulate them is essential for mental health and physical well-being [3]. Notably, affective touch is one of the most powerful ways through which affect can be regulated [4]. It is well known that physical contact between people, such as gentle stroking, hugging, and holding hands, feels pleasant and can reduce stress and negative feelings [4, 5, 6, 7, 8].

Unfortunately, this social touch is not always equally accessible. People may be physically separated from others, feel socially isolated, or have conditions that limit physical contact. Partly for these reasons, there is growing interest in the development of robotic systems that can render affective touch [9, 10, 11, 12, 13]. If a robot can produce touch that is similarly pleasant and has similar beneficial effects on how we feel, it could offer a practical way to remotely support emotional well-being in both clinical and everyday settings.

Substantial research has examined the simulation of affective touch through robotic devices, and compared it to manual touch. For example, one study revealed that linear gentle stroking delivered by a robot-controlled brush is perceived as similarly pleasant as manual brush stroking [14]. A similar pattern was discovered for gentle stroking of the back with an artificial robotic hand versus a real hand [15]. This is encouraging, given that the regulatory effects associated with affective touch are generally stronger during human-human touch than human-robot touch [16].

Most studies investigating robotic affective touch have relied on relatively simple touch patterns, typically linear back-and-forth movements. These have been implemented using robot-mounted brushes [e.g. 17, 18, 19, 20] or custom devices with discrete actuators arranged in a linear array [e.g. 9, 12, 13, 21]. Such designs are potentially limiting, as natural human social stroking tends to be less predictable and more spatially variable [22]. The few studies that have directly incorporated stroking trajectory as a variable suggest that it does shape affective touch perception [20, 22, 23]. However, findings are mixed and thus it remains unclear which specific touch trajectory properties drive changes in perceived pleasantness.

A second limitation of prior studies concerns the outcome measures used to evaluate affective touch. The traditional focus has been on perceptual subjective properties, notably pleasantness, intensity, and humanness [20, 24, 25], which is insufficient in two respects. Firstly, these properties are not explicitly linked to any existing affective frameworks, such as Russell's Circumplex model [26]. Secondly, affective states involve not just subjective experiences but also physiological responses like changes in cardiac activity [27]. Indeed, slow linear stroking touch has been shown to increase heart rate variability [19], as well as lower heart rate [28, 29]. Yet, whether these physiological effects vary

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as a function of stroking trajectory remains unknown. To the best of the author's knowledge, no prior studies have systematically examined how stroking trajectory modulates affective responses; neither subjective nor physiological.

To address these gaps, this study compared three robotic stroking trajectories that differed in their degree of predictability, while maintaining a constant stroking velocity. In addition to perceived pleasantness, subjective affect was measured along the valence and arousal dimensions of Russell's circumplex model [26], and physiological arousal was measured in terms of heart rate variability (HRV).

Given previous findings suggesting that smoother and more curvilinear stroking patterns are perceived as more pleasant than irregular ones [23], it was expected that:

- H1: More predictable stroking trajectories will result in higher perceived pleasantness.

Due to its slow and predictable nature, gentle affective touch is generally associated with calming and pleasant feelings [16]. Therefore, more predictable touch was expected to produce calmer and more positive affective responses:

- H2a: More predictable stroking trajectories will result in higher valence.
- H2b: More predictable stroking trajectories will result in lower subjective arousal.

Linear stroking touch delivered at slower velocities on the forearm has been shown to increase HRV relative to non-optimal higher velocities [19]. By analogy, it was predicted that:

- H3: More predictable stroking trajectories will result in lower physiological arousal (higher HRV).

Given the above hypothesized relationships between predictability, pleasantness, and affect, it was further expected that pleasantness and affect would be intercorrelated:

- H4a: Pleasantness will correlate positively with subjective valence.
- H4b: Pleasantness will correlate negatively with subjective arousal.
- H5: Pleasantness will correlate negatively with physiological arousal (positively with HRV).

Finally, as an exploratory analysis, the relationship between subjective and physiological arousal was examined. Since subjective and physiological measures of affect each have unique sources of variance and cannot be assumed to be interchangeable [30], no directional prediction was made a priori.

2 RELATED WORKS

This section reviews the literature relevant to the present study and hypotheses: the role of social touch in humans, the neurological mechanisms underlying affective touch, methods for measuring affective states, and an overview of existing robotic systems that replicate affective touch.

2.1 The role of social touch

The fundamental role of social touch already becomes apparent during the earlier stages of human life. Skin-to-skin contact between infants and caregivers stabilizes physiological parameters such as heart rate and temperature [31], and promotes healthy neurological development [32]. Furthermore, structured touch-based interventions for preterm infants result in improved physiological stability [33], better developmental outcomes [34, 35], and lower risk of death [36]. Consequently, touch deprivation in early life has long-term consequences for mental health: it has been linked to the development of an insecure attachment style [37] and difficulties with emotional regulation [38].

The benefits of affective touch experiences are not just relevant to childhood. Social touch continues to contribute to physiological and emotional stability in adulthood. Interpersonal touch in the form of hugging and gentle stroking has been associated with reduced cortisol levels [6, 39] and lower heart rate [40]. Moreover, hand-holding attenuates neural responses to emotional and threat-related stimuli [7, 41].

Interestingly, social touch has a buffering effect in addition to its in-the-moment regulation of emotion [5]. Studies have shown that it increases one's resilience to emotional pain [42] and to the consequences of stress such as illness [43]. In short, affective touch is not merely a developmental necessity, but a lifelong contributor to physical and emotional health.

How social touch is experienced, however, is not necessarily the same across individuals. Factors such as age, gender, cultural background, and relationship to the toucher have all been shown to influence affective touch perception [16, 44, 45]. In addition, clinical populations such as individuals with autism spectrum disorder may process social touch differently [46]. So, while affective touch is a universal human experience, its subjective impact is shaped by individual context.

2.2 Affective touch and CT afferents

Not all tactile stimulation is processed in the same way. From a neuroscientific perspective, tactile perception is divided into discriminative touch and affective touch. Discriminative touch enables the perception of physical characteristics of the environment, such as textures, vibrations, and pressure, and involves fast-conducting myelinated nerve fibers [47]. On the other hand, affective touch primarily uses a separate system of slower, unmyelinated nerve fibers [47]. A subclass of these fibers known as C-tactile (CT) afferents are particularly responsive to stimuli that typically occur during social interactions [48].

CT afferents are mainly located in hairy skin, such as on the arms, back, and face, and transmit signals to regions in the brain that are involved in emotional processing [47]. Electrophysiological studies have shown that CT afferents are most responsive to gentle stroking stimuli with a velocity between 1 and 10 cm/s [17]. Psychophysical studies corroborate this, showing that stroking within this range is perceived as the most pleasant [18, 49, 50, 51]. Notably, pleasantness ratings consistently peak around 3 cm/s, which is known as the "CT-optimal velocity" [18, 49, 51].

Interestingly, social stroking appears to be naturally tuned for CT-optimal stimulation. Croy et al. found that when stroking a romantic partner or infant, but not an artificial arm, participants automatically used velocities within the CT-optimal range [52]. But beyond velocity, the influence of spatiotemporal properties on affective touch perception remains contested. In a study by Lo et al., the spatial variability of pleasant strokes was found to be higher when manually stroking a human partner or pet dog, compared to stroking one's own arm [22]. In contrast, Katircilar et al. showed that less spatially variable touch trajectories applied by a partner were rated as more pleasant [23]. These inconsistent and sparse results highlight the need for further investigation into how touch predictability shapes pleasantness.

2.3 Measuring subjective and physiological affect

A widely adopted framework for describing affective states is Russell's Circumplex model. It organizes emotions along two dimensions: valence and arousal [26]. Valence describes whether an emotion feels positive or negative. Arousal refers to the level of activation, ranging from calm to excited. For instance, hopefulness is a low arousal and high valence emotion, while anger is a high arousal and low valence emotion.

Importantly, affects are not just a subjective experience. They are often accompanied by measurable physiological changes, such as variations in cardiac, electrodermal, and brain activity [27, 53]. Many of these physiological changes are driven by the autonomic nervous system (ANS), which consists of two subsystems that manage subconscious processes in the body: the sympathetic and the parasympathetic system. The sympathetic system is related to the "fight-or-flight" response of the body, and is activated during stressful, arousing situations. The parasympathetic system deals with "rest-and-digest" processes, and is activated during times of calm and safety [54].

Affective touch appears to directly influence this autonomic balance. For instance, Della Longa et al. found that affective touch resulted in greater heart rate deceleration compared to non-affective touch after viewing emotionally stimulating videos [40]. Similarly, Silvestri et al. found that affective touch reduced physiological arousal in terms of skin conductance in response to emotionally arousing stimuli [8]. These works show that affective touch exerts regulatory effects not just subjectively, but also on a physiological level.

Of the various markers for physiological arousal, cardiac activity stands out for its interpretability and accessibility. This is because heart rate variability (HRV), defined as the variation in time intervals between heartbeats, is closely linked to ANS activity. HRV is lower during sympathetic dominance and higher during parasympathetic dominance [54, 55]. In other words: higher HRV is associated with lower physiological arousal. Furthermore, HRV can be measured continuously and non-invasively with sensors embedded in wearable devices, such as chest straps and smartwatches. These two qualities make HRV a suitable measure of physiological arousal in the context of affective touch studies.

2.4 Robotic affective touch

A commonly used robotic device in affective touch research is the Rotary Tactile Stimulator (RTS), which consists of a brush attached to a motor that strokes the skin in a back-and-forth arc motion [17, 18, 19, 56]. While the RTS has been instrumental in establishing the relationship between velocity and perceived pleasantness during CT-targeted stroking, it has two notable limitations. Firstly, according to Schirmer et al. [20], its rotary motion conflates stroking velocity with stimulus duration. This means faster strokes result in shorter contact duration, and as such these two variables cannot be decoupled with the RTS. Secondly, its fixed arc-based design does not allow for spatiotemporal variation in the stroking trajectory, limiting the types of stimuli that can be investigated.

To overcome these limitations, alternative methods for rendering linear touch have been developed. One option is the use of a custom-built device worn directly on the forearm. For example, Fang et al. created a wearable linear stroking interface and systematically explored how end-effector shape, material, and stroking distance influence perception of affective touch [57]. In a more applied context, Zhao et al. designed a wearable device with a soft, brush-like end-effector, and demonstrated that it effectively reduced state anxiety during a stressful situation [11].

Another approach simulates continuous stroking touch through discrete actuators arranged in a linear array, which creates the sensation of directional movement without a physically moving end-effector. For instance, Huisman et al. demonstrated that pleasantness ratings for vibrotactile stroking at varying velocities matched prior findings on manual CT-optimal touch [9]. More recently, Zheng et al. demonstrated that robotic stroking, administered by their pneumatic S-CAT device at CT-optimal velocities, elicited pleasantness ratings and neurophysiological responses comparable to those of manual stroking [12].

A third methodology is the use of a robot arm or haptic device positioned adjacent to the participant, with a brush or other end-effector making contact with the skin [15, 20, 51]. This choice is particularly useful for studies examining trajectory, as it allows for systematic manipulation of the stroking path. For this reason, the present study employs a robotic haptic device capable of precise trajectory control.

3 Methodology

3.1 Participants

22 healthy adults (16 men, 6 women; age range 23-35 years; $M = 27.7$; $SD = 3.98$) were recruited for the study, most of whom were students and staff at TU Delft. 19 out of 22 participants reported being right-handed. Informed consent was obtained from each participant before experimentation commenced (Appendix A). The study was conducted in Dutch for Dutch speaking participants and in English for non-Dutch speaking participants. The study was approved by the Human Research Ethics Committee of TU Delft (application number 6266).

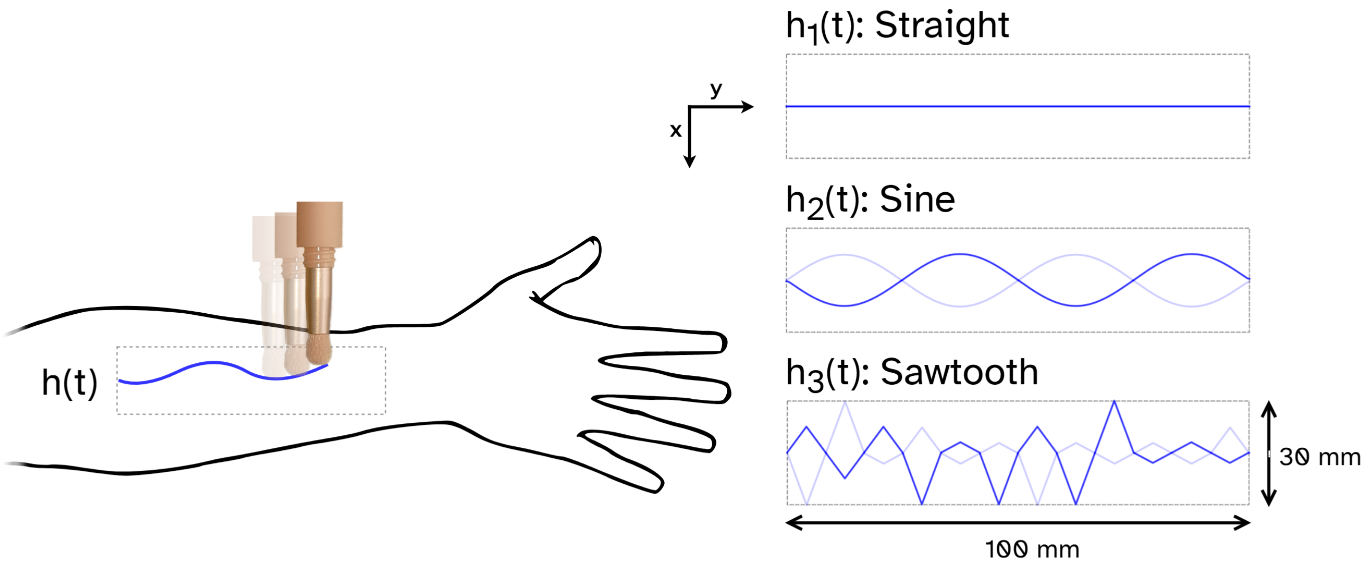

Fig. 1. Area on the forearm where the touch stimuli were applied (left). Visual examples of a single back-and-forth stroke for each of the three stroking trajectories used in the study (right). The gray rectangles indicate the two-dimensional extent of the trajectories.

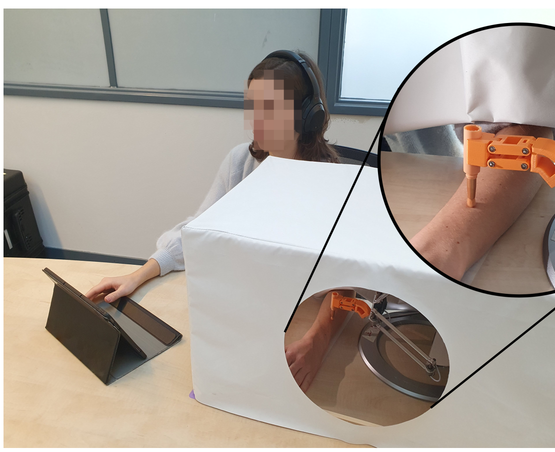

Fig. 2. Experimental setup with a participant wearing headphones, the hidden robotic device, and the tablet with digital questionnaire. The zoomed-in section shows the custom end-effector with a brush mounted on the robot.

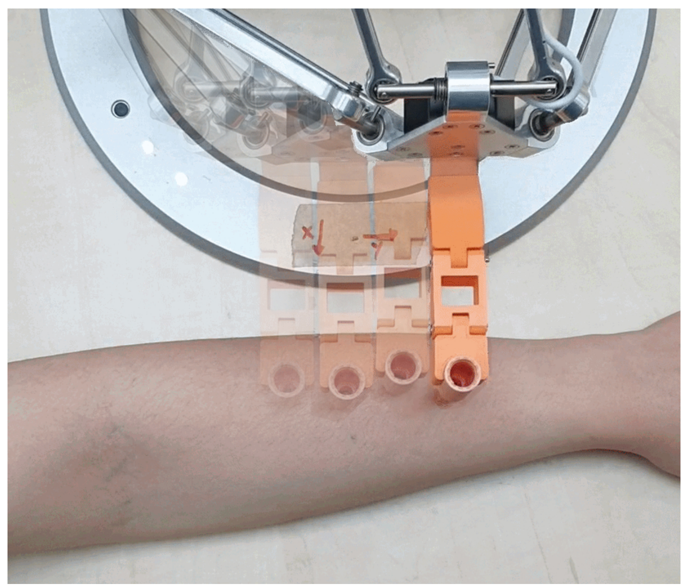

Fig. 3. The sawtooth trajectory in action.

3.2 Stimuli design and equipment

Three stroking trajectories with varying degrees of predictability were used in the study (Figure 1, right). The straight trajectory, commonly used in CT-optimal stroking research, served as the most predictable movement. The sine and sawtooth trajectories were inspired by [23], who showed that a regular sine pattern was more pleasant than an irregular sawtooth. Thus, the sine trajectory in the present study had a low frequency and constant amplitude, while the sawtooth had a higher frequency and randomly varying amplitude (Appendix B). Together, these three trajectories spanned a design space ranging from very predictable to very unpredictable spatial touch patterns.

The stroking stimuli were delivered by a ⌀7 mm soft makeup brush to the dorsal forearm (Figure 1, left). The brush was fixed to a 3 degrees-of-freedom robotic device (Omega.3, Force Dimension, Nyon, Switzerland) with a custom end-effector (Figure 2 and 3). The end-effector was designed such that the z-height and pressure of the brush on the forearm was controlled by gravity (Appendix C). The robot used position control to execute the xyz-trajectories, by means of custom code written in C++ utilizing the Force Dimension SDK.

3.3 Experimental procedure

3.3.1 Setup

The experiment was conducted in a quiet office at the university. Participants were seated comfortably at a table, with their left arm placed in a dorsal position and supported on the tabletop (Figure 2). The arm was oriented such that the robot-controlled brush was positioned directly above the midpoint of the dorsal forearm at rest.

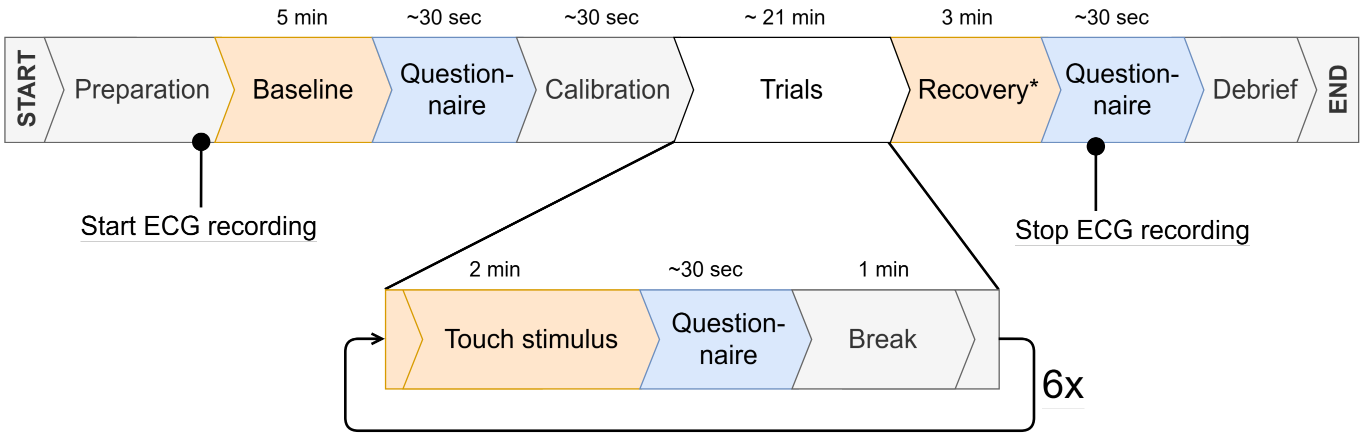

Fig. 4. Overview of the experimental protocol. *Only for 13 out of 22 participants

Participants were equipped with a commercial wireless heart rate monitor (Polar H10, Polar Electro, Kempele, Finland) to record an electrocardiogram (ECG), and active noise-cancelling headphones to suppress any background and robot noise during the experiment. Furthermore, the robot was hidden from the participant's view by a curtain (Figure 2).

The experimenter sat across from the participant, behind the robot. The experimenter's laptop displayed a continuous live ECG from the heart rate monitor to verify signal quality, and a command-line interface to control the trajectory executed by the robot. In addition, a separate tablet was placed on the table on the participant's right-hand side for reporting pleasantness and subjective affect during the experiment.

3.3.2 *Steps*

The full experimental protocol is summarized in Figure 4. At the start, participants received an explanation of the study procedure, signed the consent form (Appendix A), and donned the noise-canceling headphones and heart rate monitor. Next, participants rested quietly for five minutes while a baseline ECG was recorded. This baseline period allowed the cardiac system to return to a steady state following any preceding movement or speech, and provided baseline HRV values for within-subject comparison.

Following the baseline recording, the tactile stimuli were presented in a randomized order for each participant, with the constraint that no trajectory occurred in two consecutive trials. Each of the three trajectories was presented twice, resulting in six trials per participant.

During each trial, the brush moved repeatedly back and forth between the proximal and distal ends of the forearm within a 100 × 30 mm area for two minutes (Figure 1). This duration was chosen to obtain reliable HRV measures in accordance with previous studies on ultra-short term HRV windows [58, 59], while simultaneously minimizing the risk of habituation effects due to sensory fatigue [60].

After each trial, participants rated the pleasantness of the tactile stimulus on a 10-point scale. In addition, they reported their affective state using the Self-Assessment Manikin (SAM), a picture-based self-test consisting of two 9-point scales measuring valence and arousal [61] (Appendix D).

A one-minute break was provided between trials, during which participants remained seated. This rest period allowed physiological arousal to return toward baseline and minimized sensory fatigue from continuous tactile stimulation.

For 13 out of the 22 participants, a final 3-minute recovery recording was made similar to the baseline recording, followed by a final SAM report.

The experiment concluded with general demographic questions (age, gender, and handedness), followed by a debriefing during which participants were encouraged to elaborate on their affective experience with the touch. They were also shown their own ECG and HRV data if interested.

3.4 Data collection and analysis

3.4.1 *Pleasantness and subjective affect ratings*

Participants rated the pleasantness of each touch trial and their subjective affect using a digital questionnaire (Appendix D). Questionnaire responses were manually checked for completeness. Mean scores were computed for each participant and each trajectory for subsequent statistical analysis.

3.4.2 *ECG data*

During the experiment, the signal from the heart rate monitor was transmitted via Bluetooth to a computer and recorded at the device's native sampling rate of 130 Hz. The experimental trials were manually labeled within the continuous recording using a timer during the experiment. See Figure 5 for a visualization of these labels.

To obtain HRV metrics, the ECG signal was first preprocessed in Python with the NeuroKit2 library, as well as visually inspected, to remove artifacts and improve the accuracy of heartbeat detection. Then, ECG data were segmented according to the experimental trials and the baseline/recovery periods. For the latter two segments, only the final 2 minutes of the segments were analyzed to ensure

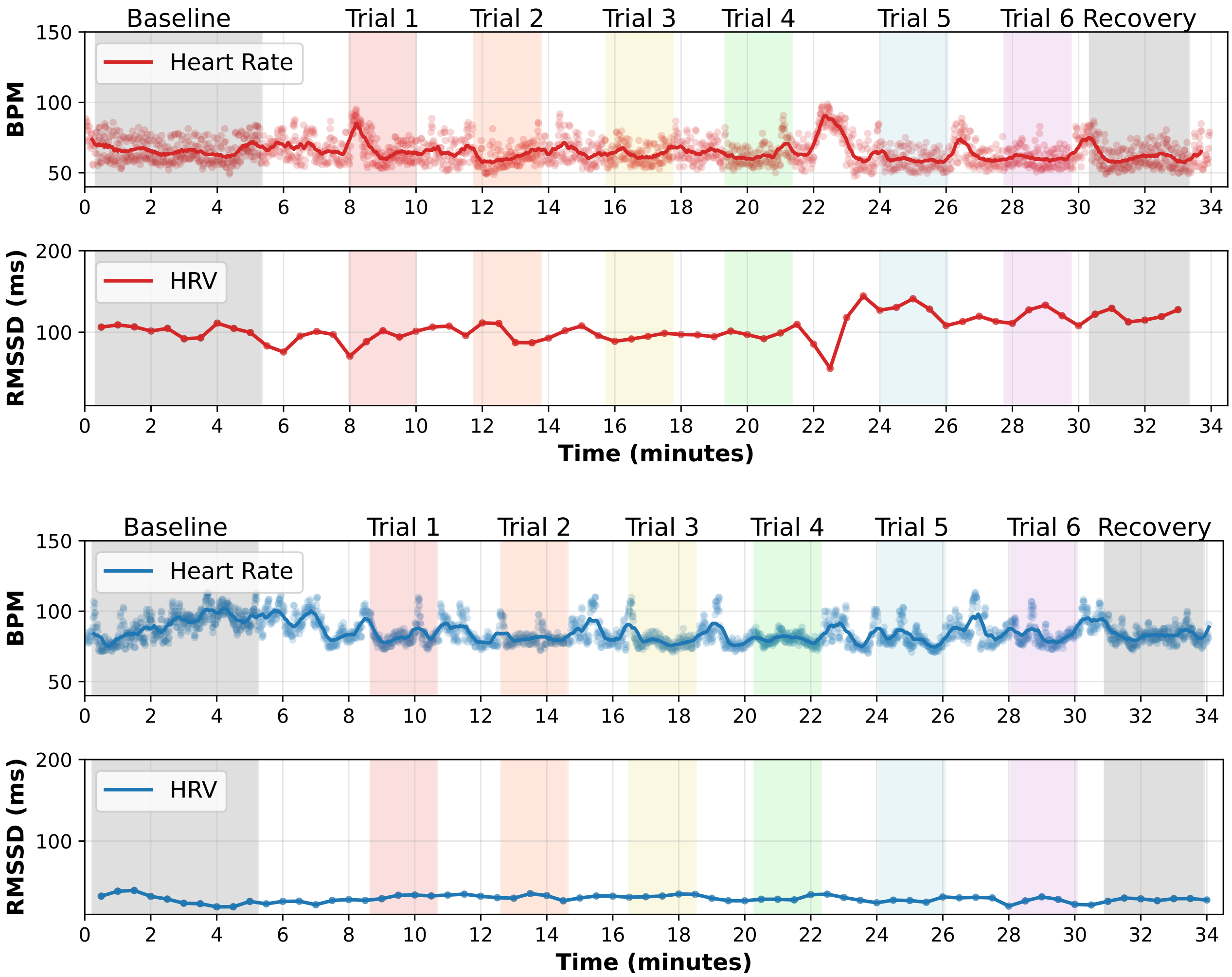

Fig. 5. Progression of heart rate (HR) and heart rate variability (HRV) during the experiment for two randomly selected participants. In the HR plot, dots indicate instantaneous heart rate in beats per minute (BPM), while the line represents the heart rate smoothened using a 30-second rolling window. In the HRV plot, dots indicate HRV values calculated over centered 30-second windows. Shaded colored areas indicate labeled periods in the recording when a trial was in progress.

physiological stability and to be consistent with the trial duration.

HRV metrics were calculated for each segment using NeuroKit2. Due to the short duration of the segments (2 min), analysis focused on the time-domain index RMSSD (Root Mean Square of the Successive Difference of the intervals between heartbeats), which is considered more robust for ultra-short term recordings than other time-domain or frequency-domain measures [58, 59]. Plus, RMSSD is explicitly linked to parasympathetic activity [62], so higher RMSSD indicates lower physiological arousal. This HRV index was log-transformed to reduce skewness (ln RMSSD), and mean values were computed for each participant and each trajectory for subsequent statistical analysis.

4 Results

This section firstly provides a brief descriptive overview of the physiological and subjective data. This includes typical patterns seen during trials and other observations that would not be visible from aggregated data alone. The hypothesis-driven analyses follow in subsequent sections.

4.1 Descriptive overview

4.1.1 Physiological data

To illustrate the structure of the physiological data, Figure 5 shows the heart rate (HR) and heart rate variability (HRV) time series for two randomly selected participants. As expected, overall HR and HRV differed strongly between participants. These differences were due to individual factors like age, gender, and fitness level [62]. Moreover, the intervals between trials were not the same length for all participants. This is because the one-minute break period only began once participants had finished completing the questionnaire for the past trial. This led to variability in the timing between trials and the total length of the ECG recording.

A typical pattern was that HR increased in the periods between trials. This is expected, as participants moved during these intervals to report pleasantness and affective

TABLE 1
Summary of results (means and standard deviations). n = 22 unless stated otherwise.

	Baseline		Trajectories						Recovery (n = 13)	
			Straight		Sine		Sawtooth			
Variable	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Pleasantness	-	-	6.18	1.48	6.07	1.44	5.64	1.60	-	-
Arousal	3.41	1.67	4.18	1.72	4.34	1.61	5.23	1.55	3.64	1.63
Valence	5.41	0.83	5.75	1.02	5.48	1.25	5.43	1.18	5.43	1.18
ln RMSSD	3.58	0.62	3.76	0.50	3.78	0.52	3.72	0.50	3.71	0.59

state using the digital questionnaire (Figure 2). They were also allowed to drink water or adjust their posture in between trials, as long as their left arm remained in position below the robot. These movements likely also account for the observed increases in HR. In contrast, HRV appeared relatively less sensitive to these short periods of motion. This is mainly because RMSSD requires a minimum 30-second rolling window to present meaningful data [58], [59]. The slight differences in HRV between trial and break periods were likely driven by the corresponding changes in HR.

Another notable pattern was a peak in heart rate and the corresponding drop in RMSSD during the first few seconds of Trial 1. This effect was observed in multiple, but not all, participants (e.g. compare top and bottom in Figure 5). Interestingly, this contrasted with the pattern seen in typical and subsequent trials, where HR decreased and HRV increased as soon as stroking began.

Finally, overall baseline and recovery HRV values appeared to differ for some participants. This could indicate long-term effects of the experiment on the participants. Appendix F goes into more depth regarding this observation.

4.1.2 Subjective data

On the pleasantness scale, participants generally avoided extreme values (Appendix E, Figure 12). The same effect was seen for the valence scale. In contrast, several participants chose values on the extreme lower end of the arousal scale, corresponding to the label ’calm’ (Appendix D). Especially the baseline condition received very low arousal scores.

The spread in pleasantness ratings was also notable: the variance was higher for the sawtooth trajectory compared to the sine and straight trajectories (Table 1). The data showed that individual participants indeed ranked the sawtooth trajectory differently relative to the other trajectories. For example, one participant rated it as the least pleasant (straight: 7.5, sine: 7.0, sawtooth: 6.5), while another rated it as the most pleasant (straight: 7.0, sine: 6.5, sawtooth: 7.5). Meanwhile, the sine was rated the second most pleasant by almost all participants (Appendix E, Figure 12).

4.2 Main effect of trajectory

The effect of stroking trajectory on perceived pleasantness, subjective valence, subjective arousal, and HRV (indexed by ln RMSSD) were statistically examined. For each of these dependent variables, a linear mixed-effects model was fitted with stroking trajectory as a fixed effect and random intercepts for participants to account for repeated measurements. Additionally, trial was included as a covariate to control for possible order effects such as fatigue or habituation. Table 1 shows aggregated means and standard deviations for each dependent variable and condition.

4.2.1 Pleasantness (H1)

As shown in Figure 6 and Table 1, participants rated the straight trajectory as most pleasant on average, followed by the sine trajectory, with the sawtooth rated as least pleasant. Compared to the sawtooth trajectory, ratings were significantly higher for the straight trajectory ($\beta = 0.553$, $SE = 0.258$, $z = 2.146$, $p = 0.032$), whereas the ratings for the sine trajectory approached but did not reach statistical significance ($\beta = 0.436$, $SE = 0.257$, $z = 1.692$, $p = 0.091$). The difference between straight and sine was also not significant ($\beta = 0.117$, $SE = 0.257$, $z = 0.456$, $p = 0.648$).

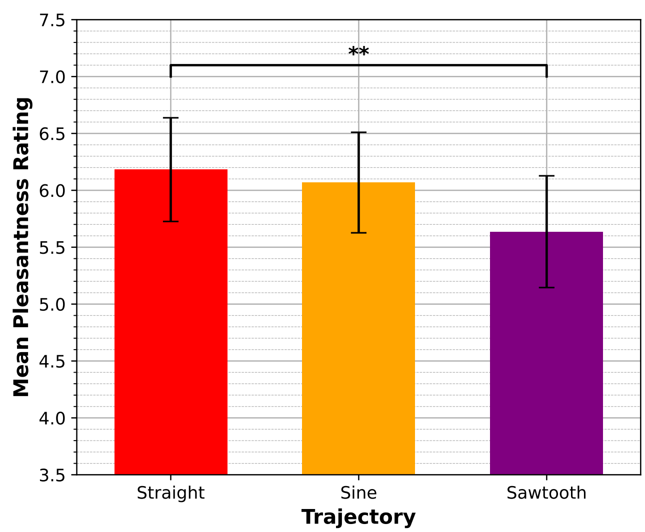

Fig. 6. Mean pleasantness ratings across trajectories. Error bars represent 95% confidence interval. **$p < 0.05$

4.2.2 Subjective arousal and valence (H2)

Figure 7 shows participants’ mean subjective affect ratings per stroking trajectory. Subjective arousal was significantly lower for both the straight ($\beta = -1.038$, $SE = 0.248$, $z = -4.180$, $p < 0.001$) and sine trajectories ($\beta = -0.883$, $SE = 0.248$, $z = -3.556$, $p < 0.001$) compared to the sawtooth trajectory. The difference between straight and sine trajectories was not significant ($\beta = -0.155$, $SE = 0.248$, $z = -0.626$, $p = 0.531$).

No significant effects of stroking trajectory were observed for valence (all $p > .05$).

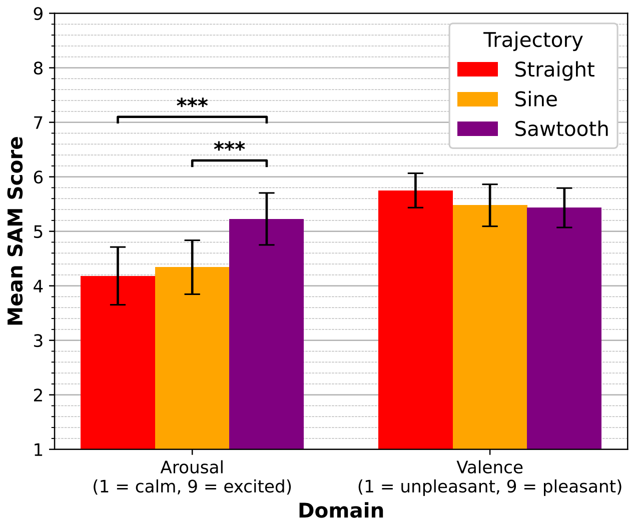

Fig. 7. Mean subjective affect scores across trajectories. Error bars represent 95% confidence interval. ***$p < 0.001$

4.2.3 Physiological arousal (H3)

No significant effect of stroking trajectory on ln RMSSD was found (sawtooth vs. straight: $\beta = 0.035$, $SE = 0.040$, $z = 0.886$, $p = 0.376$; sawtooth vs. sine: $\beta = 0.057$, $SE = 0.040$, $z = 1.417$, $p = 0.157$; straight vs sine: $\beta = -0.021$, $SE = 0.040$, $z = -0.530$, $p = 0.596$). See Appendix E, Figure 13.

4.2.4 Order effects

Across all models, trial was not a significant predictor of pleasantness ($\beta = 0.041$, $SE = 0.062$, $z = 0.663$, $p = 0.508$), subjective arousal ($\beta = 0.040$, $SE = 0.059$, $z = 0.671$, $p = 0.502$), valence ($\beta = -0.008$, $SE = 0.050$, $z = -0.168$, $p = 0.866$), or ln RMSSD ($\beta = -0.015$, $SE = 0.010$, $z = -1.591$, $p = 0.112$). Furthermore, excluding trial as a covariate did not change the pattern of significant and non-significant effects of stroking trajectory. This means the order in which the trajectories appeared had no meaningful effect on the outcome measures. Furthermore, it means there was no evidence of systematic order-related effects such as fatigue or habituation.

4.3 Pleasantness-affect relationship

To examine the relationship between pleasantness and affect, linear mixed-effects models were fitted for the dependent variables subjective arousal, subjective valence, and ln RMSSD. Pleasantness was used as a fixed effect, random intercepts for participants, and trial as a covariate.

4.3.1 Subjective arousal and valence (H4)

As shown in Figure 8, lower pleasantness ratings were generally accompanied by higher arousal ratings. The linear mixed-effects model confirmed a small but statistically reliable negative relationship between pleasantness and subjective arousal ($\beta = -0.249$, $SE = 0.090$, $z = -2.766$, $p = 0.006$). Furthermore, Figure 8 reveals a strong positive correlation between pleasantness and valence, whereby higher pleasantness ratings corresponded to higher valence ratings. This observation was also confirmed to be significant by the linear mixed-effects model ($\beta = 0.571$, $SE = 0.049$, $z = 11.656$, $p < 0.001$).

4.3.2 Physiological arousal (H5)

No significant correlation was found between pleasantness ratings and ln RMSSD ($\beta = 0.629$, $SE = 0.373$, $z = 1.683$, $p = 0.092$).

4.4 Physiological-subjective arousal relationship

Finally, to explore the potential relationship between HRV and subjective arousal, a linear mixed-effects model was fitted with ln RMSSD as the dependent variable, subjective arousal as a fixed effect, random intercepts for participants, and trial as a covariate.

No significant relationship was observed between subjective arousal and ln RMSSD ($\beta = 0.005$, $SE = 0.014$, $z = 0.380$, $p = 0.704$), and trial was also not a significant predictor ($\beta = -0.016$, $SE = 0.010$, $z = -1.647$, $p = 0.100$).

5 Discussion

The goal of this study was to investigate how different stroking touch trajectories (straight, sine, and sawtooth) at a CT-optimal velocity influence perceived pleasantness, subjective affect, and physiological arousal when applied to the forearm by a robot. In addition, the study aimed to explore the relationship between perceived pleasantness and affect. This section discusses the results, their implications for future robotic designs, limitations of the study, and suggestions for future work.

5.1 Main effect of trajectory

5.1.1 Pleasantness (H1)

Participants rated the straight trajectory as most pleasant, and the sawtooth trajectory as least pleasant. However, the sine trajectory did not differ significantly from the sawtooth or the straight trajectory (Figure 6). These results are partly in line with prior research showing that regular, predictable touch applied by finger tends to be perceived as more pleasant than irregular, unpredictable touch [23].

Interestingly, this contrasts with findings by Lo et al., who found that natural social stroking tends to be spatially variable, and argued that this variability enhances pleasantness [22]. However, this study focused on the toucher's behavior rather than the touchee's perception, and their participants applied touch manually. These methodological differences may explain why spatial variability is more pleasant in natural touch contexts, but not in robotic ones.

The lack of a significant difference in pleasantness between sine and sawtooth trajectories could be attributed to the relatively small overall separation between the three conditions. Although the straight trajectory received the highest mean pleasantness rating, and the sawtooth trajectory the lowest (Table 1), the absolute difference between these two extremes was relatively small ($\Delta = 0.54$ on

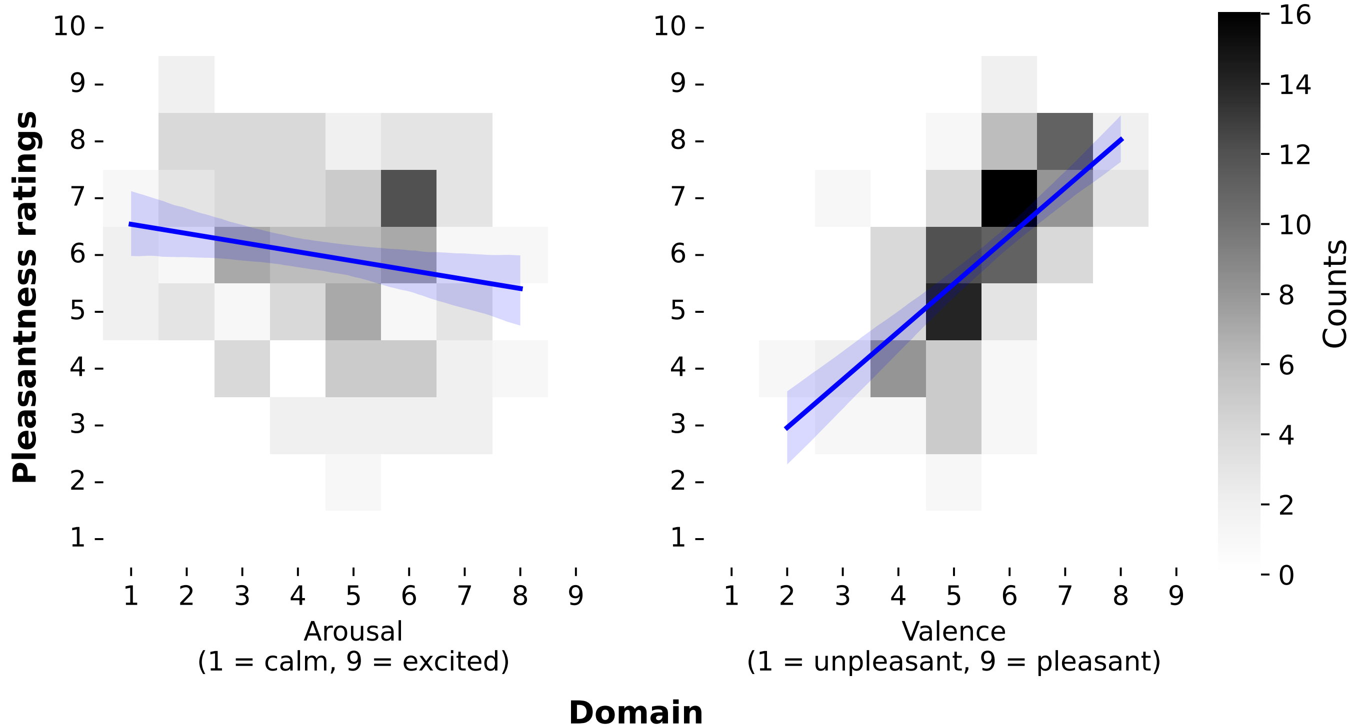

Fig. 8. Heatmap of joint participant counts for the subjective affect dimensions arousal (left) and valence (right), and perceived pleasantness ratings. Darker cells indicate higher frequencies. The blue lines are the least-squares linear regressions predicting arousal and valence from pleasantness. The shaded region represents the 95% confidence interval for the predicted mean arousal and mean valence at each level of pleasantness.

a 10-point scale). The sine trajectory fell between these values and was numerically closer to the straight trajectory than to the sawtooth trajectory. Given this narrow range of means and the reported standard errors, the study may have lacked sufficient statistical power to detect small differences between trajectories.

5.1.2 Subjective arousal and valence (H2)

The fact that straight and sine stroking trajectories resulted in significantly lower arousal than the sawtooth trajectory (Figure 7) shows that the regularity of CT-optimal touch trajectories may indeed be relevant to affective experience.

From a neurophysiological perspective, this may be explained by habituation effects. Both the straight and sine trajectory were predictable and spatially consistent over longer time periods (Figure 1). This led to repeated stimulation of the same CT-afferents, likely resulting in receptor fatigue [60]. In contrast, the randomized changes in amplitude of the sawtooth trajectory introduced more novelty by stimulating a wider set of CT-afferents, thereby reducing habituation and sustaining attention. This interpretation is further supported by informal comments by one participant that they eventually ”tuned out” the ”boring” straight and sine strokes. It also aligns with broader literature on habituation in affective touch. For example, perceived pleasantness of linear stroking was found to decrease over time due to habituation [19, 63, 64].

Aside from CT-afferent fatigue, the similarity in mean ratings for the straight and sine trajectories across subjective measures could also be explained by the sine trajectory's low frequency and amplitude, which resulted in high spatial similarity to the straight trajectory. It was noticed that several participants confused the straight trajectory for the sine trajectory or vice versa during debriefing at the end of the experiment. Future studies could focus on comparing repeated stimulation at the same location on the forearm versus systematically shifting location.

In contrast to arousal, no evidence was found to support the hypothesis that more predictable stroking trajectories result in higher positive valence. This null result may be attributable to limited sensitivity due to sample size constraints, similarly to the small absolute differences in mean pleasantness ratings discussed earlier. Since all stroking trajectories were perceived as generally pleasant on average, the limited range of ratings may have reduced sensitivity to trajectory-specific effects on valence. Even though trajectory did not significantly impact valence directly, it did significantly influence pleasantness, which in turn was significantly associated with valence (Figure 8). The pleasantness-valence relationship and its implications are further discussed in the next section.

5.1.3 Physiological arousal (H3)

Heart rate variability (HRV) as indexed by RMSSD showed no significant difference across trajectories. This implies that stroking trajectory has no effect on physiological arousal. It is possible that a higher contrast between activating and calming stimuli is required to measure changes in HRV. This study, however, used a controlled low-arousal environment whereby external stressors were deliberately minimized. As a consequence, the relatively subtle differences in stroking trajectory within the CT-optimal range were likely insufficient to cause measurable changes in autonomic activity. This explanation is consistent with the view that affective touch primarily has a regulating role [4]. Since it modulates rather than induces arousal, the impact of affective touch is therefore best measured when the autonomic nervous system is already activated.

Additional analysis revealed that mean $\ln$ RMSSD significantly increased from baseline to first trial only, regardless of condition (Appendix F). Since all three trajectories had a CT-optimal velocity, this difference in HRV may be explained by a subconscious positive response to the novelty of the touch itself, rather than the shape of the specific trajectory.

It is also possible that HRV during baseline was lower than usual due to anticipatory autonomic activation related to the upcoming experimental procedure. Some participants informally reported feeling slightly nervous or uneasy during the baseline period, because they ”did not know what to expect of the robotic touch”. So if baseline HRV was reduced due to anticipation, the higher HRV observed during the first trial could indicate a return to a more relaxed physiological state, rather than a response to the stroking trajectory. In this sense, robotic touch may have helped reduce physiological arousal that was present before stimulation began. This regulatory effect was also observed in affective touch studies where arousal was deliberately elicited [8, 40].

5.2 Pleasantness-affect relationship

5.2.1 Subjective arousal and valence (H4)

A small but significant negative relationship was found between pleasantness and subjective arousal, confirming the hypothesis. Similar to the prior discussion on the main effects of trajectory and subjective arousal, it appears that how calming the touch is, is closely related to its perceived pleasantness. This relationship also suggests that affective touch may have activating effects on human affect when less pleasant stroking is applied.

The strong positive correlation between pleasantness and valence was particularly striking: after two minutes of touch perceived as pleasant, participants immediately reported feeling more positive themselves. One possibility is that participants automatically associated ”pleasant touch” with ”I feel pleasant” while completing the questionnaire, as the two scales had similarly labeled extremes (Appendix D). Whether this reflects a cognitive association or a deeper conceptual overlap between the two variables warrants further investigation.

More importantly, the pleasantness-valence relationship raises a theoretical question about the concept of ”perceived pleasantness” as used in CT-optimal touch research. Pleasantness is typically treated as a perceptual property of touch, akin to intensity, humanness, and roughness, rather than as an affective state. However, the findings of this study suggest it may be functionally equivalent to the valence dimension of Russell's Circumplex model [26]. If pleasantness and valence are measuring the same underlying concept, prior studies reporting pleasantness as an outcome may have been implicitly measuring affective valence all along, without framing it as such. This would have implications for how findings in the CT-optimal touch literature are interpreted and compared across studies.

5.2.2 Physiological arousal (H5)

No correlation was found between pleasantness and physiological arousal, resulting in the rejection of this hypothesis. This null result can be attributed to the same limitations discussed for H3.

5.3 Physiological-subjective arousal relationship

There was no correlation between arousal ratings and $\ln$ RMSSD. This discrepancy is likely explained by the fact that “physiological arousal” does not represent a single affective experience. It can result from a variety of experiences, including stress, anxiety, alertness, and mental effort [65, 66]. Consequently, specific physiological markers may only measure some components of subjective arousal. For example, an increase in RMSSD is mainly linked to parasympathetic activity [62] and stress regulation [67]. Therefore, this index could be more sensitive to changes in stress levels, rather than to changes in alertness or excitement as measured by the subjective Self-Assessment Manikin framework (Appendix D).

Another factor may be the difference in timing between subjective and physiological arousal measurements. Subjective ratings were given after two minutes of continuous touch, and represent participants' state at a single moment in time. Meanwhile, RMSSD measured continuous changes in autonomic nervous system activity during the two-minute touch trials. As mentioned earlier, pleasantness tends to decrease over time during continuous long-term CT-optimal stroking while HRV increases [19, 64]. In a similar vein, subjective arousal could also increase or decrease over time during long-term stroking touch. Future studies should shed light on this.

Finally, physiological measures like HRV reflect the unconscious regulation of sympathetic and parasympathetic nervous system activity, and not necessarily emotional activity [30]. People are not always fully aware of their physiological affective state or they may interpret it differently, especially in individuals with conditions such as depression [68, 69]. Indeed, the body can be stressed without the mind being aware. This phenomenon could further explain the disconnect between subjective and physiological arousal.

5.4 Implications for robotics

The above findings have important implications for the design of robotic affective touch systems, namely that they may benefit from spatial variation in addition to their optimized linear velocity and force.

The present finding that the sawtooth trajectory produced significantly higher subjective arousal than both the straight and sine trajectories suggests that trajectory shape can be used not only to calm but also to activate. This is a degree of affective control that linear-only devices cannot achieve without resorting to non-CT-optimal velocities. Custom affective haptic devices [such as 12, 13, 21] could therefore implement two-dimensional actuator layouts so that affect can be modulated beyond low-arousal states. For example, they could potentially increase alertness during rehabilitation exercises, prolonged desk work, and virtual reality games.

Aside from wearable haptics for affect regulation, companion robots [e.g. 70] could also incorporate spatial variations in their touch to make their interactions more realistic and human-like. The present study showed that varying trajectory shape alone shifted participants between calmer, more pleasant states and more activated, less pleasant ones. A companion robot capable of varying its stroking pattern could therefore subtly adapt its touch to the social context at hand, without adjusting velocity. For instance, slower predictable strokes could be used to soothe, and less predictable patterns could sustain alertness during play or conversation.

5.5 Limitations & future work

The findings of this study should be interpreted in light of several methodological limitations that remain to be addressed in future work.

5.5.1 Individual differences

A notable limitation concerns individual differences, particularly in forearm hair density. Several participants commented that the sawtooth trajectory felt particularly unpleasant because it frequently moved sharply against the direction of forearm hair growth. Although anecdotal, this observation suggests that hair direction and density may play a role in affective touch perception. Unfortunately, forearm hair density was not measured or controlled for in the present study.

While previous research has compared the perceived pleasantness of affective touch on hairy skin (e.g. forearm, back) versus glabrous skin (e.g. lips, palms) [71, 72, 73], relatively few studies have explored variability of hair density within hairy skin itself. One exception is work by Jönsson et al. [56], which only reported a weak association between hair density and pleasantness ratings. More research is needed to determine whether hair density influences not only perceived pleasantness, but also physiological and subjective affect during CT-optimal stimulation with nonlinear trajectories.

In addition to hair density, several other individual differences were not controlled for that may have contributed to variability in subjective responses. These include individual tactile sensitivity, prior exposure to CT-optimal touch, comfort with human-robot interaction, and baseline affective state (e.g. due to prior stress or caffeine consumption). Future work should include these stratification variables to better understand how and why individuals differ in their responses to affective touch with varying predictability.

5.5.2 Lack of prior arousing stimuli

One methodological limitation stems from the absence of an experimentally induced arousing context prior to or during the touch conditions. As discussed previously, this study deliberately minimized external stimuli, with the goal of isolating responses to subtle spatial differences in CT-optimal touch trajectories. Prior work used a similar approach [14, 20, 23]. However, this design choice meant that participants' internal cognitive and emotional states were not controlled for. For example, one participant reported thinking about a ”funny meme” during a trial, which may have unintentionally altered their affective state.

Future research could add controlled arousal manipulation to the experimental procedure, such as a cognitively demanding task or emotionally arousing video. This would help determine whether CT-optimal touch modulates affect differently under varying baseline conditions. Furthermore, this approach would help align findings with previous studies that also deliberately elicited emotional arousal prior to administering affective touch [40, 74].

5.5.3 Recovery recordings

Another methodological limitation relates to the missing recovery data for 9 participants (Figure 4, Table 1). Post-trials ECG recordings and questionnaires were only added to the experimental procedure after the first few participants had already completed the study, because preliminary analyses and further literature review [19] hinted at possible longer-term effects of the touch trials on affect and HRV.

As shown in Appendix F, no significant difference between baseline and recovery HRV was found for the remaining 13 participants. Although these results remain exploratory, the observed patterns indicate that further investigation into the longer-term physiological effects of affective touch may be warranted. It is recommended that future studies systematically incorporate recovery or post-trial measurements to examine how HRV and other physiological indices of arousal evolve over time during and after affective robotic touch.

5.5.4 Position-controlled robot

A final limitation stems from the robot that was used in this study, the Force Dimension Omega.3, which is position-controlled. Given different arm widths, tissue composition (fat and muscle density), and skin compliance, the z-height had to be adjustable across participants. To account for this, endpoint force control was originally attempted. However, the combined low stiffness of both the brush and arm resulted in instability and major oscillations in the z-axis. Moreover, the target contact forces for gentle touch were so small that they approached the noise floor of the robot motors' current measurements. These limitations made reliable impedance control infeasible.

This is why endpoint position control was eventually used, combined with z-height calibration and a custom 3D-printed hinged end effector (Appendix C) to keep force as constant as possible across participants. This does mean, however, that the touch may have felt more intense to some participants than others, which could have influenced the results. In fact, some physiological markers like pupillary activity have been found to be modulated by the intensity of the touch, and not by perceived pleasantness [24].

In a future study, a force-controlled robotic system should be used instead. Alternatively, custom haptic devices that render affective touch using an array of actuators [e.g. 12, 13, 21] provide a more cost-effective solution. Either of these options would allow for better control of force and pressure on the forearm alongside velocity.

6 Conclusion

This study investigated how the predictability of stroking trajectories shapes affective experiences during robotic CT-optimal touch. Three trajectories (straight, sine, and sawtooth) were administered to the forearms of 22 healthy adults by a robot-mounted brush. Perceived pleasantness, subjective affect, and physiological arousal (HRV) were measured.

The results partly support the hypotheses. The straight trajectory was rated as significantly more pleasant than the sawtooth trajectory, while both the straight and sine trajectories produced significantly lower subjective arousal than the sawtooth. No significant differences were found for valence or physiological arousal. Together, these findings suggest that the spatial predictability of affective touch influences subjective affective experience: more predictable trajectories were perceived as more pleasant and calming, though this did not translate into more positive self-reported affect. The absence of physiological differences is likely due to the low-arousal experimental design. The subtle differences in trajectory shape were thus insufficient to produce measurable changes in autonomic activity as represented by HRV.

Notably, a strong positive correlation between pleasantness and valence, and a smaller but significant negative correlation between pleasantness and subjective arousal, were observed. Especially the close correspondence between pleasantness and valence raises a broader theoretical question about whether ”perceived pleasantness”, as commonly reported in affective touch research, may be functionally equivalent to Russell’s valence dimension.

These findings have practical implications for the design of robotic affective touch systems, namely that spatial trajectory is a meaningful design parameter alongside velocity and force. Future work should examine trajectory effects under physiologically arousing conditions, with larger and more diverse samples, to further establish the role of touch predictability in affect regulation.

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Appendix A
Informed consent form

Participant information

You are being invited to participate in a research study titled "*Effect of stroking trajectory on physiological and subjective affect during CT-targeted robotic touch*". This study is being done by Mees Chammat, a Masters student supervised by Dr. Michaël Wiertlewski and Dr. Deborah Forster from TU Delft. We would like to thank you for your interest in participating in this study. This document will explain the purpose of the research, the experimental procedure, and data confidentiality.

Purpose of study

The purpose of this study is to explore how different stroking trajectories influence people's emotional and physiological responses when a robot applies touch to the forearm. This research will contribute to a better understanding of how humans emotionally respond to robotic touch, which may improve the design of social and therapeutic robots.

Experimental procedure

You will be seated comfortably and asked to rest your left arm on a table next to a hidden robotic device holding a soft brush (Figure 1). You will wear a chest strap heart monitor (Figure 2) to record your heart activity (electrocardiogram, ECG), and headphones to minimize background noise.

Figure 1: Hidden robotic device

Figure 2: Heart monitor

The session begins with a 5-minute baseline recording of your heart activity while you remain seated and relaxed. Then, the robot will apply 6 stroking trajectories to your forearm, each lasting 2 minutes. After each of these 6 trials, you will be asked to rate the pleasantness of the touch and indicate your emotional state on a 9-point scale. You will have a 1-minute break between trials, and may request longer breaks or stop at any time. The full session will take up to 1 hour.

Potential risks of participating

There are no known risks associated with this study beyond those encountered in everyday life. The robot is a CE-certified device with appropriate safety measures built-in. The experimenter will remain in the room during the entire study and can shut down the robot at any point. Some participants may experience mild skin sensitivity or ticklish sensations on the forearm. You may pause, stop, or withdraw from the experiment at any time if you feel discomfort.

Confidentiality of data
This study requires the following personal data to be collected and used: gender, age, handedness (left or right handed), and electrocardiogram (ECG) recordings.

To safeguard and maintain confidentiality of your personal data, all collected data will be pseudo-anonymized and stored under a participant number, with no reference to your name or your consent form. The data will be stored in a secure storage environment at the TU Delft for up to 10 years, after which it will be permanently deleted. The data will only be accessible to the core research team. Study results may be published, but your identity will never be revealed. Pseudo-anonymous data may be shared in a semi-open archive (4TU.ResearchData), but only with your explicit consent.

Procedures for withdrawal
Your participation in this study is entirely voluntary and you can withdraw at any time without giving a reason. You can request access to and erasure of personal data. If you choose to withdraw or request erasure, your data will be deleted (if technically feasible), unless it has already been anonymized and included in completed analyses or published results.

Contact information
For any questions about the study, please contact:

Student Researcher:
- Mees Chammat

Responsible Researchers (Supervisors)
- Michaël Wiertlewski
- Deborah Forster

Explicit consent points

Please tick the appropriate boxes *Yes* *No*

A: General agreement - Research goals, participant tasks, and voluntary participation

1. I have read and understood the study information dated 12/01/2026, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.

2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.

3. I understand that taking part in the study involves:
- Providing my name and signature (on the consent form)
- Providing my age, gender, and handedness (on a separate online form)
- Wearing a chest heart monitor which records an electrocardiogram (ECG) of my heart activity
- Having a robot continuously apply stroking touch to my forearm in two-minute blocks
- Rating the pleasantness of the touch and indicating my emotional state on an online form

4. I understand that no compensation will be given for my participation

5. I understand that the study will end in 1 hour.

B: Potential risks of participating (including data protection)

6. I understand that taking part in the study involves the following risks: mild skin sensitivity or ticklish sensations on the forearm. I understand that I can request to stop the experiment at any point.

7. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) (first name and email, for administrative purposes) and associated personally identifiable research data (PIRD) (gender, age, handedness, ECG) and I herewith consent to the processing of this personal data.

8. I understand that ECG data is considered sensitive data within GDPR legislation, and I herewith consent to the processing of such data for the purpose of this research.

9. I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach:
- Pseudo-anonymization of ECG recordings and ratings (use of participant number, no name)
- Secure data storage on TU Delft servers

	Yes	No
10. I understand that personal information collected about me that can directly identify me, such as my name and email, will not be shared beyond the study team.	☐	☐
11. I understand that the (identifiable) personal data I provide will be destroyed in ten years from the start of this study, in accordance with the TU Delft Research Data Framework Policy.	☐	☐
C: Research publication, dissemination and application		
12. I understand that after the research study the pseudo-anonymized information I provide will be used for a Master's thesis and possible publication.	☐	☐
D: Data storage, access and reuse		
13. I give permission for the **pseudo-anonymous personal data** that I provide (ECGs, gender, age, handedness) to be archived in the 4TU.ResearchData repository so it can be used for future research and learning.	☐	☐

Signatures

______________________________	______________________________	________________
Name of participant	Signature	Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

______________________________	____________________________	________________
Researcher name	Signature	Date

Study contact details for further information: Mees Chammat, +316[redacted]
y.chammat@student.tudelft.nl

Appendix B
Trajectory generation

The three stroking trajectories were generated in Python as time-continuous position signals along two anatomical axes of the forearm: $h(t) = \begin{cases} x(t) \\ y(t) \end{cases}$ (Figure 1).

Longitudinal, proximal-distal movement along the forearm $y(t)$ was defined as a triangular waveform oscillating between workspace boundaries, producing a continuous back-and-forth motion at a CT-optimal velocity of 3 cm/s.

Lateral movement across the forearm $x(t)$ depended on trajectory shape (Figure 1): for the straight trajectory, $x(t) = 0$; for the sine and sawtooth trajectories, $x(t) = A_c s(t)$, where $s(t)$ was either a sinusoidal or triangle waveform.

The amplitude A_c was constant for the sine trajectory, but for the sawtooth trajectory, it was randomly selected from three predefined levels for each half-cycle of the waveform. A fixed random seed was used to ensure the amplitudes of the sawtooth signal were reproducible.

The x- and y-coordinates of the trajectories were sampled from the generated signals at the robot's refresh rate of 20 Hz and exported to .csv format.

Appendix C
Custom end-effector design

To account for variations in arm height (z-axis), a calibration routine was added to the robot's control system in which six points on the participant's forearm were manually probed. These points were used to generate a rough height map of the forearm via bilinear interpolation. The hinged design of the custom end effector (Figure 9 and 10) compensated for additional differences in surface height during trajectory execution.

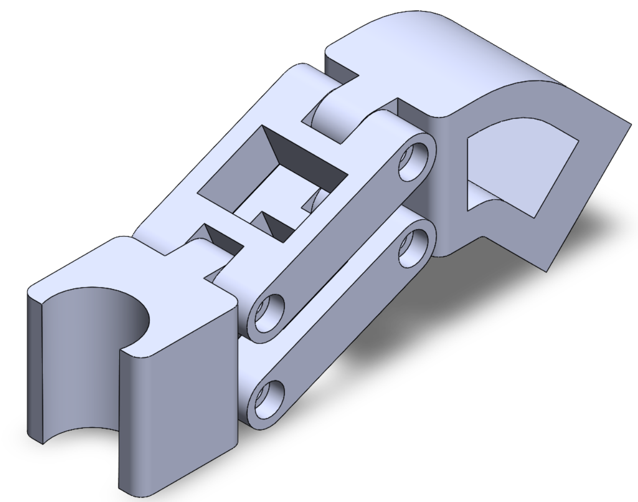


Fig. 10. Isometric view of the 3D model of the end effector.

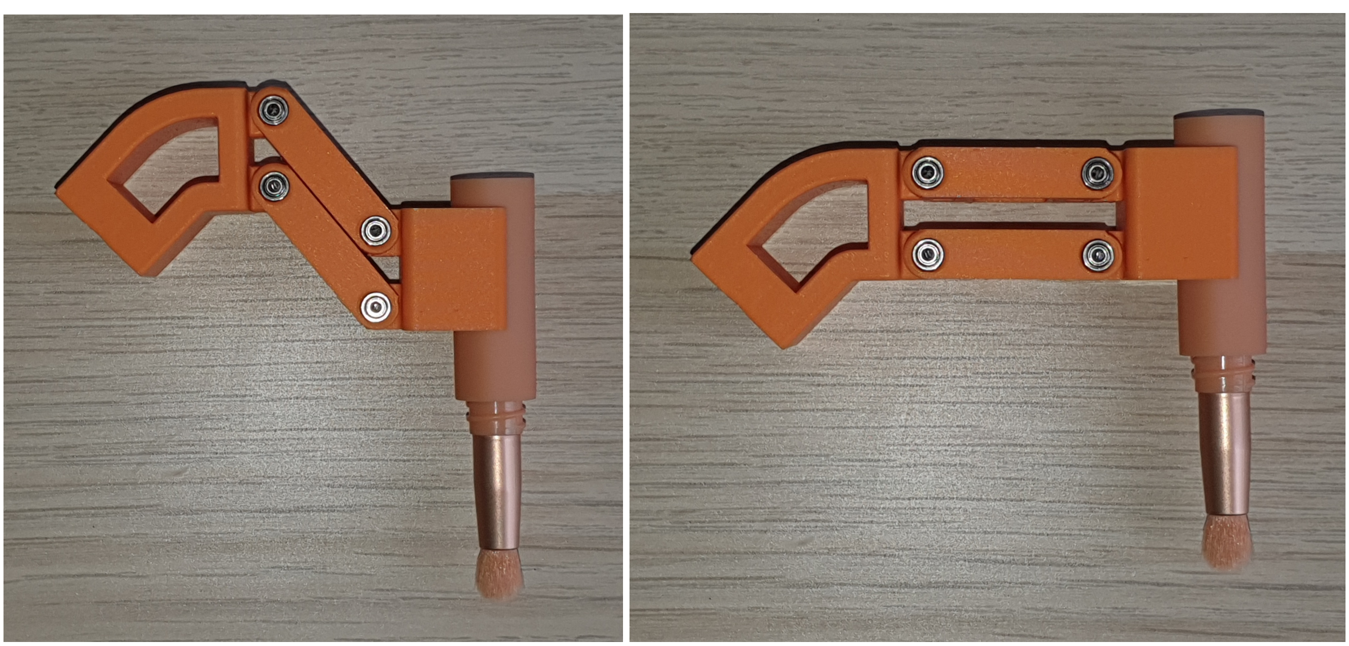


Fig. 9. Photo of the 3D printed end effector in an angled (left) and straight (right) position.

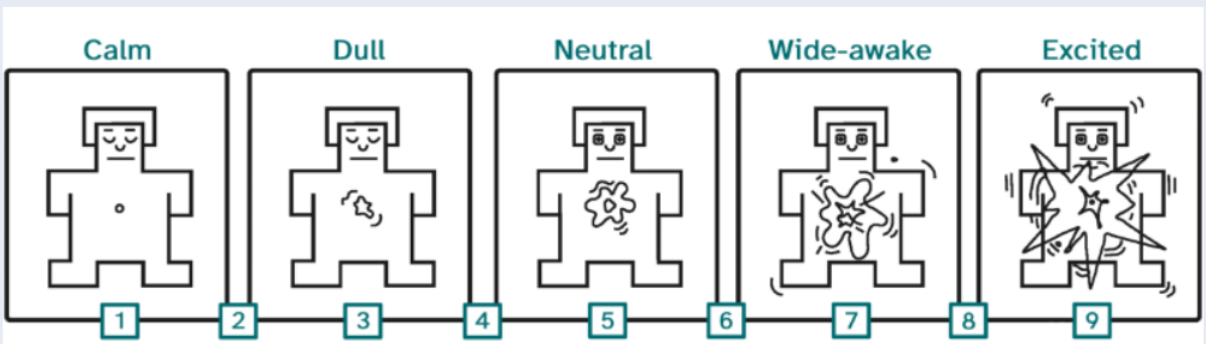
APPENDIX D
PLEASANTNESS AND SUBJECTIVE AFFECT QUESTIONNAIRE

[1P] How would you rate the pleasantness of the touch? *

1	2	3	4	5	6	7	8	9	10

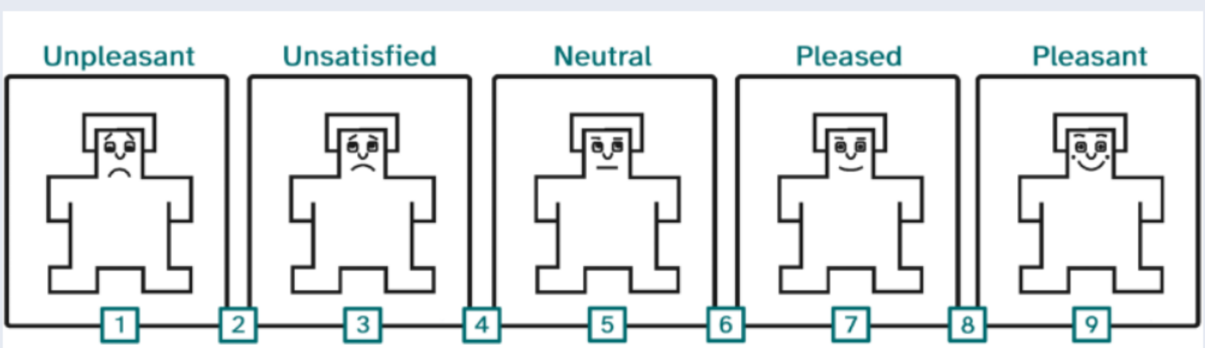
Very unpleasant — Very pleasant

[1A] How do you feel? *



1	2	3	4	5	6	7	8	9

[1V] How do you feel? *



1	2	3	4	5	6	7	8	9

Fig. 11. Questionnaire items for trial 1, asking the participant to rate the pleasantness of the touch trajectory and their arousal and valence on the Self-Assessment Manikin scale.

APPENDIX E
SUPPLEMENTARY FIGURES

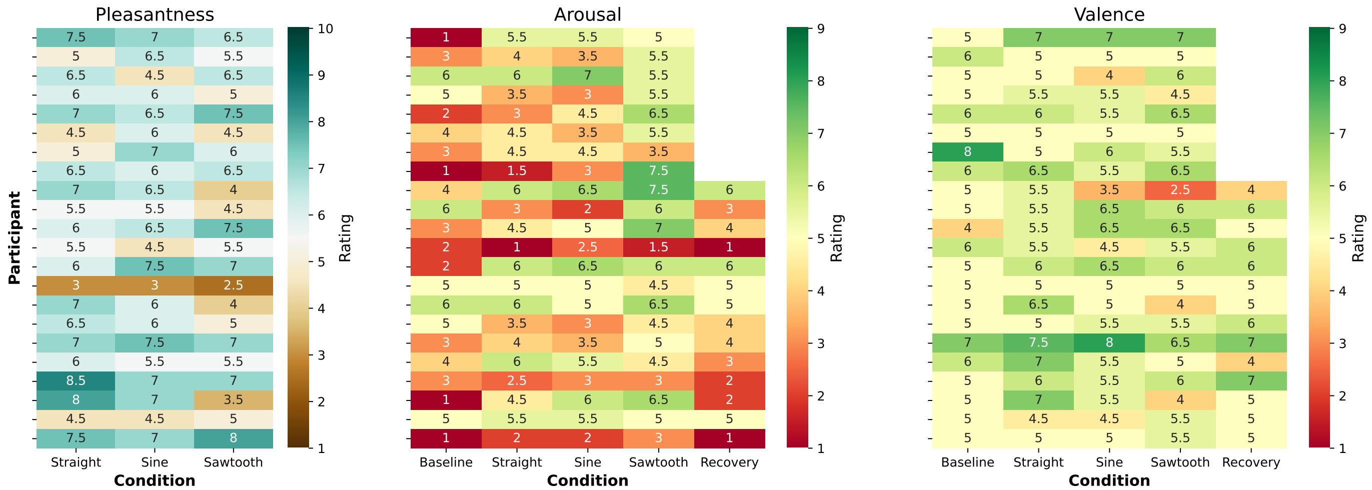


Fig. 12. Heatmaps of (mean) ratings given by individual participants on the pleasantness, arousal, and valence scales.

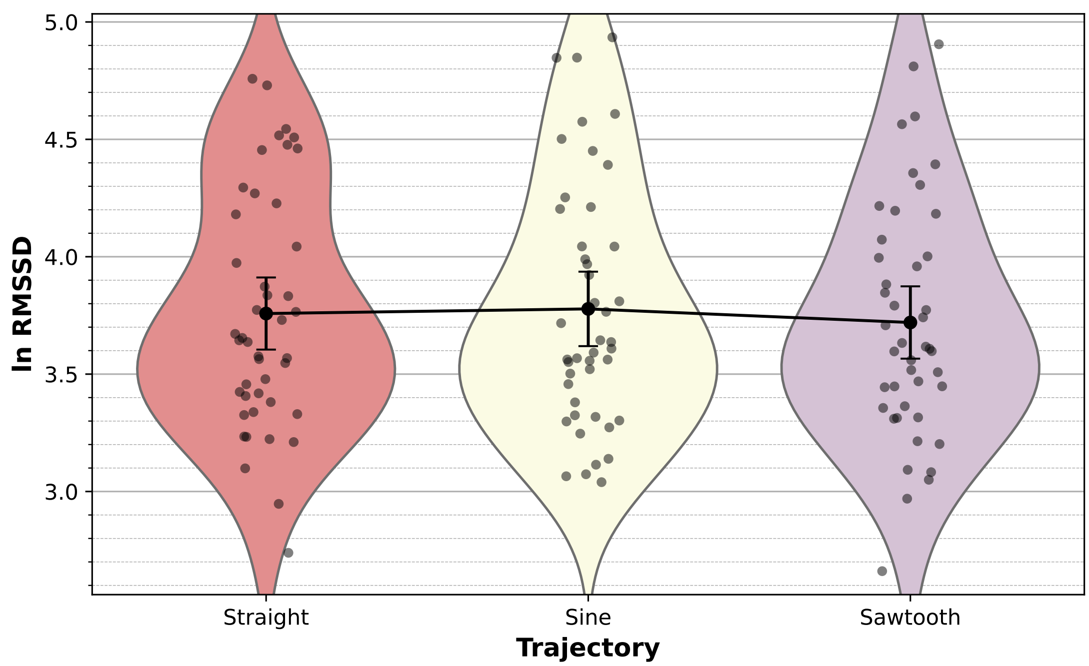


Fig. 13. Mean $\ln$ RMSSD across trajectories. Violin plots visualize the spread in individual $\ln$ RMSSD values. Error bars represent 95% confidence interval.

Appendix F
HRV over time

Because of the lack of significance of trajectory on HRV, $\ln$ RMSSD was additionally examined on a trial-by-trial basis. Figure 14 shows how participants' HRV varied over time for the full duration of the experiment. Visually, HRV appears to increase from baseline to trial 1, and then gradually return toward baseline levels as the experiment progresses. This could mean that the first touch trial causes a brief increase in HRV.

To formally evaluate this observation, paired-samples t-tests were conducted comparing $\ln$ RMSSD for baseline, trial 1, and recovery. Trial 1 values ($M = 3.810$, $SD = 0.482$) were significantly higher than baseline ($M = 3.584$, $SD = 0.634$), $t(21) = -2.39$, $p = 0.03$, with a moderate effect size (Cohen's $dz = 0.51$). In contrast, recovery HRV ($M = 3.711$, $SD = 0.611$) did not differ significantly from baseline ($M = 3.566$, $SD = 0.711$) for the 13 participants with a recovery recording, $t(12) = -1.72$, $p = 0.11$, although the effect size was moderate (Cohen's $dz = 0.46$). Normality assumptions were met for both comparisons (both Shapiro-Wilk $p > 0.05$).

These findings suggest that the first touch trajectory, irrespective of which trajectory it was, resulted in a notable increase in HRV relative to baseline. It also suggests that no significant difference is observed between HRV values before and after experiencing all 6 touch trials.

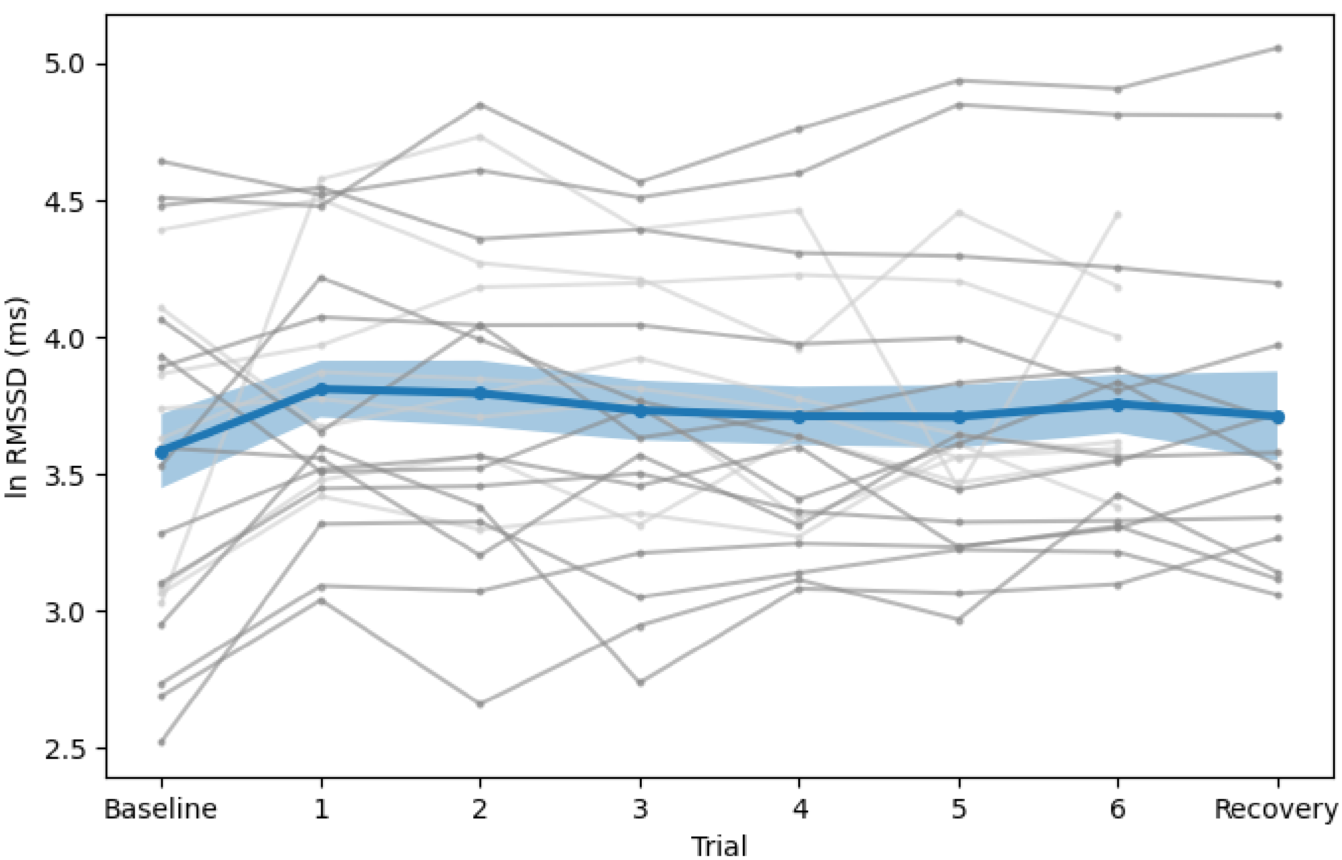


Fig. 14. Heart rate variability ($\ln$ RMSSD) per trial. Each dot represents one participant. Participants without a recovery recording are represented by lighter grey lines. The blue dots are the mean values when averaging across participants. The blue shaded area represents the standard error of the mean (SEM).