Title of Thesis

Psychophysical Studies on the Perception of Human Affective Touch across Skin Sites

2019 September

Jiabin Yu

The Graduate School of

Natural Science and Technology

(Doctor’ s Course)

OKAYAMA UNIVERSITY

Contents

1. Introduction

Touch plays an important role in navigating the physical world and communicating emotions. In daily life, we manipulate and explore objects throughout the day, and we can obtain information about objects' physical properties, such as shape, context, size and orientation just by touching. On the other hand, tactile experience also gives rise to emotional changes in daily interpersonal interactions. This kind of affective touch, ranging from a daily hug to a sensual caress, can be a source of pleasantness and can serve as the basis for interpersonal bonding and social interactions. Therefore, the experience of touch leads to sensations that involve both discriminative and emotional aspects. According to these theories, the experiences of touch are mediated by two separable dimensions, classified as sensory-discriminative and motivational-affective. Although much more is known about the perception of discriminative touch, such as roughness, shape and vibration discrimination, little is known about affective touch, which plays a critically important role in interpersonal communication.

It is widely accepted that human discriminative touch is mediated through low-threshold mechanoreceptors with large, myelinated A-beta (Aβ) fibers. In contrast, recent studies have suggested that unmyelinated, small-diameter, lower-threshold mechanoreceptive afferents (C-LTMRs), also called C tactile or CT afferents, are involved in the transmission of affective aspects of touch. There is no evidence for the existence of CT afferents in the glabrous skin. Further functional imaging researches in GL patients (lacking large myelinated afferents but whose C fibers are intact) indicated that CT afferents project to insular cortex rather than somatosensory area S1 and S2.

Moreover, the hedonic aspects of affective touch are not only related to the physical factors of the tactile stimuli, such as temperature, softness, force and velocity, but also to intrinsic factors such as oxytocin, and top-down mechanisms related to integrating contextual information from multisensory and prior experiences. The majority of previous behavioral studies have focused on pleasantness ratings at different levels of stroking velocities over skin sites; these studies have all consistently suggested that the glabrous skin of the palm presents a flatter, inverted U-shaped stroking velocity-pleasantness rating profile compared to the hairy skin of the forearm. However, how stroking area, hardness and visual context affect the perception of affective touch across skin sites remains largely unclear.

1.1 Affective touch

Affective touch provides a variety of health benefits, including relief from stress and depression and plays a vital role in social interactions and communication [1]. For example, autonomic functions are positively affected by touch from professionals in healthcare institutions [2, 3] and by the touch from a significant person [4, 5] Affective touch can be seen everywhere in our daily life in different forms, and its value is also known to us. Whether it's a strong handshake, an inspiring pat on the shoulder, a sensual caress, a gentle kiss, or a soft brush stroking, physical contact can convey a vitality and immediacy, sometimes stronger than language [6]. In fact, the interpersonal touch is the most common among affective touch. Skin-to-skin contact between individuals is usually very pleasant, transmitting important social and contact signals in humans and other primates. Interpersonal touch is also critical in physical and cognitive development [7] as demonstrated by the controversial studies of Harlow [8] where an infant monkey reared in captivity chose the warm/soft surrogate rather than the cold/wire framed surrogate to deliver food.

Interpersonal touch is a form of nonverbal behavior in which meaning comes from numerous environmental and personal cues [9]. The most significant forms of non-sexual, positive, and happy social contact can be temporarily divided into two categories: “simple” touch and “protracted” touch [10]. “Simple” touch involves short, intentional contact with a relatively limited position on the body surface of the receiver during social interaction. Many studies also show that simple touch between individuals can not only increase mutual feelings, but also bring convenience and benefit return. Recipients of such “simple” touches are more likely to be submissive or selfless: tipping more in a restaurant [9], spending more money in a shop [11], or giving away a cigarette [12]. On the other hand, “protracted” touch can also have positive outcomes and concomitants in affiliative behavior. For example, skin-to-skin contact has been shown to have an analgesic effect in human babies undergoing surgery for small tissue damage [13], as well as have clinical benefits for premature infants [14]. Stroking an infant can not only produce positive emotions in the baby, but also regulate negative emotions compared to other forms of touch. In addition, holding the hand of a loved one can reduce the anxiety from an impending threat [15].

Recent research has shown that emotions can be identified by the simple experience of a stranger touching your arm without any other hints from that person [16, 17].

Hertenstein et al. (2006) [16] demonstrated that different types of touch were used to signal different emotions, and the recipient can recognize emotions with an accuracy ranging from 48% to 83%. This range is comparable to the accuracy of decoding facial and sound-transmitting emotions [18]. Interestingly, the touch used to express “sadness” was interpreted as sympathy or love by the perceiver, suggesting that the interpretation of vague interpersonal tactile stimuli may be biased towards positive emotions. Despite affective touch is very important for our emotional well-being and social activity, the interpersonal and emotional aspects of touch remain largely unknown.

1.2 Tactile afferents

Skin is our largest sensory organ, which transmits pain, temperature, itch and tactile information to the central nervous system. Touch sensations are transmitted by different combinations of mechanosensory end organs and the low-threshold mechanoreceptors (LTMRs). The experience of touch leads to sensations that involve both discriminative and emotional aspects [19]. Skin is classified as either glabrous, found only on the plantar and palmar surfaces, or hairy, which is found on the rest of the body. In the context, glabrous skin is specialized for discrimination touch, which subserves the perception of pressure, slip, vibration and texture, all critical in providing haptic information about handled objects and during exploratory procedures. On the other hand, hairy skin covers more than 90% of the body surface. Although it has much lower spatial acuity than glabrous skin, it also has a discriminatory touch. Hairy skin is strongly related to affective touch which can evoke an emotional response. These particular skin regions are associated with different combinations of LTMRs, making each region distinct in neurophysiology and function [20].

1.2.1 Myelinated tactile afferents

It is well known that myelinated, A-beta, mechanoreceptive afferents (Aβ afferents) are typically described as the mediators of discriminative touch [19]. These afferents are present in hairy and glabrous skin and transmit accurate tactile information to the brain for accurate detection of the content, location ,and duration of touch stimuli, as well as signal information about force and roughness [21, 22].

In glabrous skin, four types of LTMRs with fast conduction velocity (Aβ LTMRs) have been defined, each of which has a unique terminal morphology and regulatory property [23-25]: 1) Aβ SA1-LTMR dominates Merkel cells of basal epidermis and reports the static properties of tactile stimulation., 2) Aβ SA2- LTMRs are hypothesized to terminate in Ruffini corpuscles in the dermis, with special sensitivity to skin stretch, 3) Aβ RA1-LTMRs innervate Meissner's corpuscles in dermal papillae and are sensitive to movement across the skin, and 4) Aβ RA2-LTMRs terminate in Pacinian corpuscles in the depth of the dermis, tuning to high-frequency vibration. In hairy skin, several LTMRs form specialized ends associated with hair follicles, allowing the tactile sensation to extend beyond the skin's surface. Aβ SA1-LTMRs and Merkel cells form complexes called touch domes that detect skin indentations [26, 27]. The hair follicle shaft is supplied by collars of mechanoreceptor terminals, including at least three LTMR subtypes with longitudinal lanceolate terminals and one with circumscribed terminals These subtypes differ in their sensitivities, adaptation properties, and conduction velocities [28, 29].

1.2.2 Unmyelinated tactile afferents

Recent studies have suggested that unmyelinated, small-diameter, lower-threshold mechanoreceptive afferents (C-LTMRs), also called C tactile or CT afferents, are involved in the transmission of affective aspects of touch [19, 30-32]. CT afferents were first discovered in the hairy skin of rodents in 1939 [33], and were continuously found in the hairy skin of mammals [34, 35] including human [36], which were thought to be involved in the transmissions of the hedonic aspects of affective touch. In humans, CT afferents respond to a low mechanical threshold (< 5 mN) as tested with von Frey monofilaments. CT afferents can produce high-frequency (50-100impulses/s) trains of action potentials to a slow velocity of gentle touch. They have intermediate adaptability, which responds initially with a high rate pulses and then often drop to zero after a few seconds of sustained indentation [37]. Another characteristic of CT afferents is that they are easy to fatigue under repeated stimulation, and their discharge frequency can be reduced when the stimulation interval is short [38-40]. It has been reported that the time to recover from fatigue varies from 30 seconds for humans to 30 minutes for cats [40].

CT afferents are physiologically different from nociceptors because they do not respond to soft brush strokes, and their response to soft touches is usually small with only a small number of low-frequency pulses [37]. Studies of CT units have shown that they respond poorly to fast moving stimuli but respond strongly to slow moving stimuli

[36, 37]. Therefore, CT units seem unable to encode rapid events, although they are sensitive to dynamic stimuli, but only in the low-frequency range. CT afferents have been known to exist exclusively in the hairy skin, which are absent in the glabrous skin [35, 41, 42], and preferentially active in low indentation force, slow velocity of gentle touch [31, 43]. To our knowledge, the relationship between firing frequency of CT afferents and pleasantness rating was investigated in 2009 [31], firstly demonstrating that psychophysical hedonic ratings positively correlates with the level of CT afferents firing frequency. The majority of previous studies have focused on how pleasantness ratings were at different levels of stroking velocities over skin sites [31, 44], which all consistently suggested that more hedonic value was experienced at the level of stroking velocities range 1-10cm/s compared to slower velocities or faster velocities and an inverted U-shape pleasantness rating pattern was presented across stroking velocities.

1.3 Touch pathways

1.3.1 Large-fiber pathway

Tactile impulses are transmitted to the ventral posterior lateral nucleus of the thalamus via large myelinated Aβ afferents [45]. From thalamus to cortex, afferents project to the primary and secondary somatosensory cortex (SI, SII) (**Fig 1.1**) [46], the insular cortex [47], and the posterior parietal cortex, Brodmann’s areas 5 and 7b [48]. In addition, the thalamocortical afferents convey tactile signals to primary somatosensory cortex where the sensory information from all body surfaces is mapped in a somatotopic (body-mapped) manner [49, 50].

1.3.2 Small-fiber pathway

The current consensus is that CT afferents project to the superficial layers of the dorsal horn in lamina II [35, 51], as has been classically described for other small-diameter (Aδ and C) fibers responding to noxious, temperature and itching stimuli, and possibly connect via interneurons to lamina I [52]. The lamina I neurons project somatotopically in the spinothalamic pathway in the ventral horn of the spinal cord to the ventral posterior nucleus of the thalamus [53]. Further studies show that CT afferents, like other types of thinly myelinated and unmyelinated fibers, project via lamina I/II of the spinothalamic tract to posterior/basal ventral medial nucleus and posterior insular cortex [54, 55].

1.4 Cortical processing of CT afferent input

Previous functional magnetic resonance imaging (fMRI) studies [30, 56] have shown that CT-targeted touch mainly projects to the insular cortex rather than the somatosensory cortices. The recent positron emission tomography (PET) study [57] showed affective touch on the arm give significant activations of the posterior insular cortex and mid-anterior orbitofrontal cortex (OFC) in comparison to the palm, while the opposite contrast (touch on the arm minus touch on the palm) showed a significant activation of the somatosensory cortices. Further, the dissociation of insula function suggests posterior and anterior insula involvement in distinct yet interacting processes: coding physical stimulation and affective interpretation of touch by investigating brain responses to CT-targeted touch in the experience versus imagine conditions [58].

1.5 The purpose of present dissertation

Touch sensations are transmitted by different combinations of mechanoreceptors. The experience of touch leads to sensations that involve both discriminative and emotional aspects. According to these theories, the experiences of touch are mediated by two separable dimensions, classified as sensory-discriminative and motivational-affective. Although much more is known about the perception of discriminative touch, such as roughness, shape and vibration discrimination, little is known about affective touch, which plays a critically important role in interpersonal communication. Therefore, the aim of the present study is to clarify how physical factors and contextual information affect the perception of affective touch and how the perception of affective touch differs across human skin.

1.6 The contents of the dissertation

In the present study, we conducted several psychophysical experiments to investigate how physical factors and contextual information affect the perception of affective touch and how the perception of affective touch differs across human skin.

Firstly, to investigate how stroking area affects the perception of affective touch between the glabrous skin of the palm and the hairy skin of the forearm. We used two different hardness of brushes to stroke the glabrous skin of the palm and the hairy skin of the forearm. Meanwhile, a series of plastic films with different areas of windows exposed the skin to the moving brush and assured maintenance of a different spatial relationship between the brush and the body part. In addition, stimuli were delivered successively on the palm and arm (or arm and palm or a pseudo-random order) in different days to eliminate the influence of the order of stimulus presentation. The current study suggests that stroking area have an effect on the perception of affective touch and the stimulus is perceived to be more intense as the area of stimulation increases.

Secondly, to investigate how stroking hardness affects the perception of affective touch. Affective tactile stimulation was given with four different hardness of brushes at three different forces, which were presented to either palm or forearm. To quantify the physical factors of the stimuli (brush hardness), ten naïve, healthy participants assessed brush hardness using a seven-point scale. Based on these ten participants, five more participants were added to rate the hedonic value of brush stroking using a visual analogue scale (VAS). The current study suggests that pleasantness ratings over the skin resulted in a preference for light, soft stroking, which was rated as more pleasant when compared to heavy, hard stroking and show that the hairy skin of the forearm is more susceptible to stroking hardness than the glabrous of the palm in terms of the perception of pleasantness. These findings of the current study extend the growing literature related to the effect of stroking characteristics on pleasantness ratings.

Thirdly, to investigate whether visual stimulus size and viewpoint of observation affect the perception of affective touch across human skin. Five naïve, healthy participants selected three appropriate viewpoints of observation from 24 different viewpoints using a seven-point scale. Then, fifteen healthy participants rated tactile pleasantness on a visual analogue scale (VAS) when they were stroked with a soft brush on the palm or forearm accompanied by viewing different sizes of visual stimulation from different viewpoints. The current study suggests that the viewpoint of observation affects the perception of tactile pleasantness, but visual stimulus size has no significant effect on tactile perception.

Lastly, to investigate the effects of visual contexts (facial expressions, scenes) with different visual types (unpleasant, neutral, pleasant) on affective touch pleasantness across different skin sites. Ten naïve, healthy participants selected 60 facial expression images (20 unpleasant, 20 neutral, 20 pleasant images) and 60 scene images (20 unpleasant, 20 neutral, 20 pleasant images) using a seven-point scale. Then, fifteen healthy participants rated tactile pleasantness on a visual analogue scale (VAS) when they were stroked with a soft brush at three stroking forces on the palm or forearm accompanied by viewing facial expression or scene images. The current study replicates and extends the findings regarding the influences of visual context on the perception of affective touch and highlights the same effects of visual context on the tactile pleasantness ratings from the glabrous skin of the palm and the hairy skin of the forearm. Furthermore, this study also reveals that, compared to the scene visual context, the visual context of facial expressions with a social component increased the differences between the effects of the three stroking forces on the perception of affective touch.

Finally, we discussed the reasons for the different effects of these factors on the perception of human affective touch across skin sites and presented our future direction.

2. Stroking Area Affects the Perception of Affective Touch Pleasantness across Different Skin Sites

Summary

The skin is our largest sensory organ, which transmits temperature, pain, itching and tactile information to the central nervous system. These input channels can be further classified as providing spatial and temporal sensory functions, identifying and providing basic information for controlling and guiding exploratory tactile behavior, and emotional functions. Previous studies have shown that the hedonic value of touch, the pleasantness or unpleasantness, is intrinsically related to the physical characteristics of tactile stimuli, like softness, temperature, force, and velocity. However, it is little known how the area stimulated (stroking area) affects the perception of affective touch across human skin sites. We used two different hardness of brushes to stroke the glabrous skin of the palm and the hairy skin of the forearm. Meanwhile, a series of plastic films with different areas of windows exposed the skin to the moving brush and assured maintenance of a different spatial relationship between the brush and the body part. The current study demonstrated that stroking area have an effect on the perception of affective touch at certain different stroking areas and the stimulus is perceived to be more intense as the area of stimulation increases.

Keywords: hedonic value, stroking area, human skin, affective touch

2.1 Background

The skin is our largest sensory organ, which transmits temperature, pain, itching and tactile information to the central nervous system. These input channels can be further classified as providing spatial and temporal sensory functions, identifying and providing basic information for controlling and guiding exploratory tactile behavior, and emotional functions. In spite of considerable progress in the understanding of human touch, the majority of previous investigations have focused on discriminative touch, such as shape, curvature, size and orientation discrimination, whereas only a few studies have targeted affective touch.

Human skin comprises both glabrous and hairy skin. Glabrous skin mainly occupies the palm and sole of human and hairy skin covers more than 90% of the body surface. It is well known that glabrous skin, which is specialized for discriminative touch, determine shape and texture to accurately recognize objects and provide feedback to the central nervous system to mediate proper grip control, reaching, and locomotion [59]. In contrast, hairy skin is strongly involved in affective touch [31, 60].

Earlier, human tactile sensibility was thought to be mediated only by low-threshold mechanoreceptors with large myelinated (Aβ) afferents conducting impulses at high speed (around 50 m/s). The myelinated Aβ mechanoreceptive afferents which are found in glabrous and hairy skin, are typically described as the mediators of discriminative touch [60]. In glabrous skin, four types of LTMRs with fast conduction velocity (Aβ LTMRs) have been defined, each of which has a unique terminal morphology and regulatory property [23-25]: 1) Aβ SA1-LTMR dominates Merkel cells in the basal epidermis and report the static nature of touch stimuli, 2) Aβ SA2- LTMRs are hypothesized to terminate in Ruffini corpuscles in the dermis and are particularly sensitive to skin stretch, 3) Aβ RA1-LTMRs innervate Meissner's corpuscles in dermal papillae and are sensitive to movement across the skin, and 4) Aβ RA2-LTMRs terminate in Pacinian corpuscles deep in the dermis and are tuned to high-frequency vibration. Hairy skin does not contain Meissner afferents, but instead contains the myelinated, rapidly-adapting hair and field mechanoreceptive afferents, and the unmyelinated C- tactile (CT) afferents [37, 61, 62]. Therefore, it is one of the most important research directions to investigate the difference between hairy skin and hairless skin in tactile perception. It has been previously confirmed to be different between glabrous skin and hairy skin in the stroking velocity-pleasantness profile [31, 63]. Therefore, we want to investigate how the perception of the hedonic aspect of tactile stimulation differs between the hairy skin of the arm, and the glabrous skin of the palm. In addition, the hedonic value of touch, the pleasantness or unpleasantness, is intrinsically related to the physical characteristics of tactile stimuli, like softness [64], temperature [65, 66], force and velocity [31]. However, it is little known how the area stimulated (stroking area) affects the perception of affective touch across human skin sites.

To investigate stroking area affects the perception of affective touch, we used two different hardness of brushes to stroke the glabrous skin of the palm and the hairy skin of the forearm. Meanwhile, a series of plastic films with different areas of windows exposed the skin to the moving brush and assured maintenance of a different spatial relationship between the brush and the body part. On the basis of the literature related to human skin, we hypothesized that stroking area have an effect on the perception of affective touch and the stimulus is perceived to be more intense as the area of stimulation increases.

2.2 Materials and Methods

2.2.1 participants

In total, 10 healthy volunteers ranging in age from 20 to 30 years, took part in the experiment. All the participants were right-handed and given basic information about the experiment. Written informed consent was obtained from all the participants prior to their participation.

2.2.2 Experimental setting and procedure

After receiving a written explanation of the experiment, which included a description of the experimental setting and instructions on how to rate the stimuli, the temperature of the experimental room was adjusted to a suitable temperature by the air conditioner [67, 68]. The participants were then comfortably seated in an adjustable chair, and the fingers of each participant were wrapped in a piece of surgical tape to insure that the brush would not touch the participants' fingers during palm stimulation.

Stimulations were all made with four types of artist's flat, 50-mm-wide, watercolor brushes, each with different levels of hardness. Although the bristles are different materials (goat's hair, pig's hair) for all brushes, the bristles were wrapped in aluminum skin to insure that the bristles are all 20mm deep. The caress-like strokes were administered by a well-trained research experimenter on a palm/forearm to fingertip direction at a rate of approximately 3 cm/s, a CT-optimal stroking speed [31]. The participants' hands (forearms) were fixed during the experiment to prevent movement. Tactile sensations were explored over the following two skin sites: left palm (in the center, equidistant from the bottom of the third finger and the wrist) and left forearm (on the volar side, equidistant from the wrist and elbow) [63]. Meanwhile, a series of plastic films with different areas of windows exposed the skin to the moving brush and assured maintenance of a different spatial relationship between the brush and the body part. Three different areas of windows (width × length: 3cm × 2cm, 3cm × 4cm, 3cm × 8cm) were used during stimulation presented to the glabrous skin of the palm. For the hairy skin of the forearm, there were also three different areas of windows (width × length: 3cm × 4cm, 3cm × 8cm, 3cm × 16cm).

In addition, stimuli were delivered successively on the palm and arm (or arm and palm or a pseudo-random order) in different days to eliminate the influence of the order of stimulus presentation. Following each brush stroke, the participants were instructed to rate the pleasantness of the brushing experience using a visual analogue scale (VAS) placed next to the right hand, ranging from -10 (unpleasant) over a neutral (0) midpoint to 10 (pleasant). The participants were required to rate the pleasantness of the stimulation with a 10 s response interval. Each trial was repeated twenty times per skin site (palm/forearm) using two brushes (soft, hard). The data of each participant were collected over two sessions conducted on different days. Each session lasted for approximately 40 min.

2.2.3 Statistical analysis.

All statistical data were presented as means ± standard error of the mean (±SEM) (see **Table 2.1**) and analyzed using SPSS (SPSS Statistics, Version 17; IBM, Armonk, NY). Significance was set at the $p < 0.05$ level, with up to three significant figures. The mean pleasantness scores from the glabrous skin of the palm and the hairy skin of forearm were entered into separate ANOVA analyses to split the data into groups of glabrous and hairy factors. Hence, the mean tactile pleasantness data were submitted to a 2 × 3 repeated-measures ANOVA with 2 within-subject factors: stroking area (3cm × 2cm, 3cm × 4cm, 3cm × 8cm) and stroking hardness (soft, hard) based on the glabrous skin of the palm; stroking area (3cm × 4cm, 3cm × 8cm, 3cm × 16cm) and stroking hardness (soft, hard) based on the hairy skin of the forearm.

The descriptive statistics were analyzed, and a full factorial model was used to explore the factors and the factor interactions. If the sphericity was violated according to Mauchly's sphericity test, the Greenhouse-Geisser (G-G) correction was used to correct the degrees of freedom, and P-values were then recalculated. Then, post hoc tests were performed with paired-samples t-tests with a Bonferroni correction. Furthermore, a 2 × 3 repeated measures ANOVA with 2 within-subject factors: stroking area (3cm × 2cm, 3cm × 4cm, 3cm × 8cm) and stroking hardness (soft, hard) for the glabrous skin of the palm; stroking area (3cm × 4cm, 3cm × 8cm, 3cm × 16cm) and stroking hardness (soft, hard) for the hairy skin of the forearm on the pleasantness ratings of affective touch revealed significant main effects and interaction effects, and Bonferroni correction was used for low-level multiple comparisons. Moreover, separate paired-sample t-tests were conducted at each stroking hardness in the context of the palm and forearm to assess whether the pleasantness ratings statistically differed among stroking area.

2.3 Results

The tactile pleasantness data were analyzed by conducting a repeated measures ANOVA to reveal significant differences in the perception of affective touch for the different stroking hardness and stroking areas at the different skin sites.

For the glabrous skin of the palm (**Figure 2.1A**), there were significant main effects of stroking hardness ($F_{1,9} = 7.989$, $p = 0.020$) and stroking area ($F_{2,18} = 5.935$, $p = 0.010$) on tactile pleasantness ratings, showing that tactile pleasantness was rated as more pleasant when stroked by a soft brush than by a hard brush. Meanwhile, it suggests that stroking area have an effect on the perception of affective touch and the stimulus is perceived to be more intense as the area of stimulation increases. Bonferroni post hoc tests showed that brush strokes with a stroking area of 3cm × 8cm were rated as significantly more intense than a stroking area of 3cm × 2cm in terms of tactile pleasantness ratings, but there was no significant difference between stroking area of 3cm × 8cm and stroking area of 3cm × 4cm. There was a significant interaction effect between stroking hardness and stroking area. The simple effects were further conducted to reveal significant differences among stroking areas under a soft brush, where a significant difference ($p = 0.049$) between stroking area of 3cm × 2cm (0.84 ± 0.22) and 3cm × 4cm (1.18 ± 0.28), a significant difference ($p = 0.015$) between stroking area of 3cm× 4cm (1.18 ± 0.28) and 3cm × 8cm (1.69 ± 0.37) and a significant difference ($p = 0.014$) between stroking area of 3cm × 2cm (0.84 ± 0.22) and 3cm × 8cm (1.69 ± 0.37) were found. However, there were no significant differences among stroking areas under a hard brush.

Table 2.1. The mean scores for pleasantness ratings.

Skin sites	Stroking hardness	Stroking area	Mean ± SEM
Palm	Soft	3cm × 2cm	0.84 ± 0.22
		3cm × 4cm	1.18 ± 0.28
		3cm × 8cm	1.69 ± 0.37
	Hard	3cm × 2cm	-0.21 ± 0.30
		3cm × 4cm	-0.28 ± 0.41
		3cm × 8cm	-0.48 ± 0.54
Forearm	Soft	3cm × 4cm	0.62 ± 0.26
		3cm × 8cm	0.70 ± 0.28
		3cm × 16cm	0.85 ± 0.48
	Hard	3cm × 4cm	-0.62 ± 0.34
		3cm × 8cm	-0.72 ± 0.44
		3cm × 16cm	-1.03 ± 0.58

The table shows pleasantness ratings of affective touch over different stroking areas of the skin sites using different hardness of brushes.

Similarly, for the hairy skin of the forearm (**Figure 2.1B**), there was a significant main effect of stroking hardness ($F_{1,9} = 7.979$, $p = 0.020$), but no significant main effect of stroking area was found. Further, we found that there was no significant interaction effect between stroking hardness and stroking area.

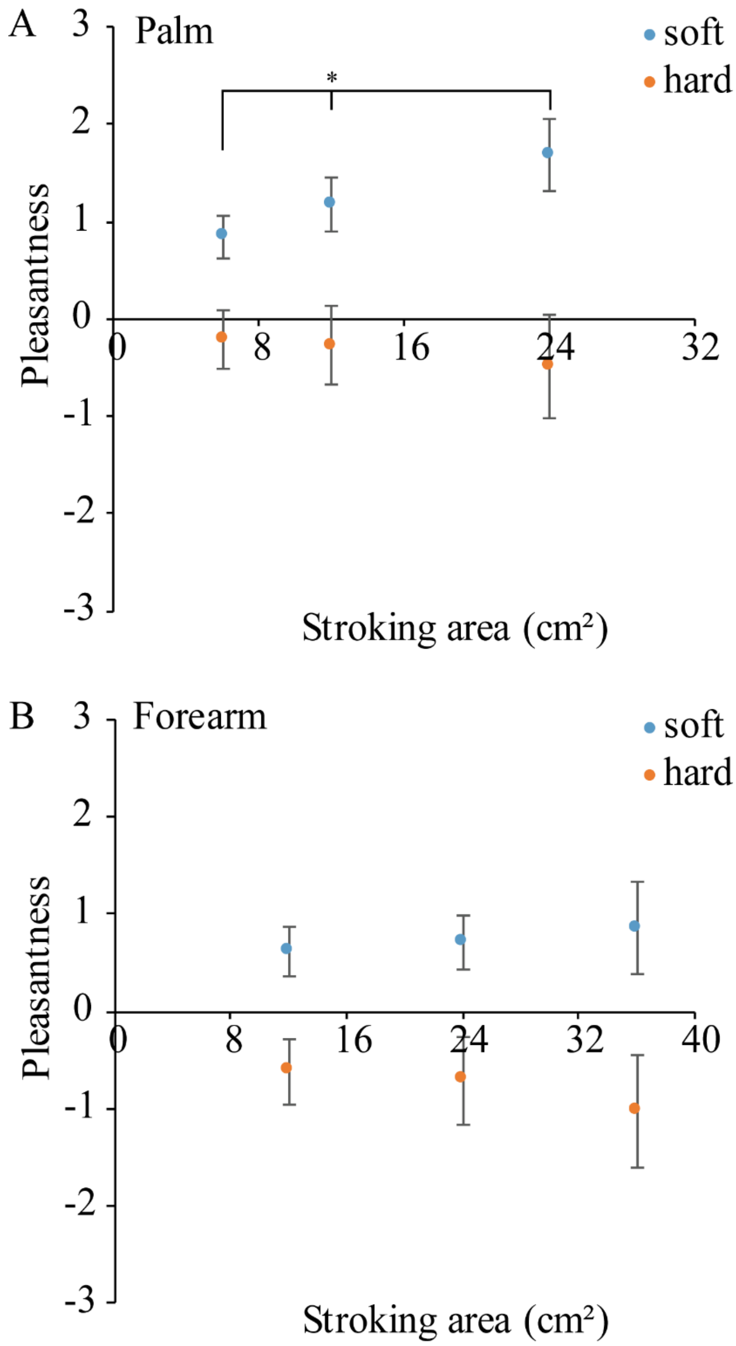

Figure 2.1. Pleasantness ratings of affective touch over different stroking areas of the skin sites. Tactile pleasantness on both the palm **(A)** and forearm **(B)** was rated as more pleasant when stroked by a soft brush than by a hard brush. For the palm **(A)**, there was a significant difference among the three stroking areas in terms of tactile pleasantness ratings when stroked by a soft brush, and the stimulus is perceived to be more pleasant as the area of stimulation

increases. There was no significant difference among the three stroking areas when stroked by a hard brush. For the forearm **(B)**, there were no significant differences among the three stroking areas in terms of tactile pleasantness ratings when stroked by both a soft brush and hard brush. The rating scale was from −10 to +10. Error bars correspond to ±SEM.

To investigate whether there was a difference between the glabrous skin of the palm and the hairy skin of the forearm under the same stroking area, we conducted a paired samples t - test on the tactile pleasantness ratings from the palm and forearm at the stroking area 3cm × 8cm.

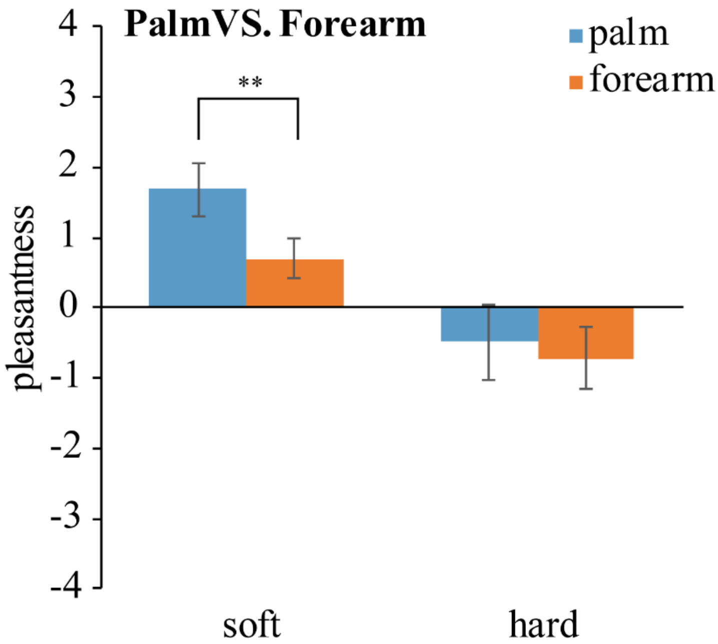

Figure 2.2. The comparison of pleasantness ratings between the palm and forearm at different stroking hardness of brushes. There was a significant difference between the palm and forearm in terms of tactile pleasantness ratings when stroked by a soft brush and tactile pleasantness on the palm was rated as more pleasant compared to on the forearm. However, there was no significant difference between the palm and forearm when stroked a hard brush.

A paired-samples t - test showed that the palm vs. forearm differed under a soft brush across the stroking area 3cm × 8cm, paired-samples $t(9) = 3.777$, $p < 0.01$, with stroking on the palm perceived as more pleasant than on the forearm (**Figure 2.2**). However, there was no significant difference between the palm and forearm under a hard brush.

2.4 Discussion

In this study, we investigated the effect of stroking area on tactile pleasantness ratings by using two different hardness of brushes to stroke the glabrous skin of the palm and the hairy skin of the forearm. The findings of the current study showed that stroking hardness affects the tactile pleasantness ratings on both the palm and the forearm with soft brush stroking perceived as more pleasant than hard brush stroking (**Figure 2.1**). This result is in line with the hypothesis that soft stimulation is rated as significantly more pleasant compared to hard stimulation [69]. And stroking area has an effect on the perception of affective touch and the stimulus is perceived to be more intense as the area of stimulation increases for the palm. Interestingly, there was no significant main effect of stroking area for the hairy skin of the forearm.

Previous studies have shown that the skin, our largest organ, encompasses the entire body and mediates our sense of touch [59]. It will lead to skin vibration when brush stroking is applied to present stimulation to human skin. Pioneering studies of correlation between the firing rate of peripheral units and perception was performed by Mountcastle and his peers [70], and found that linear relations between neural data from monkey and psychophysical data from humans allowing the conclusions that RAI

(Meissner) units are particularly significant for the sensation of low-frequency vibration, whereas Pacini units cover high-frequency components. The current study shows that stroking area have an effect on the perception of affective touch and the stimulus is perceived to be more intense as the area of stimulation increases for the palm. This may be because the larger the stroking area, the longer time tactile stimulation last, and it will lead to a longer firing time of Aβ myelinated low-threshold mechanoreceptors (LTMs). Another possibility is that the larger stroking area will cause greater amounts of Aβ afferents activation. Interestingly, there was no significant main effect of stroking area for the hairy skin of the forearm. We speculate that this may be due to the fact that although the three stroking areas on the forearm cause different scales of afferents activation, there is no difference in the sensory intensity caused by the three scales.

Previous studies testing the pleasantness perception of stroking on glabrous and hairy skin have found variable results. For example, Löken et al. (2011) [71] found brush stroking was perceived as more pleasant on the arm compared to palm, and Ackerley et al. (2014) [63] found a contrary result that tactile stimulation was rated as more pleasant on the palm than on the forearm. Our data show that brush stroking was perceived as more intense on the palm than on the forearm under a soft brush stroking, but the same intensity was found between the palm and forearm under a hard brush stroking. The glabrous skin of the palm contains dense myelinated tactile afferents [72] that send fast, temporally-accurate touch information to the brain, hence their high tactile acuity. It has been widely known that the pleasantness of touch is a more complex percept and the hedonic ratings probably depend not only on bottom-up neural signaling but also on top-down factors related to context, previous experience, expectation and culture [19, 31, 60]. Myelinated afferents code other aspects of touch well, including force, friction and texture.

The current study demonstrates that stroking area have an effect on the perception of affective touch at certain different stroking areas and the stimulus is perceived to be more intense as the area of stimulation increases. In addition, taken together with previous physiological findings on pleasantness ratings of affective touch, we give the possibility of reasons that glabrous skin where CTs are not present can feel the sensation of pleasantness. Finally, we explain why the pleasantness perception of stroking on glabrous and hairy skin have found variable results. We think that the paradigm and control variables are different between the various experiments, but it may also be because the pleasantness of touch is a more complex percept which depends not only on bottom-up neural signaling but also on top-down factors.

3. Stroking Hardness Changes the Perception of Affective Touch Pleasantness across Different Skin Sites

Summary

Human unmyelinated tactile afferents (CT afferents) in hairy skin are thought to be involved in the transmission of affective aspects of touch. How the perception of affective touch differs across human skin has made substantial progress; however, the majority of previous studies have mainly focused on the relationship between stroking velocities and pleasantness ratings. Here, we investigate how stroking hardness affects the perception of affective touch. Affective tactile stimulation was given with four different hardness of brushes at three different forces, which were presented to either palm or forearm. To quantify the physical factors of the stimuli (brush hardness), ten naïve, healthy participants assessed brush hardness using a seven-point scale. Based on these ten participants, five more participants were added to rate the hedonic value of brush stroking using a visual analogue scale (VAS). We found that pleasantness ratings over the skin resulted in a preference for light, soft stroking, which was rated as more pleasant when compared to heavy, hard stroking. Our results show that the hairy skin of the forearm is more susceptible to stroking hardness than the glabrous of the palm in terms of the perception of pleasantness. These findings of the current study extend the growing literature related to the effect of stroking characteristics on pleasantness ratings.

Keywords: CT afferents, affective tactile, stroking hardness, pleasantness ratings, physical factors

3.1 Background

Touch sensations are transmitted by different combinations of mechanoreceptors. The experience of touch leads to sensations that involve both discriminative and emotional aspects [19]. According to these theories, the experiences of touch are mediated by two separable dimensions, classified as sensory-discriminative and motivational-affective [10]. Although much more is known about the perception of discriminative touch, such as roughness, shape and vibration discrimination, little is known about affective touch, which plays a critically important role in interpersonal communication [1].

It is widely accepted that human discriminative touch is mediated through low-threshold mechanoreceptors with large, myelinated A-beta (Aβ) fibers [72, 73]. In contrast, recent studies have suggested that unmyelinated, small-diameter, lower-threshold mechanoreceptive afferents (C-LTMRs), also called C tactile or CT afferents, are involved in the transmission of affective aspects of touch [19, 31, 32, 74]. There is no evidence for existence of CT afferents in the glabrous skin [31, 37, 60, 74-76], yet the phenomenon that glabrous skin touch perceived as pleasant is very common. In addition, previous studies have shown that sensory factors such as hardness [64], temperature [67], force and velocity [31, 63], contribute to pleasantness ratings of affective touch. Here, the focus of our research is to investigate the relationship between stroking hardness and affective touch over two different skin sites.

The majority of previous behavioral studies have focused on pleasantness ratings at different levels of stroking velocities over skin sites [31, 63, 71]; these studies have all consistently suggested that the glabrous skin of the palm presents a flatter, inverted U-shaped stroking velocity-pleasantness rating profile compared to the hairy skin of the forearm. Previous functional magnetic resonance imaging (fMRI) studies [56, 74] have shown that CT-targeted touch mainly projects to the insular cortex rather than the somatosensory cortices. The recent positron emission tomography (PET) study [57] showed affective touch on the arm give significant activations of the posterior insular cortex and mid-anterior orbitofrontal cortex (OFC) in comparison to the palm, while the opposite contrast (touch on the arm minus touch on the palm) showed a significant activation of the somatosensory cortices. Further, the dissociation of insula function suggests posterior and anterior insula involvement in distinct yet interacting processes: coding physical stimulation and affective interpretation of touch by investigating brain responses to CT-targeted touch in the experience versus imagine conditions [58]. From these studies, stroking velocities also have different effects on the perception of affective touch on the palm and the forearm, and experiencing affective touch to arm and palm recruit either overlapping or distinct brain responses. We hypothesize that physical characteristics, particularly stroking hardness, may also have different effects on the perception of pleasantness from hairy and glabrous skin just like stroking velocities.

Here, a 2×3×4 factorial experiment was designed, with the factors being 2 locations, 3 stroking forces and 4 stroking hardness grades. We investigated the relationship between stroking forces and affective touch over two different skin sites. Since the light touch seems suitable for human social interaction, we predicted that the light stroking force would be more pleasant than the heavy stroking force. We also wanted to investigate whether stroking hardness has a different effect on pleasantness ratings of affective touch on the hairy skin of the forearm and the glabrous skin of the palm. We predicted that the hairy skin of the forearm is more susceptible to stroking hardness than the glabrous of the palm in terms of the perception of affective touch pleasantness. We tested this hypothesis by contrasting the slope of the regression line between hardness and the perception of affective touch administered to the hairy skin of the forearm versus the glabrous skin of the palm.

3.2 Materials and Methods

3.2.1 Experiment 1 (Measurement of brush hardness)

Experiment 1 was designed to measure the hardness of the brushes used in the affective touch experiment (experiment 2).

Participants. In total, 10 participants (5 males, Mean age 25.6 years, and 2.3 SD; 5 females, Mean age 26.6 years, and 2.4 SD) took part in the study. The study was approved by the ethics committee of the University of Okayama. All the participants were right-handed and given basic information about the experiment. Written informed consent was obtained from all the participants prior to their participation.

Experimental setting and procedure. After receiving a written explanation of the experiment, which included a description of the experimental setting and instructions on how to rate the stimuli, the temperature of the experimental room was adjusted to a suitable temperature by the air conditioner [66, 68]. During the experiment, an accurate digital alarm clock with thermometer Sensor (BC247L, Seiko Co., Ltd., Japan) was placed within one meter of the participants, and the temperature was recorded every five minutes. The actual temperature of the experimental room was Mean 24 ± SD 0.5 °C. The participants were then comfortably seated in an adjustable chair, and the fingers of each participant were wrapped in a piece of surgical tape to insure that the brush would not touch the participants' fingers during palm stimulation (**Figure 3.1**). The participants naturally put their left hands or left forearms on a high-precision, portable, digital scale (hand: KD192, Tanita Corporation, Japan; forearm: CS-20KS, Custom Corporation, Japan) during palm or forearm stimulations. A baffle was used to shield the participants from seeing the tactile stimulation.

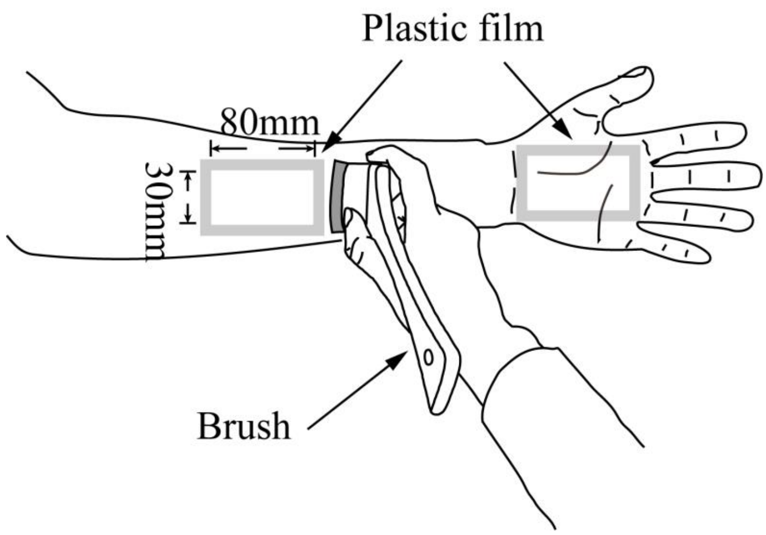

Figure 3.1. Diagrammatic representations of the stroking stimuli. An assistant conducted the stimuli using a soft brush, and stroking forces were controlled by observing the display of electronic scales. A window (30 × 80 mm) in the plastic film exposed the skin to the moving brush and assured maintenance of a constant spatial relationship between the brush and the body part.

Stimulations were all made with four types of artist's flat, 50-mm-wide, watercolor brushes, each with different levels of hardness. Although the bristles are different materials (goat's hair, mixed wool, artificial wool, pig's hair) for all brushes, the bristles were wrapped in aluminum skin to insure that the bristles are all 20mm deep. To investigate the physical properties of the brushes, we took a 2 × 2 mm² area sample unit from the center of each brush bristle and then count the number of bristles in the sample. The number of bristles per unit area (1 mm²) in the sample is approximately the density of the bristle. Subsequently, we took a sample of 100 bristles from the center of each brush bristle. In order to objectively investigate the diameter of the bristles, the diameters of the tip and middle of the 100 bristles were all measured using a high precision outside micrometer (M110-25, Mitutoyo Co., Ltd., Japan). The average tip/middle diameter of the sample is approximately the tip/middle diameter of the bristle. The physical parameters of the brushes are listed in **Table 3.1**.

Table 3.1. Main Physical Properties of Bristles

Brush	Material	Density	Tip Diameter (μm) Mean ± SD	Middle Diameter (μm) Mean ± SD
Brush1	Fiber 100%	68	52.80 ± 13.58	94.42 ± 11.32
Brush2	PET 60%; PP 20%; Goat hair 20%	88	37.20 ±13.22	70.17 ± 16.13
Brush3	Goat hair 50%; Chemical fiber 50%	75	72.79 ± 33.55	85.24 ± 33.41
Brush4	Pig hair 100%	33	73.99 ± 26.30	143.62 ± 22.01

The table shows the main physical properties of the brush bristles used in the experiment.

Material: the material of the bristles; PET: Polyethylene terephthalate, PP: Polypropylene; The number indicates the proportion of each component.

Density: the number of the bristles per 1 mm^2 area located in the center part of the brush bristles material

Tip diameter: the mean ± SD diameter (μm) of the tip of 100 bristles located in the center part of the brush bristles material

Middle diameter: the mean ± SD diameter (μm) of the middle (equidistant from bristle tip and root) of 100 bristles located in the center part of the brush bristles material

The caress-like strokes were administered by a well-trained research experimenter on a palm/forearm to fingertip direction at a rate of approximately 3 cm/s, a CT-optimal stroking speed [31]. The participants' hands (forearms) were fixed during the experiment to prevent movement on the weighing platform of the high-precision digital scale, thereby insuring the highest possible accuracy. The experimenter applied different forces to the brushes and achieved three different desired forces 1N, 1.7N, 3N by observing the display on the high-precision digital scale. Despite the error, the experimenter controlled the error below 0.15N as much as possible. We collected the actual exerted forces of one participant at the three time points (the starting time point, the intermediate time point, and the end time point) in each brush stroke using a high-speed camera (HDE-CX630V, Panasonic Corporation, Japan). Finally, we plotted the figure of the average actual forces corresponding to the average expected forces and gave the error bars of the standard deviation (**Figure 3.2**).

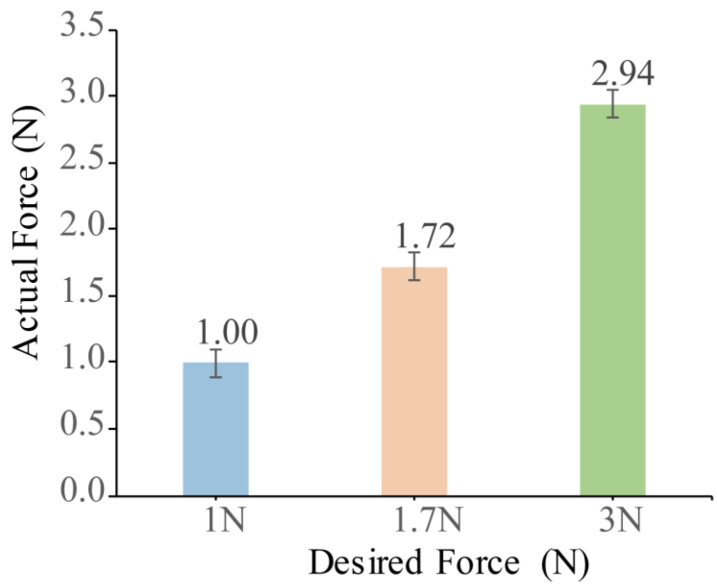

Figure 3.2. The actual exerted mean forces at different desired forces. The y-axis represents the actual exerted mean force corresponding to the desired force. Corresponding to the desired force of 1N, 1.7N, 3N, the actual exerted mean force is 1N, 1.72N, and 2.94N, respectively. The error bars represent the standard deviation (SD) of the means.

Tactile sensations were explored over the following two skin sites: left palm (in the center, equidistant from the bottom of the third finger and the wrist) and left forearm (on the volar side, equidistant from the wrist and elbow) [63]. In addition, a window (30 × 80 mm) in the plastic film exposed the skin to the moving brush and assured maintenance of a constant spatial relationship between the brush and the body part. Following each brush stroke, the participants were instructed to rate the sensation on two subsequently presented seven-point Likert-like scales [77, 78], using a custom-made scale, which was fixed to a table in front of the participant. In the first Likert-like scale, the participants were asked to answer the question: “how hard was the brush?”. The rating scale consisted of 7 choices (ranging from 1 = extremely soft to 7 = extremely hard). In the second Likert-like scale, which occurred directly after the first, the participants were asked to answer the question: “how rough was the brush?”. The rating scale consisted of 7 choices (ranging from 1 = extremely smooth to 7 = extremely rough). As the study was conducted in Japan, the descriptors of the scales were presented in Japanese. Therefore, the responses were also recorded in Japanese and subsequently translated into English. The translation was carried out independently by two fluent Japanese-speaking, native British individuals, and the descriptors were also compared to dictionary definitions of the words. It was also back-translated into Japanese by an individual, who knew nothing about the original Japanese descriptors. Since the back-translated to Japanese corresponded to the original Japanese descriptors, the translation into English was considered satisfactory. Although we provided two items (roughness, hardness) for the participants to answer, the main focus of the research was to investigate the influence of hardness on pleasantness ratings of gentle stroking. The participants had 5 s to complete both Likert-like scales. Therefore, this experiment consisted of a 2×3×4 design, where the Site condition had two levels (palm, forearm), the Force condition had three levels (1 N, 1.7 N, 3 N), and the Hardness condition had four levels. Each trial was repeated five times in a pseudo-random order.

Statistical analysis. The average raw scores for hardness ratings at different stimulation conditions have been shown in **Figure 3.3**. Since the basic data obtained from measurements using an ordinal scale were not normally distributed, the transformation of the ordinal scale to interval scale should be done before parametric statistics. In addition, although the scale values of the stimuli were defined as projected upon a psychological continuum, the method of equal-appearing intervals makes an implausible assumption of "equal intervals". Therefore, all the data were analyzed using the method of successive interval (MSI) [79-81]. In the study, n = 12 stimuli were rated by 10 participants on a 7-point Likert-like scale ranging from extremely soft, to neutral, to extremely hard. From the proportion of each option, the cumulative distributions for each stimulus are given in **Table 3.2**.

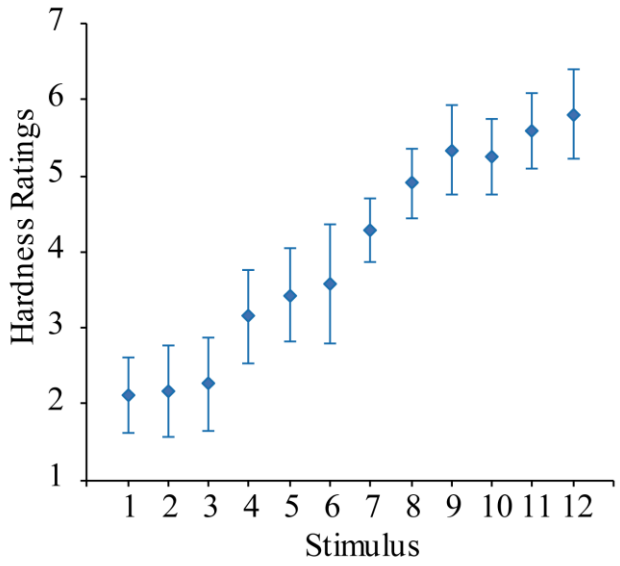

Figure 3.3. The average raw scores for hardness ratings at different stimulation conditions. The x-axis represents the 12 different stimulus conditions (3 force × 4 hardness), which has been stated in table 2. The y-axis is the average raw scores for stroking hardness in context of a seven-point scale used to elicit answers. Error bars correspond to ±SD.

Table 3.2. Cumulative Proportion of Judgement for Stimuli

	Rating Category						
Stimulus	1	2	3	4	5	6	7
1. f1h1	0.17	0.76	0.98	0.99	0.99	1.00	1.00
2. f2h1	0.16	0.70	0.98	0.99	1.00	1.00	1.00
3. f3h1	0.13	0.65	0.96	1.00	1.00	1.00	1.00
4. f1h2	0.01	0.28	0.69	0.89	0.98	1.00	1.00
5. f2h2	0.01	0.17	0.59	0.82	0.98	1.00	1.00
6. f3h2	0.01	0.18	0.52	0.73	0.97	1.00	1.00
7. f1h3	0.01	0.02	0.16	0.60	0.92	1.00	1.00
8. f2h3	0.00	0.00	0.05	0.34	0.73	0.98	1.00
9. f3h3	0.00	0.01	0.03	0.14	0.54	0.94	1.00
10. f1h4	0.00	0.00	0.03	0.16	0.62	0.95	1.00
11. f2h4	0.00	0.00	0.02	0.04	0.42	0.93	1.00
12. f3h4	0.00	0.00	0.01	0.04	0.28	0.84	1.00

Table 3.2 is an n × r matrix, where n is the number of stimuli and r is the number of rating categories. Let the general element of Table 1 be p_{jk}, which shows the proportion of rating a given stimulus j in the kth category or below; $1-p_{jk}$ is the proportion of rating stimulus j above the kth category. f1 = force 1N, f2 = force 1.7N, f3 = force 3N. h1 = hardness of brush 1, h2 = hardness of brush 2, h3 = hardness of brush 3, and h4 = hardness of brush 4. Stimulus 1 of f1h1 indicates the stroke of brush 1 under downward force 1N. Similarly, stimulus 12 of f3h4 indicates the stroke of brush 4 under downward force 3N.

Assuming that the judgements for each stimulus are normally distributed on a psychological continuum, the boundaries of categories can be expressed as standard normal deviates. The area under the standard normal curve is divided into 7 sections according to the proportion of each option, and the area in each section is then obtained from the frequency of choice. If the table of cumulative proportion is entered with value p_{jk}, the corresponding standard normal deviate X_{jk} will be the upper limit of the kth category over the rating stimulus j. Stimulus 2, for example, provides estimates of the upper limits of categories 1, 2, 3, and 4. Expressed as standard normal deviates, these upper boundaries are -0.99, 0.52, 2.05, and 2.33, respectively. It is important to note that the lower limit of category 1 and the upper limit of category 7 are indeterminate because they are the endpoints. Let Y_{jk} be the density value corresponding to the upper limit of the kth category. $Y_{j(k-1)}$ can be understood as the density value corresponding to the lower limit of the kth category. In particular, the density value Y_{j0}, corresponding to the lower limit of category 1, and the density value Y_{j7}, corresponding to the upper limit of category 7, are expressed as 0. All the subsequent calculations are based on the data in **Table 3.2**. Therefore, the scale value (SV) for each category will be computed by

$$SV_k = \frac{Y_{k-1} - Y_k}{P_k - P_{k-1}} \tag{3.1}$$

where SV_k is the scale value of category k. Y_k is the density value corresponding to the upper limit of category k. Y_{k-1} is the density value corresponding to the lower limit of category k. P_k is the cumulative proportion of category k. The denominator $P_k - P_{k-1}$ is the proportion of category k. When $P_k - P_{k-1}$ is 0, the scale value will be ignored. The scale values of each category of the other stimuli are obtained in the same manner; thus, the means of all the stimuli will be defined as the scale values of each category. These scale values for each category are -2.19, -1.29, -0.87, 0, 0.40, 1.45, and 1.98. To transform SV_1 (the scale value for category 1) so that it equals 1, 3.19 needs to be added. This same amount is added to each of the other SV categories as well. The final SVs will be 1.00, 1.90, 2.31, 3.18, 3.58, 4.64, and 5.17.

After obtaining the final SV, the ordinal scale will be changed to the distance (interval) scale. Brush hardness can be obtained by calculating the normalized basic data and are 1.91, 2.66, 3.66, and 4.17. From **Table 3.1**, we found that stroking hardness was not linearly related to the density or the tip/middle diameter of the bristles.

3.2.2 Experiment 2 (Ratings of Pleasantness)

To determine how stroking hardness affects pleasantness ratings from skin sites at different levels of stroking force, we conducted the second experiment. Here, stroking hardness was measured using a seven-point Likert-like scale in Experiment 1.

Participants. Fifteen healthy participants (8 males, Mean age 26.9 years, and 2.6 SD; 7 females, Mean age 26.6 years, and 2.4 SD) were recruited from Okayama University. Eight participants were male. Ten of the participants took part in Experiment 1. The study was approved by the ethics committee of the University of Okayama. All the participants were right-handed and given basic information about the experiment, and written informed consent was obtained from all the participants prior to their participation.

Experimental setting and procedure. The experimental setting and procedure of Experiment 2 were identical to Experiment 1 in terms of the factorial design. Experiment 2 also consisted of a 2×3×4 design, where the Site condition had two levels (palm and forearm), the Force condition had three levels (1 N, 1.7 N, 3 N), and the Hardness condition had four levels (1.91, 2.66, 3.66, and 4.17). Following each brush stroke, the participants were instructed to rate the pleasantness of the brushing experience using a visual analogue scale (VAS) placed next to the right hand, ranging from -10 (unpleasant) over a neutral (0) midpoint to 10 (pleasant).

The participants were required to rate the pleasantness of the stimulation with a 10 s response interval. Each trial was repeated twenty times per skin site (palm/forearm) using brushes of different hardness with different stroking forces in a pseudo-random order. The data from each participant were collected over four sessions conducted on different days. Each session lasted for approximately 30 min.

Statistical analysis. All the statistical data were analyzed using SPSS (SPSS Statistics, Version 17; IBM, Armonk, NY). Significance was obtained at the $p < 0.05$ level, with up to three significant figures. The raw average scores for pleasantness ratings from the palm and forearm was shown in **Figure 3.4A-B**. The data were first tested for normality of distribution using one-sample Kolmogorov-Smirnov tests. From the test results, the tactile pleasantness ratings were found to be normally distributed (Kolmogorov-Smirnov test $p > 0.05$) and were analyzed using parametric tests. The mean tactile pleasantness data were analyzed using a repeated-measures analysis of variance (ANOVA) with 3 within-subject factors: site (arm and forearm), force (1 N, 1.7 N, and 3 N), and hardness (1.91, 2.66, 3.66, and 4.17). Descriptive statistics were analyzed, and a full factorial model was used to explore the factors and the factor interactions. If the assumption of sphericity was violated in the Mauchly's sphericity test, the Greenhouse-Geisser (G-G) correction coefficient epsilon was used to correct the degrees of freedom, and P-values were then recalculated. Further, the main effects of each factor were compared, and post hoc tests were conducted to contrast the different levels of the factors by using Bonferroni-corrected pairwise comparisons of the estimated marginal means, controlling for multiple comparisons. Simple-simple main effects were further conducted to reveal whether there were significant differences between stimulation sites (palm/forearm) for pleasantness ratings under a combination of the factors force and hardness. Finally, to investigate the relationship between tactile pleasantness ratings and stroking forces, linear regression analyses were performed. The pleasantness of a stimulus was defined as the dependent variable, with stroking forces as independent variables.

3.3 Results

The tactile pleasantness data were analyzed using repeated measures ANOVA to reveal significant differences in the pleasantness ratings for different skin sites, stroking forces and stroking hardness. Main effects of skin sites ($F_{1,14}$ = 7.43, p = 0.016), stroking forces ($F_{1.11,15.50}$ = 28.23, p < 0.001) and stroking hardness ($F_{1.17,16.41}$ = 38.52, p < 0.001) were found. The main effects can be seen in **Figure 3.4A-B**, where tactile stimuli with light stroking hardness to be rated as more significantly pleasant than the other stimuli at high stroking hardness; a light stroking force was rated as more significantly pleasant than a heavy stroking force of the skin sites.

There were significant interaction effects between the skin sites and stroking forces ($F_{1.42,19.83}$ = 7.47, p = 0.007) as well as between the skin sites and stroking hardness ($F_{1.91,26.79}$ = 11.92, p < 0.001). There was also a significant interaction effect between stroking force and hardness ($F_{6,84}$ = 6.55, p < 0.001). Although there was no significant three-way interaction among skin sites, stroking forces and stroking hardness, main two-way interaction effects showed significance, and there were multiple levels for each factor; thus, extensive analyses (simple-simple main effects) were deemed necessary to uncover the influences of stroking hardness on the skin sites among stroking forces, and to detect subtle effects over different factor levels.

Extensive analyses showing the main effect of skin site at each level of stroking force were shown in **Figure 3.5A-C,** where stroking hardness has a different effect on the perception of pleasantness for the palm and the forearm. We found no significant main effect of skin site at the level of stroking hardness 1.91, but there were significant main effects of skin site at levels of stroking hardness of 2.66 (p = 0.009), 3.66 (p = 0.003), and 4.17 (p = 0.001) for the 1N level of stroking force. For the level of stroking force

1.7N, there were significant main effects of skin site at all levels of stroking hardness of 1.91 (p = 0.031), 2.66 (p = 0.007), 3.66 (p = 0.003), and 4.17 (p = 0.001). Intriguingly, significant main effects of skin site were found at the levels of stroking hardness of 1.91 (p = 0.024), 3.66 (p = 0.018), and 4.17 (p = 0.021), but no significant main effect of skin site at the level of stroking hardness 2.66 was found for the 3N level of stroking force.

Linear regression analyses were conducted to explore the relationship between tactile pleasantness ratings and stroking forces, per stroking hardness. For the palm skin site, all the linear regressions were significant: stroking hardness of 2.66 (R^2 = 0.158, p = 0.007), stroking hardness of 3.66 (R^2 = 0.152, p = 0.008), and stroking hardness of 4.17 (R^2 = 0.197, p = 0.002). For the forearm skin site, the following linear regressions were significant: stroking hardness of 2.66 (R^2 = 0.239, p = 0.001), stroking hardness of 3.66 (R^2 = 0.150, p = 0.009), and stroking hardness of 4.17 (R^2 = 0.089, p = 0.046). No significant linear regression was found at a stroking hardness of 1.91 for both skin sites.

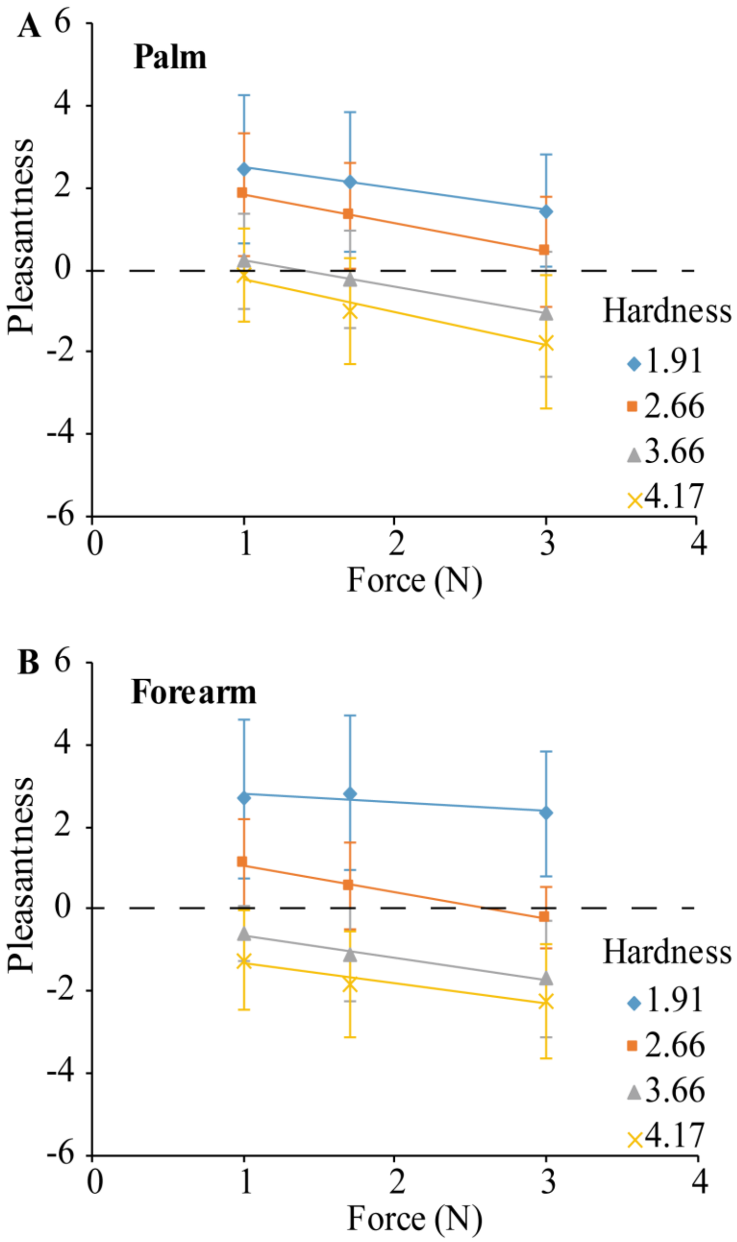

Figure 3.4. Pleasantness ratings at different stroking forces with different brush hardness levels over skin sites. The y-axis **(A-B)** is the raw average scores for pleasantness ratings from the palm **(A)** and forearm **(B)** in context of the ratings scale (-10, 10) used to elicit answers**.** Main significant effects were found for all factors, including stroking forces ($p < 0.001$), stroking hardness ($p < 0.001$), and skin sites ($p = 0.016$). The lighter forces were rated as more significantly pleasant compared to heavier stroking forces for all skin sites. Higher stroking hardness led to less pleasantness ratings than lower stroking hardness for all skin sites. Error bars correspond to ±SD.

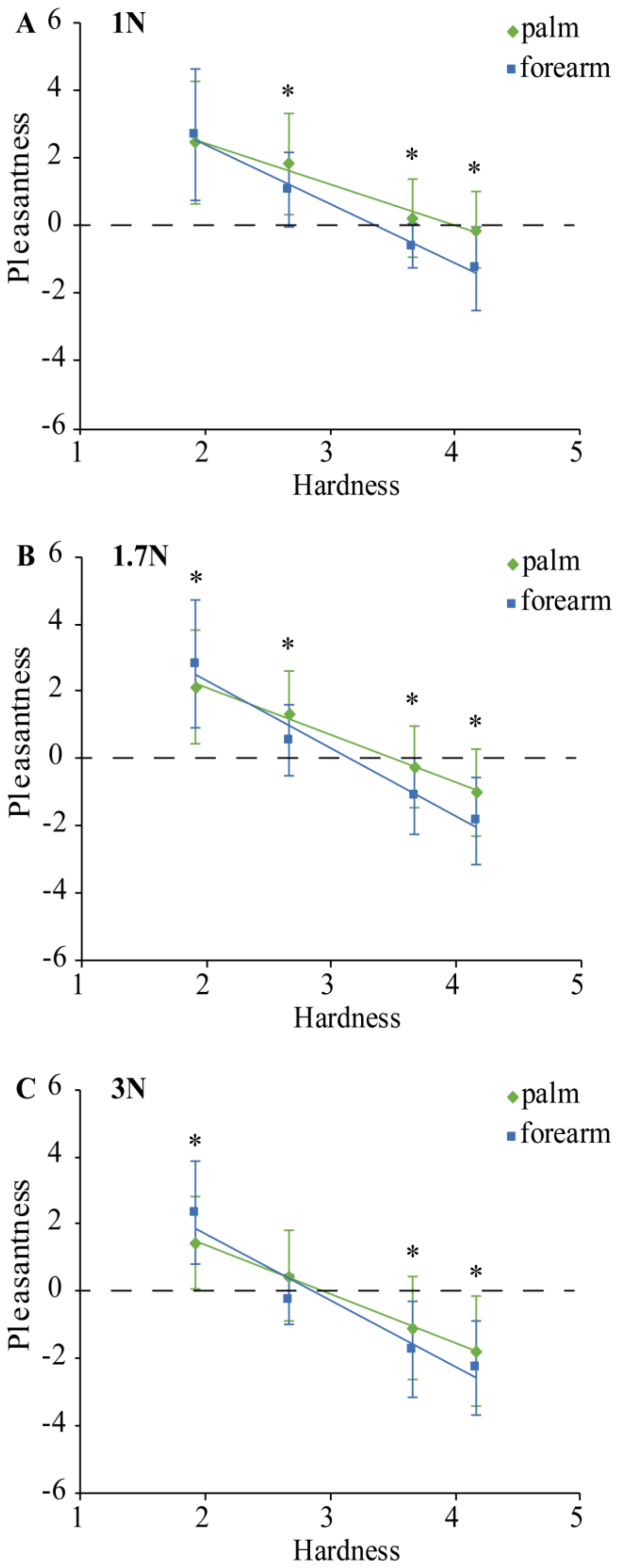

Figure 3.5. The effect of skin site on pleasantness ratings for different levels of stroking hardness. The y-axis **(A-C)** is the raw average scores for pleasantness ratings from the palm and forearm in context of the rating scale (-10, 10) used to elicit answers. There were main effects of skin site on a stroking hardness of 2.66, hardness of 3.66, and hardness of 4.17 for the level of stroking force (A) 1N. For the level of stroking force (B) 1.7N, there were significant main effects of skin site at all levels of stroking hardness. And for the level of stroking force (C) 3N, significant main effects of skin site were found on a stroking hardness of 1.91, hardness of 3.66, and hardness of 4.17 (* indicates significant differences, $p < 0.05$). Furthermore, pleasantness decreased at a faster rate for stroking over the forearm compared to over the palm as stroking hardness becomes harder. Error bars correspond to ±SD.

3.5 Discussion

In this study, we investigated the effect of stroking hardness on pleasantness ratings by stroking four different brushes on two different skin sites using three stroking forces. In terms of pleasantness ratings, the hairy skin of the forearm is more susceptible to stroking hardness than the glabrous skin of the palm, independent of the effects of forces. This result suggests that pleasantness ratings from hairy skin decrease at a faster rate compared to glabrous skin as stroking hardness becomes harder and that there is an interaction between stroking hardness and stroking sites on ratings of pleasantness (**Figure 3.5**). Adding to previous research on affective touch [31, 63, 71, 82], there are different effects of stroking hardness on the perception of pleasantness for palm and forearm stimulation.

The main finding in the current study is that the hairy skin of the forearm is more susceptible to stroking hardness than the glabrous skin of the palm in the range perceived as affective touch. It is well known that CT afferents involved in the transmission of affective tactile signals are exclusively innervated in hairy skin (e.g., the forearm) (Löken et al., 2009), and the stroking velocity-pleasantness profile has previously been confirmed to be different between glabrous and hairy skin [31, 63, 83]. Previous fMRI studies [56, 57, 84, 85] have shown that CT-targeted touch on the forearm mainly project onto the insular cortex when compared to the palm, while the opposite contrast (touch on the palm minus touch on the arm) showed a significant activation of somatosensory cortices. We speculate that these differential effects may be related to not only the distinct brain responses, but also cutaneous receptors responding to skin deformation. In line with previous studies [57, 86, 87], our results suggested that gentle skin stroking of the glabrous skin, where the unmyelinated CT afferents are never found, is also perceived as pleasant. Hence, Aβ fibers (that are present in both the hairy and glabrous skin) also seem to play a key role in the transmission of the affective aspects of touch by conveying discriminative information (e.g., concerning the speed and force of stimulation [19, 60]) to the brain.

Previous studies have demonstrated that CT afferent discharges prefer gentle touch with low indentation forces [19, 31, 43]. To make the experimental results more objective, we also considered stroking forces as a factor in the experimental design. It should be noted that stroking hardness is a psychological perception based on complex interaction between stiffness of brush, its endpoint characteristics, sheer forces in the brush filament and skin indentation. However, a significant interaction between stroking force and hardness was found, which indicated that force and hardness were not similar dimensions despite inseparable. Therefore, it was considered that the subjects tended to evaluate the hardness of brushes according to the characteristics of bristles, despite the contribution of the exerted downward forces to hardness ratings. Our results suggest that the light stroking forces were considered more significantly pleasant when compared to heavy stroking forces. A previous study of passive fingertip (glabrous skin) stimulation showed that the average roughness of touch plates and friction force were negatively related to pleasantness and that there was no significant correlation between the force of stimulus application or stimulus temperature and pleasantness [86]. This result indicates that the perception of pleasantness in response to affective touch can be modulated by the physical properties of stimuli as well as by its force and velocity profile. Furthermore, we found that pleasantness ratings from the hairy skin of the forearm are more sensitive than the glabrous skin of the palm and that an interaction was present between stroking hardness and stroking sites independent of the effects of force. The differential effect of stroking hardness on the perception of affective touch to the palm and forearm may be attributed to several factors, such as the type of skin (e.g. the differential presence of CT afferents between glabrous skin and hairy skin), its innervation and central signal extraction mechanisms. Because the difference between glabrous and hairy skin is divided not only by CT afferents, but also other factors. For instance, myelinated fibers in the hairy skin are irregularly distributed around the follicles in a high density compared to their homogeneous population of glabrous skin. These nerve fibers' are entangled in glabrous skin, but straight and stretched in hairy skin [88]. In addition, Meissner corpuscles are uniquely present in the glabrous skin to encoding discriminative aspects of touch, while the hair follicle endings in the hairy play a role in this aspect. These difference may also result in different responses to stimulation of glabrous and hairy skin.

Another possibility of affecting the perception of affective touch is roughness. A Hard–Soft dimension has also been identified to be an important tactile attribute [89]. A passive fingertip stimulation study indicated that the mean roughness of skin-stimulus interface was negatively correlated with pleasantness [86]. In addition, it has been found that the smooth brush and fur were rated as significantly more pleasant than the rough sandpaper [87]. However, it is difficult for the present study to dissociate the influences of hardness and roughness on the perception of affective touch, and then omit limitation of the study. Thus, dissociating the influences of hardness and roughness on the perception of affective touch is one of future research. A second issue is the hand dominance. Despite extensive studies on handedness regarding the discrimination aspects of touch, it is still unknown whether dominant hand affects the perception of affective touch. In many previous studies [56, 71, 90], tactile affective stimulation has been applied to either hand, but it does not mean that the emotional perception of touch is not affected by hand dominance. Therefore, the issue of hand dominance also needs further examination in future studies of affective touch.

These findings of the current study extend the growing literature related to the effect of stroking characteristics on pleasantness ratings and show that the hairy skin of the forearm is more susceptible to stroking hardness than the glabrous skin of the palm. However, despite their different innervations, there were many similarities in perception between the forearm and the palm, which needs further examination in future studies. In addition, our experiment only investigated two stroking sites on the palm and forearm; therefore, there are limitations in explaining the differential effects between hairy and glabrous skin. The experiment was also conducted as a behavioral one, making it difficult to attribute the affective feelings of hairless skin to the top-down mechanism. Hence, further studies are needed to incorporate more stroking sites into the experimental design and to extend fMRI approaches to the experiments to better investigate the top-down mechanism.

4. Incongruent Multisensory Stimuli Alter the Perception of Affective Touch

Summary

Previous studies have shown that viewing the non-informative body enhances tactile acuity and tactile spatial discrimination, compared to viewing a neutral object at the same location. Similarly, for emotional aspects of touch, a recent study indicated tactile stimulation was rated as less pleasant when watching an angry facial expression and more pleasant when accompanied by watching a happy facial expression. Although visuo-tactile integration related to emotional perception has received detailed investigation in recent years, little is known about whether the size of visual stimulus or viewpoint of observation affects the perception of tactile pleasantness. The present study aims to investigate the hedonic aspects of tactile perception in different visual sizes and viewpoints of observation via brush stroking across skin sites. The current study showed that viewpoint of observation affects the perception of affective touch and tactile stimuli accompanied by viewing visual stimulation from front view were rated as more significantly pleasant than from side view. However, there were no effects of visual size on pleasantness ratings of affective touch.

Keywords: affective touch, viewpoint, visual size, scene, pleasantness ratings

4.1 Background

Human touch is an essential factor in social interaction, and this factor is often accompanied by visual context to contribute to social interaction. It has been widely reported that visual context affects tactile discrimination. For example, previous studies have shown that viewing the non-informative body enhances tactile acuity [91] and tactile spatial discrimination [92], compared to viewing a neutral object at the same location. Similarly, for emotional aspects of touch, a recent study [93] indicated tactile stimulation was rated as less pleasant when watching an angry facial expression and more pleasant when accompanied by watching a happy facial expression.

The similarities and differences between glabrous and hairy skin have been one of the issues discussed in the study of affective touch perception. Similarly, we cannot ignore this issue when investigating affective touch perception in the context of visual information. Previous studies have shown that unmyelinated low-threshold C-tactile afferents (CT afferents) convey signals related to the hedonic value of affective touch [31, 37, 43, 94]. Linear regression between CT firing frequency and subjective ratings of tactile pleasantness across a stroking velocity range (0.1, 0.3, 1, 3, 10, 30cm/s) further supported the close correlation between CT afferents and the hedonic value of tactile stimulation [31]. On the other hand, these afferents are exclusively present in hairy skin and not in the glabrous skin [37, 41, 95, 96]. Therefore, comparison of the perception of tactile pleasantness between hairy and glabrous skin is one of the investigation points in this study. Functional imaging in GL patients (lacking large myelinated afferents but whose C fibers are intact) indicated that CT afferents project to insular cortex rather than somatosensory area S1 and S2 [74]. Subsequently, significant activations of the posterior insular cortex and mid-anterior orbitofrontal cortex were found in contrasting gentle stroking on the forearm with the palm while the opposite contrast (touch on the arm minus touch on the palm) showed significant activation of the somatosensory cortices during positron emission tomography (PET) [57]. All the above-mentioned studies suggest that both the psychophysical performance and brain processing of tactile pleasantness differ between glabrous and hairy skin. In addition, it is well documented that the perception of tactile pleasantness involves not only bottom-up neural transmissions like CT afferents signaling, but also top-down factors such as previous experience, attention and contextual information [97-99]. Therefore, it will be interesting to investigate whether the perception of tactile pleasantness differs between glabrous and hairy skin under visual contextual information.

Although visuo-tactile integration related to emotional perception has received detailed investigation in recent years, little is known about whether the size of visual stimulus or viewpoint of observation affects the perception of tactile pleasantness. The present study aims to investigate the hedonic aspects of tactile perception in different visual sizes and viewpoints of observation via brush stroking across skin sites. In the contribution to social interaction, affective touch does not always exist as a single sensory but is accompanied by the inputs of other sensory modalities [100, 101], of which visual input is the most common. Recent evidence suggests that affective touch may involve the construction and maintenance of body ownership [102-105], which is defined as the body's psychological sense of "belonging to me" [106]. In the past 20 years, psychophysical and computational studies have shown that the sense of body ownership depends on the integration of information from different sensory modalities, so-called multi-sensory integration [107]. Well-known examples such as “rubber hand illusion” [108] and “full body illusion” [109, 110] have proved that the temporal and spatial congruence between sensory events felt and seen sensory gives rise to feelings of body ownership, even for plastic or virtual body parts.

Here, a 2×3×3 factorial experiment was designed, with the factors being 2 locations, 3 visual sizes, and 3 viewpoints. We investigated the relationship between visual size and affective touch over two different skin sites. Since we always are exposed to people of different ages and different body size, we predicted that pleasantness ratings of affective touch are independent of visual size. We also wanted to investigate whether viewpoint has a different effect on pleasantness ratings of affective touch on the glabrous skin of the palm and the hairy skin of the forearm. We predicted that the tactile stimulation accompanied by viewing tactile stimulation from front view were rated as more pleasant than from side and back view.

4.2 Materials and methods

4.2.1 Experiment 1 (Selection of the viewpoint)

Experiment 1 was designed to select appropriate viewpoints to be used in the affective touch experiment (experiment 2).

Participants. In total, 5 participants (male 4; average age 29.67 years ± 2.88 SD) participated in the study. The study was approved by the ethics committee of the University of Okayama. All the participants were right-handed and given basic information about the experiment. Written informed consent to participate in the study prior to their participation.

Experimental setting and procedure. After receiving a written explanation of the experiment that included a description of the experimental content and special instructions on how to rate visual stimuli, the participants were instructed to sit comfortably in a chair approximately 40 cm in front of a 23.8-in. computer screen (Acer SA240YAbmi, 75HZ, 1920 × 1080 Pixels), which was placed face up on the table (see **Figure 4.1**). Each participant was tested individually in a quiet room and not allowed to talk to anyone during the breaks. The participant's palm/forearm was projected onto the computer screen in front of the participant by a high-speed camera (HDE-CX630V, Panasonic Corporation, Japan), which was connected to the display via a high-fidelity data cable, placed directly above the hand. Each visual stimulation with different viewpoint was presented on a computer monitor by rotating the camera at 15 degrees (**Figure 4.2**). Therefore, a total of 24 visual stimuli with different viewpoint were presented on the computer screen for each stimulation location and each visual stimulus was repeated ten times in a pseudo-random order. The participants were instructed to look at each image and then evaluate its naturalness using a seven-point scale (ranging from 1 = very unnatural over a neutral 4 to 7 = very natural). The rating scale was presented on the monitor of a laptop placed next to the right hand of the participants. The rating task was self-paced for each scale without enforcing a time-limit and lasted for approximately 25 minutes. All visual stimuli and rating scales were presented using e-Prime 1.0 (Psychology Software Tools, Inc.).

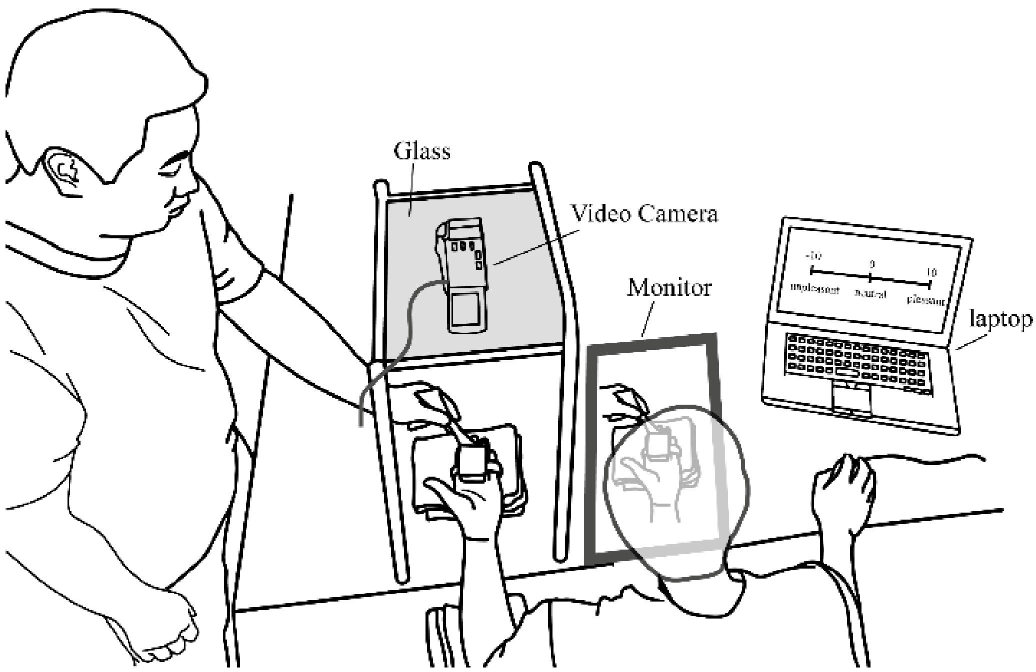

Figure 4.1. Illustration of the experimental procedure (palm stimulation). The participant's forearm was fixed with a vacuum pillow on the table and a divider was used to shield the

participants from seeing the tactile stimulation and the experimenter. A camera was placed on the glass surface of the shelf above the palm and we can present visual stimulation in different orientations and different sizes on the monitor in front of subjects by adjusting the camera. The plastic film with a window (30mm × 80 mm) was attached to the corresponding stimulation area so that the skin area exposed to brush stimulation keep constant. The experimenter conducted the stimuli using a soft brush. While viewing visual stimulation on a computer screen, the participants received concomitant tactile stimulation on the left palm and rate the pleasantness of tactile stimulation using a mouse.

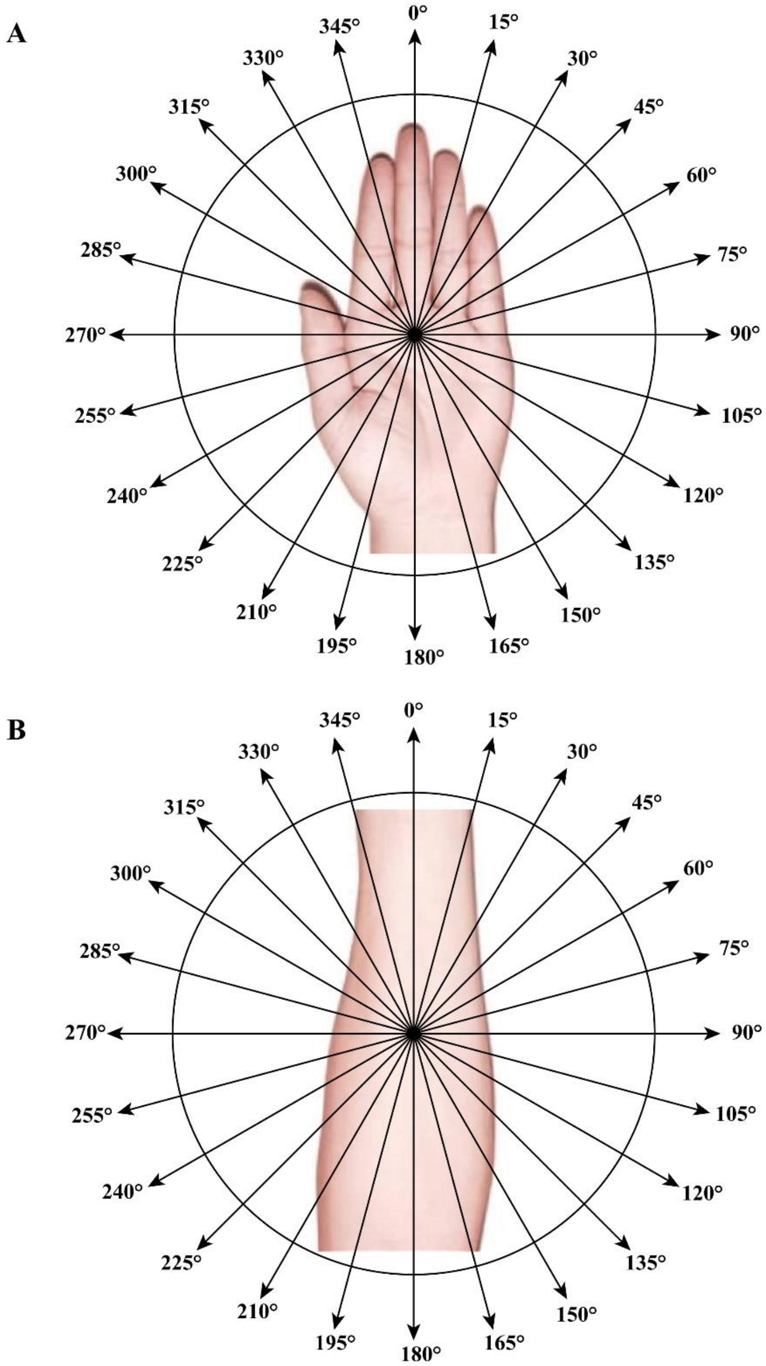

Figure 4.2. All visual stimuli with different orientations of the palm (A) and forearm (B). Each visual stimulation with different viewpoint was presented on a computer monitor by rotating the camera at 15 degrees

Statistical analysis. All the data were analyzed using the rank-order method. After receiving the ratings of 5 participants, the average score of each visual stimulation was calculated in terms of naturalness. 24 visual stimuli of the palm and 24 visual stimuli of the forearm were ranked from most natural to least natural, respectively. Since the top visual stimulus based on the average scores was the front view of palm/forearm, it was selected as the natural visual stimulus. We found the visual stimulus with the mid scores was the side view of palm/forearm, so it was selected as the neutral visual stimulus. Similarly, we tried to select the back view of palm/forearm as an unnatural visual stimulus. We looked at the ranking of the scores and found that the back view of palm/forearm were low on the naturalness ratings, so we thought it would be appropriate to select the back view as an unnatural visual stimulus (**Figure 4.3**).

4.2.2 Experiment 2 (Visuo-Tactile Stroking)

To determine how the visual context with different sizes at different viewpoint affects pleasantness ratings of affective touch on human skin, we conducted the second experiment. Here, the viewpoints were selected using the seven-point scale, as described in Experiment 1.

Participants. Fifteen participants (male 13; average age 25 years ± 3.4 SD) were recruited from Okayama University, and ten of the participants took part in Experiment 1. The study was approved by the ethics committee of the University of Okayama. All the participants were right-handed and given basic information about the experiment. Written informed consent was obtained from all participants prior to their participation.

Experimental setting and procedure. The experiment was carried out in a well-ventilated and quiet room with constant artificial lighting. The tactile stimuli were provided using a 50 mm wide flat, soft water color brush made of smooth, synthetic fibre hair (type 4905533116722, Handy Crown Corporation, Japan). The bristles were wrapped in an aluminum casing to ensure that the bristles were 20 mm long. The participants were seated in a comfortable chair in front of a computer monitor, and a divider was used to shield the participants from seeing the tactile stimulation and the experimenter. The brush strokes were administered by a well-trained experimenter on the left palm (in the center, equidistant from the bottom of the third finger and the wrist) or left forearm (on the volar side, equidistant from the wrist and elbow) [63] in a proximal-to-distal direction at a velocity of approximately 3 cm/s (CT-optimal gentle stroking touch velocity) [31]. The participants' fingers were affixed with medical tape to avoid being touched by the brush during the palm stimulation. In addition, the corresponding stimulus positions were covered with a plastic film with a window of 30 mm × 80 mm to maintain a constant area of stimulation at both skin sites.

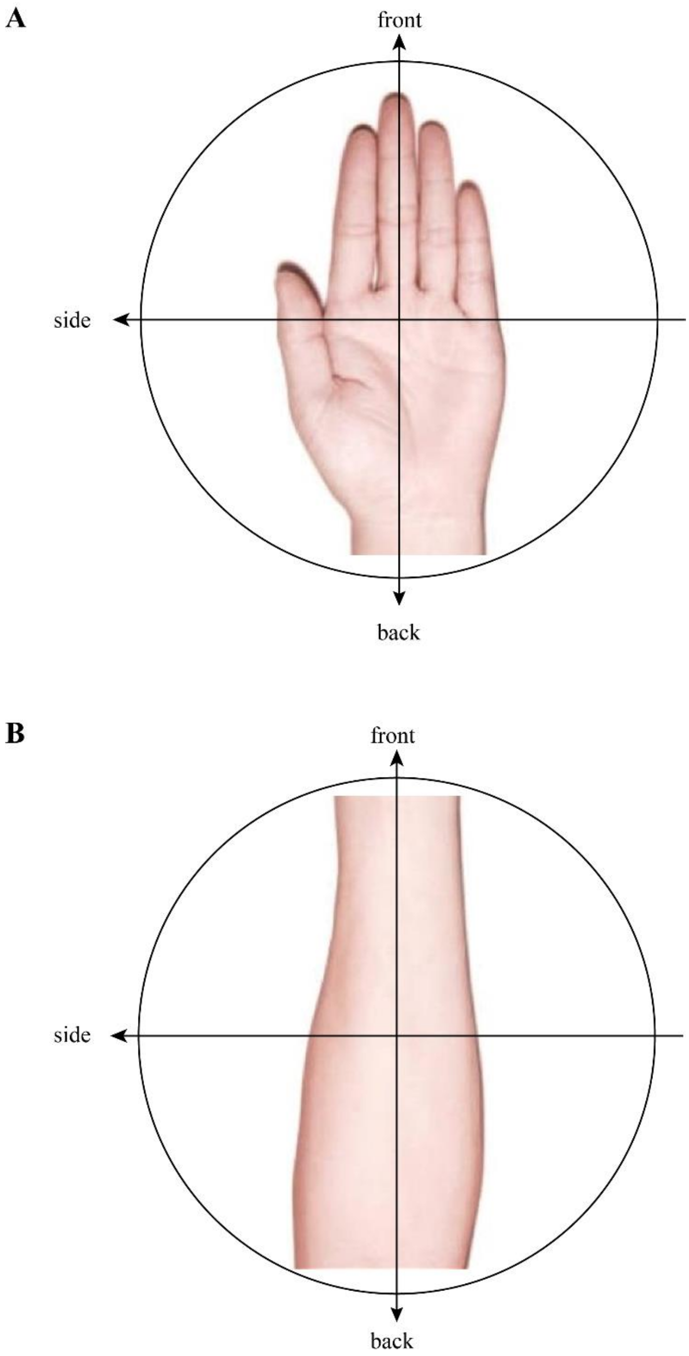

Figure 4.3. Visual stimuli with three different directions of the palm (A) and forearm (B). The palm and forearm are presented in the display in three different directions (front, side, back) so that subjects in experiment 2 can view visual stimuli from three different viewpoints (front view, side view, back view).

The visual stimuli can be divided into front view, side view and back according to viewpoint. The visual stimuli from each viewpoint were also presented on the computer monitor in three sizes (small size, standard size, large size) by adjusting the high-speed camera. The standard size refers to the same size as the palm/forearm of participants, and the small size and the large size refer to 0.56 times and 1.56 times of the original size, respectively (**Figure 4.4**). Therefore, a total of 9 visual stimuli (3 visual size × 3 viewpoint) were presented on the monitor to participants. Each visual stimulus was presented ten times and combined with soft brush stroking to form stimulus pairs. All participants took part in two sessions (palm, forearm), and each session took about one hour. We used a fully counterbalanced order to present tactile stimulation on the palm or forearm. Following each stimulus, a visual analogue scale (VAS) presented using e-Prime software ranging from -10 (unpleasant) to a neutral (0) midpoint to 10 (pleasant) was presented until the participant rated the pleasantness of the brushing experience using a mouse (**Fig. 4.1**). Therefore, a 2 × 3 × 3 factorial experiment was designed, with the factors being 2 skin sites (palm, forearm), 3 visual sizes (small size, standard size, large size), and 3 viewpoints (front view, side view, back view). In addition, simple tactile stimulation on the palm and forearm as a control group was also experienced by each participant, and it took a total of 25 minutes.

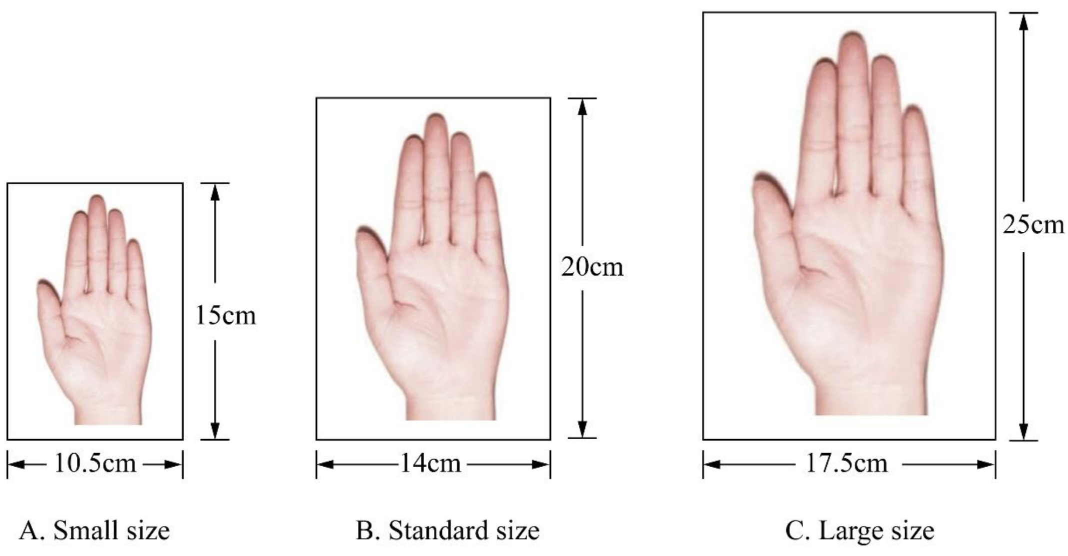

Figure 4.4 Visual stimuli with three different sizes (palm stimulation). The white mat with an area of 14 cm*20 cm under the hand was used as a reference to adjust the camera, thereby achieving enlargement and reduction of the palm. The palm will be presented in the display in three sizes, where the standard size is the original size of the palm while the small and large sizes are 0.56 and 1.56 times the original size of the palm, respectively.

Statistical analysis. All the statistical data were analyzed using SPSS (SPSS Statistics, Version 17; IBM, Armonk, NY). Significance was obtained at the $p < 0.05$ level, with up to three significant figures. The raw average scores for pleasantness ratings on the palm and forearm were shown in **Figure 5.1A-B**. The mean tactile pleasantness data were analyzed using a repeated-measures analysis of variance (ANOVA) with 3 within-subject factors: site (arm and forearm), visual size (small size, standard size, large size), and viewpoint (front view, side view, back view). Descriptive statistics were analyzed, and a full factorial model was used to explore the factors and the factor interactions. If the assumption of sphericity was violated in the Mauchly's sphericity test, the Greenhouse-Geisser (G-G) correction coefficient epsilon was used to correct the degrees of freedom, and P-values were then recalculated. Further, the main effects of each factor were compared, and post hoc tests were conducted to contrast the different levels of the factors by using Bonferroni-corrected pairwise comparisons of the estimated marginal means, controlling for multiple comparisons. Simple-simple main effects were further conducted to reveal whether there were significant differences between stimulation sites (palm/forearm) for pleasantness ratings under a combination of the factors visual size and viewpoint.

4.3 Results

The tactile pleasantness data were analyzed using repeated measures ANOVA to reveal significant differences in the pleasantness ratings for different skin sites, stroking forces and stroking hardness. Main effects of viewpoint ($F_{1.03,14.44}$ = 8.706, p = 0.01) were found, but there were no significant main effects of skin sites and visual sizes. Bonferroni post hoc tests showed that tactile stimuli accompanied by viewing visual stimulation from front view were rated as more significantly pleasant than from side view (p = 0.043) and back view (p = 0.022), but there was no significant difference between side view and back view. All possible two-way interactions and the three-way interactions were not significant.

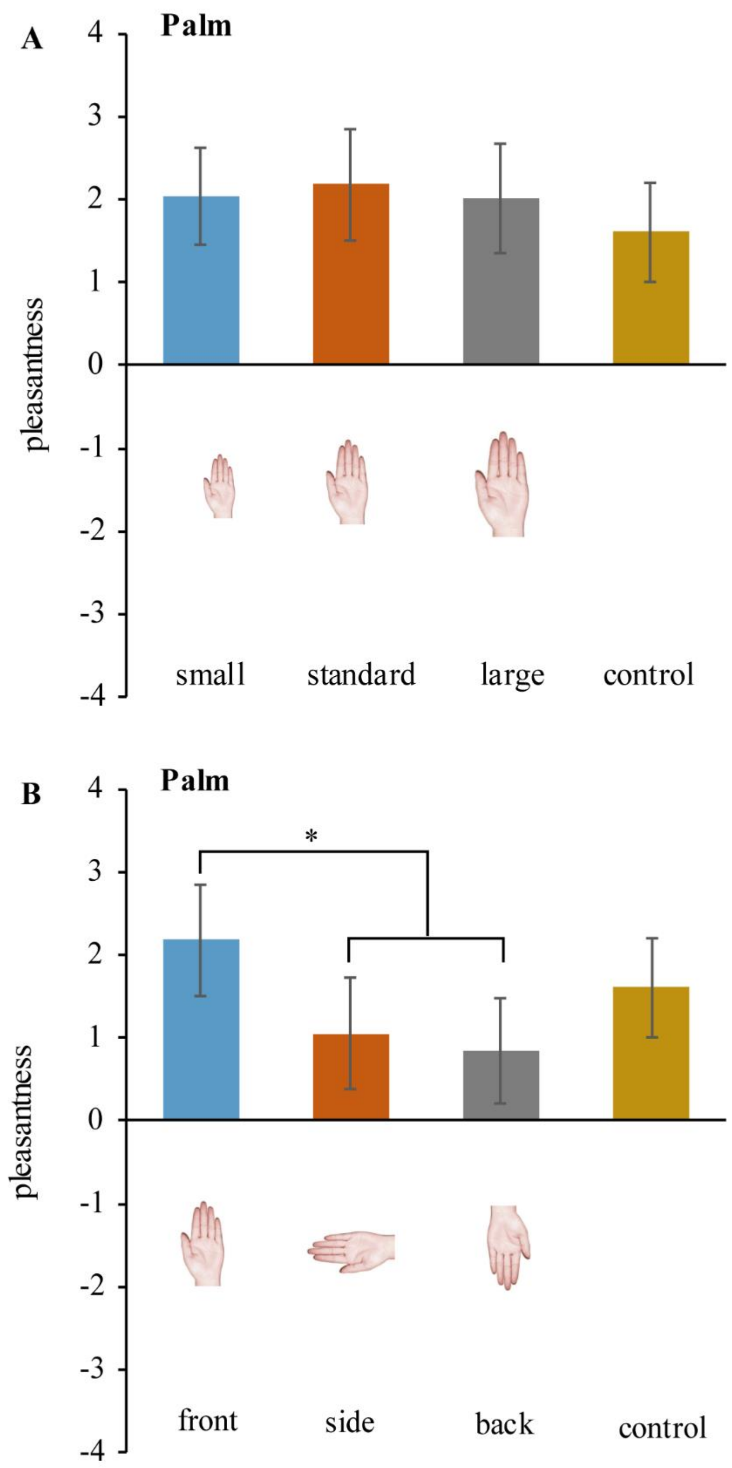

Figure 4.5. Pleasantness ratings on the palm at different visual sizes (A) and different viewpoints (B). There was no significant difference among visual sizes in terms of tactile pleasantness for the palm and the perception of tactile pleasantness accompanied by viewing visual stimuli of different sizes did not differ from the control group (only tactile stimuli) **(A)**. Although the perception of tactile pleasantness accompanied by viewing visual stimuli of

different viewpoints (directions) did not differ from the control group (only tactile stimuli), the perception of tactile pleasantness accompanied by viewing visual stimuli from the front view was rated as more pleasant compared to viewing visual stimuli from the side view or back view **(B)**. Error bars correspond to ±SEM.

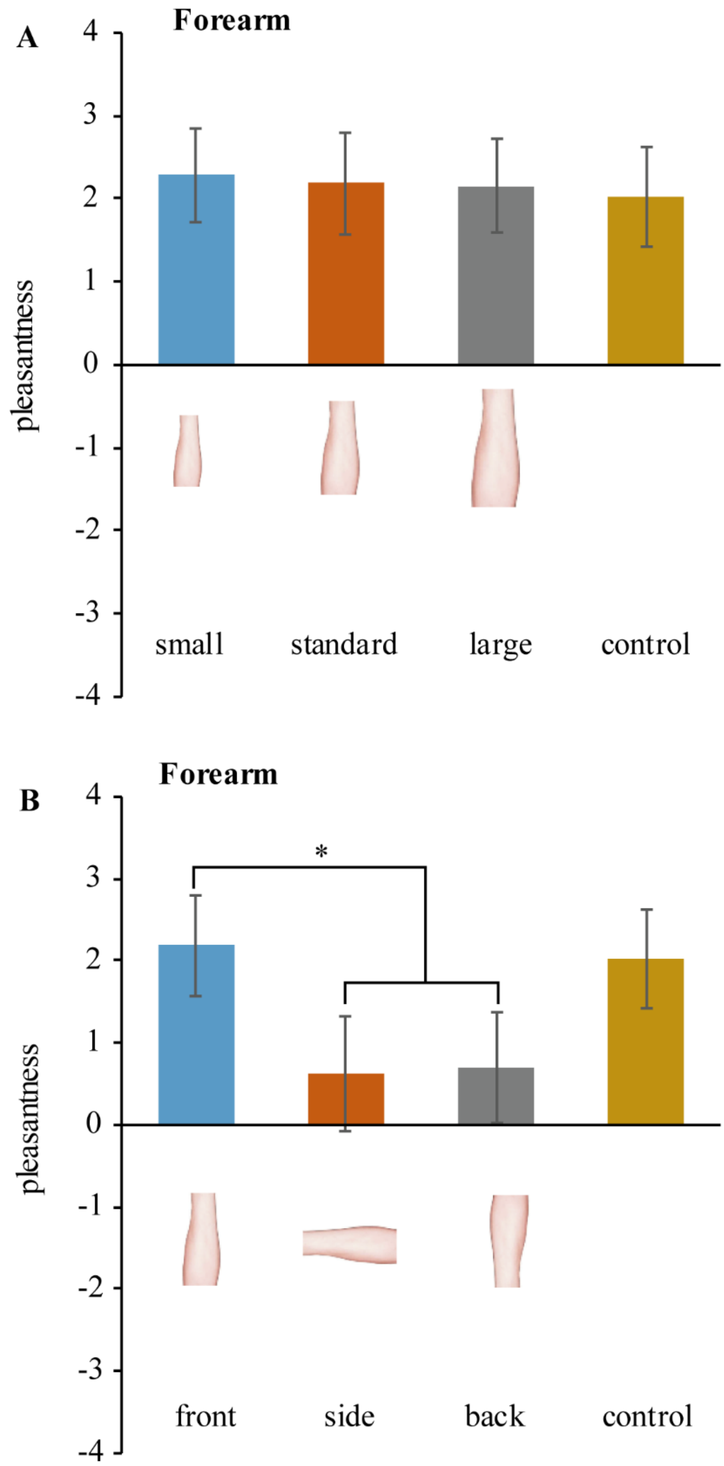

Figure 4.6. Pleasantness ratings on the forearm at different visual sizes (A) and different viewpoints (B). There was no significant difference among visual sizes in terms of tactile pleasantness for the forearm and the perception of tactile pleasantness accompanied by viewing visual stimuli of different sizes did not differ from the control group (only tactile stimuli) **(A)**. Although the perception of tactile pleasantness accompanied by viewing visual stimuli of different viewpoints (directions) did not differ from the control group (only tactile stimuli), the perception of tactile pleasantness accompanied by viewing visual stimuli from the front view was rated as more pleasant compared to viewing visual stimuli from the side view or back view **(B)**. Error bars correspond to ±SEM.

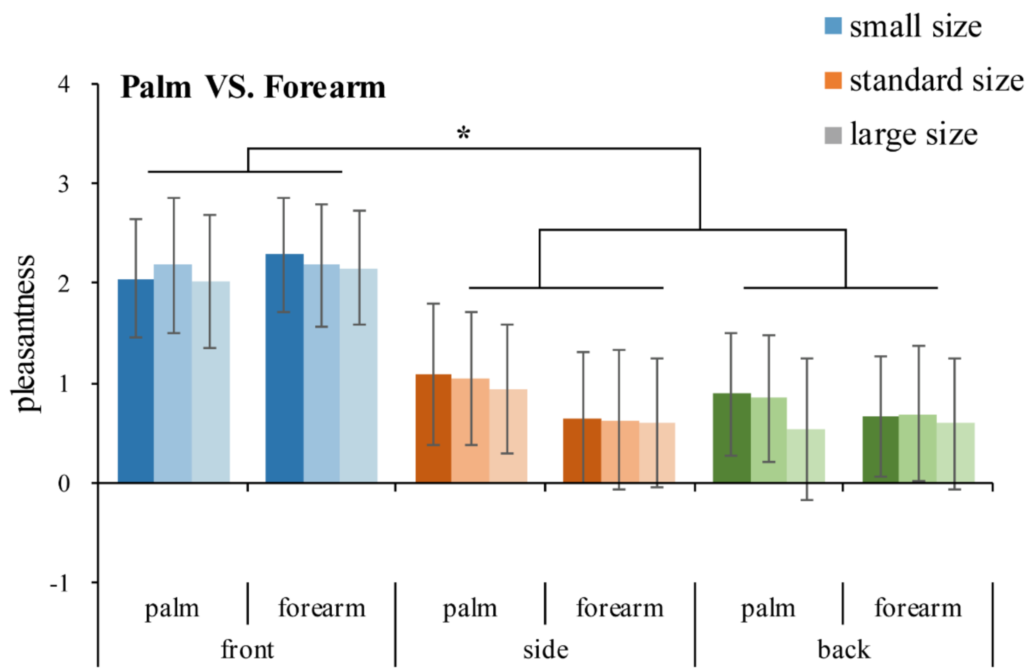

Figure 4.7. Pleasantness ratings on the palm/forearm at different viewpoints with different visual sizes. The perception of tactile pleasantness accompanied by viewing visual stimuli from the front view was rated as more pleasant compared to viewing visual stimuli from the side view or back view. Error bars correspond to ±SEM.

4.4 Discussion

In this study, we investigated the hedonic aspects of tactile perception in different visual sizes and viewpoints of observation via brush stroking across skin sites. our results showed that viewpoint of observation affects the perception of affective touch and tactile stimuli accompanied by viewing visual stimulation from front view were rated as more significantly pleasant than from side view. However, there were no effects of visual size on pleasantness ratings of affective touch.

Previous studies have shown that visual information has an effect on relative activation differences elicited by varying tactile texture characteristics in early somatosensory cortex. Crossmodal influences on somatosensory cortex were already reported by Meehan and Staines (2009) [111] and Dionne et al. (2010) [112], using vibrotactile stimulation. Both studies found variations of somatosensory elicited BOLD responses in postcentral gyrus with visual information. The present finding, in conjunction with the previous findings, supports the hypothesis that visual information of viewpoint also affects the hedonic aspects of touch. In addition, previous studies have shown that affective touch may involve the construction and maintenance of body ownership [102-105] and temporal and spatial congruence between felt and seen sensory events gives rise to feelings of body ownership. Since we always are exposed to people of different ages and different body size, the visual size is more difficult to cause feelings of body ownership than the viewpoint. In contrast to visual size, observation of front view is more difficult to give rise to feelings of body ownership than side view and back view. When participants think that the touched hand or forearm is their own, they will be more likely to imagine themselves in the touch of social interaction, which is more likely to generate social feelings.

Previous studies have suggested that crossmodal attention highlight the substantial influence of spatial attention upon both unimodal and multimodal brain areas [113]. Further evidence for crossmodal influences on unimodal brain areas in the context of spatial attention comes from a recent event-related fMRI study [114]. Therefore, another possibility is that visual attention interferes with pleasantness ratings of affective touch. The current results also showed that the perception of affective touch on both palm and forearm accompanied by viewing visual stimulation of side view and back view were rated as less pleasant compared to the control group. It may be because the visual stimuli of the side view and the back view give a strange or strange feeling, which attracts the attention of the participants.

These findings of the current study extend the growing literature related to the effect of visual context on pleasantness ratings and show that the perception of affective touch is influenced by the viewpoint of visual stimuli and is independent of the visual size. Based on the results of previous studies, we believe that the visual context affecting the perception of tactile pleasantness in this study involve feelings of body ownership and spatial attention. However, the experiment was conducted as a behavioral one, making it difficult to fully attribute the influence of visual context on tactile perception to body ownership and spatial attention. Therefore, future research further studies are needed to specifically design an experiment of tactile pleasantness perception under visual spatial attention disturbance, and directly observe the activation of brain cortex in this process by fMRI approaches.

5. The Perception of Affective Touch Dependent on the Visual Context Effect: No Difference between Skin Sites

Summary

Facial expressions alter the perception of affective touch. However, the effects of visual contexts beyond facial expressions on tactile pleasantness ratings are not clear. Moreover, the influence of visual contexts on the perception of tactile pleasantness at different skin sites has not been established. We investigated the effects of visual contexts (facial expressions, scenes) with different visual types (unpleasant, neutral, pleasant) on gentle touch pleasantness across different skin sites. Ten naïve, healthy participants participated in Experiment 1 to select 60 facial expression images (20 unpleasant, 20 neutral, 20 pleasant images) and 60 scene images (20 unpleasant, 20 neutral, 20 pleasant images) using a seven-point scale. In Experiment 2, fifteen healthy participants rated tactile pleasantness on a visual analogue scale (VAS) when they were stroked with a soft brush with three stroking forces (1N, 17N, 3N) on the palm or forearm accompanied by viewing facial expression or scene images. Tactile stimuli were rated as significantly more pleasant when accompanied by viewing a pleasant facial expression (or scene) and least pleasant when accompanied by an unpleasant image. The current study replicated and extended the findings regarding the influences of visual context on the perception of gentle touch and highlights the same effects of visual context on the tactile pleasantness ratings from the glabrous skin of the palm and the hairy skin of the forearm. Furthermore, this study also revealed that, compared to the scene visual context, the visual context of facial expressions with a social component increased the differences between the effects of the three stroking forces on the perception of gentle touch.

Keywords: affective touch, visual context, facial expression, scene, pleasantness ratings, stroking force

5.1 Background

Touch plays a vital role in social communication and physiological development and creates an emotional bond for interpersonal interactions. Although interpersonal touch communicates distinct emotions [16], it is mainly considered to convey positive emotional messages, such as pleasantness, encouragement and consolation [115]. The earliest emotional interaction occurs when parents provide caressing touch to their infants [13], and the importance of this caressing touch has been firmly supported in several studies of infant psychological development [116-118]. Social touch exists in our lives in a variety of forms, ranging from a daily hug to a sensual caress. The most likely reason for the great contribution of touch to interpersonal communication is that touch can be pleasant [10]. Moreover, the appraisal of perceived touch is not only related to the physical factors of the tactile stimuli, such as temperature [67], softness [64], force and velocity [31], but also to intrinsic factors such as oxytocin [93], mechanisms and multisensory context [119].

The majority of previous behavioral studies of gentle touch have focused purely on how the visual contexts alter the perception of gentle touch [93, 120], but it is still unclear how visual contexts affect the perception of gentle touch of different types of skin, such as the skin on the palm (glabrous skin) and the skin on the forearm (hairy skin). It is widely accepted that happy expressions can increase the pleasantness of gentle touch, while unhappy expressions can reduce the pleasantness of gentle touch. For instance, a pat on the shoulder by a familiar person with a smiling face, which is often interpreted as consolation, is pleasant touch; conversely, being patted by a stronger person with a strict face will make an individual uncomfortable and uneasy. Recent studies have suggested that unmyelinated, small-diameter, lower-threshold mechanoreceptive C-tactile (CT) afferents, which are exclusively found in hairy skin, are closely related to gentle touch [31, 35, 121]. The asymmetric presence of CT afferents in the skin leads to many different physiological responses to the perception of gentle touch from glabrous skin and hairy skin. The most notable behavioral difference is that the glabrous skin of the palm shows a flatter, inverted U shape in the velocity-pleasantness profile compared to hairy skin (e.g., arm, thigh, and forehead) [122]. Although CT afferents are not present in the glabrous skin of the palm, the palm also experiences the hedonic value of gentle touch and even promotes social interactions, such as handshakes. There are many explanations for the above contradiction; the most common of which is the top-down mechanism. Previous psychophysical and neurophysiological studies have shown that experiences of affective touch (e.g., gentle touch) are shaped not only by bottom-up neural pathways but also by top-down mechanisms related to integrating contextual information from multisensory and prior experiences [98, 119, 123]. Therefore, it is interesting to further investigate whether the differences between glabrous and hairy skin are also reflected in the influence of context on gentle touch appraisal.

It has been demonstrated that facial expressions can alter the perception of gentle touch. The pleasant appraisal of gentle touch was lowest in the context of a negative concomitant expression, such as an angry face, and highest when associated with a happy face, even though the participants were well aware that the one performing the gentle stroking touch was not the same person exhibiting the facial expression [93]. Thus far, the most common interpretation of the abovementioned findings is that a pleasant appraisal of gentle touch depends not only on ascending neural signaling but also on top-down factors related to previous experiences, context and expectations [97, 99, 119]. Although many studies have recently emerged to investigate how the visual context of facial expression influences gentle touch experiences, visual context is not only limited to facial expressions but also includes external environments such as scenes. However, it remains unclear how other visual contexts, such as scenes, influence the perception of gentle touch and whether the influence differs from that of facial expressions in terms of gentle touch experience. Previous functional magnetic resonance imaging (fMRI) studies have shown that CT-targeted gentle touch on the forearm elicited a strong activation in the insular cortex compared to the reaction associated with gentle touch on the palm and a significant activation of the somatosensory cortices based on the opposite contrast (touch on palm minus forearm) of the fMRI [57, 124]. Facial expressions and the surrounding scene are both presented in visual forms and can be divided into three types (positive, neutral and positive) according to the hedonic value, but unlike scenes, facial expressions are included in the visual components of social interaction. In daily life, the friendliness of an individual can be captured and felt by observing their facial expression. Considering the abovementioned concepts, it is socially meaningful to explore how external factors shape the hedonic value of touch.

Here, we investigated how visual types (unpleasant, neutral, pleasant) of visual contexts affect tactile pleasantness ratings by stroking a soft brush on two different skin sites with three stroking forces. On the basis of the literature related to the effects of context on the perception of gentle touch [125-127], we hypothesized that tactile stimuli would be rated as significantly more pleasant when accompanied by viewing a pleasant facial expression (or scene) and least pleasant when accompanied by an unpleasant image. The facial expressions have more of a social component than scenes; thus, we expected to observe that, compared to scene visual context, the visual context of facial expressions increased the differences between the effects of the three stroking forces on the perception of gentle touch. Finally, we also predicted that the visual contexts may have the same effects on the perception of the hedonic aspect of tactile stimulation on the hairy skin of the arm and on the glabrous skin of the palm according to the brain mechanisms underpinning the top–down modulation of touch [119].

5.2 Materials and methods

5.2.1 Experiment 1 (Selection of Visual Stimuli)

Experiment 1 was designed to select the visual stimuli to be used in the gentle touch experiment (experiment 2).

Participants. In total, 10 participants (male 7; average age 25.8 ± 3.1 years SD) participated in the study. The study was approved by the ethics committee of the University of Okayama. All the participants were right-handed and given basic information about the experiment. Written informed consent to participate in the study prior to their participation.

Experimental setting and procedure. After receiving a written explanation of the experiment that included a description of the experimental content and special instructions on how to rate visual stimuli, the participants were instructed to sit comfortably in a chair approximately 40 cm in front of a 23.8-in. computer screen (Acer SA240YAbmi, 75HZ, 1920 × 1080 Pixels). Each participant was tested individually in a quiet room and not allowed to talk to anyone during the breaks. The JAFFE database collection of 213 grayscale images (256 × 256 pixels) of 10 Japanese females was used for the visual stimuli (facial expression), and seven facial expressions were included in the facial database: anger, disgust, fear, happiness, neutral, sadness and surprise [128]. Each expression image was presented on a computer monitor at a size of 10 cm × 10 cm. In addition, 427 color scene images (358 × 256 pixels) were captured from the web to be used as visual stimuli (scenes), which described the following scenes: polluted air, polluted land, polluted ocean, a garbage dump, rotten food, a disgusting bug, a verdant mountain, a clear river, a beautiful seaside and a clear sky. These scene images were presented on a computer monitor at a size of 11 cm × 10 cm. To reduce the visual fatigue of the participants, 12 mosaic-processed images (358 × 256 pixels) and a blank photo (358 × 256 pixels) were added to the image library to select the appropriate visual stimuli to be used in experiment 2. Therefore, a total of 653 pictures were presented to the participants in a random order on the computer monitor to perform the ratings.

The participants were instructed to look at each image and then evaluate its pleasantness using a seven-point scale (ranging from 1 = very unpleasant over a neutral 4 to 7 = very pleasant). The rating scale was directly displayed below each image so that the participants could easily perform the ratings. The rating task was self-paced for each scale without enforcing a time-limit and lasted for approximately 25 minutes. All visual stimuli and rating scales were presented using e-Prime 2.0 (Psychology Software Tools, Inc.).

Statistical analysis. All the data were analyzed using the rank-order method. After receiving the ratings of 10 participants, the average score of each image was calculated in terms of pleasantness. 213 facial expression images and 427 scene images were ranked from most pleasant to least pleasant, respectively. The top 20 facial expression images based on the average scores were selected as the pleasant visual stimuli (facial expression) from the sorted images, and the 20 facial expression images with the lowest scores were selected as the unpleasant visual stimuli (facial expression). Furthermore, the 20 images with a score close to the midrange (dividing the sum of the highest and lowest scores by two) were selected as the neutral visual stimuli (facial expression).

Similarly, 20 unpleasant scene images, 20 neutral scene images and 20 pleasant scene images were selected as visual stimuli (scene) in the same way.

5.2.2 Experiment 2 (Visuo-Tactile Stroking)

To determine how the visual context affects pleasantness ratings of different levels of stroking force at various skin sites, we conducted the second experiment. Here, the visual stimuli were selected using the seven-point scale, as described in Experiment 1.

Participants. Fifteen participants (male 10; average age 26.4 ± 3.2 years SD) were recruited from Okayama University, and ten of the participants took part in Experiment 1. The study was approved by the ethics committee of the University of Okayama. All the participants were right-handed and given basic information about the experiment. Written informed consent was obtained from all participants prior to their participation.

Experimental setting and procedure. The experiment was carried out in a well-ventilated and quiet room with constant artificial lighting. The room temperature was adjusted to a comfort temperature 23 °C by the air conditioner [67].

The tactile stimuli were provided using a 50 mm wide flat, soft water color brush made of smooth, synthetic fibre hair (type 4905533116722, Handy Crown Corporation, Japan). The bristles were wrapped in an aluminum casing to ensure that the bristles were 20 mm long. The participants were seated in a comfortable chair in front of a computer monitor, and a divider was used to shield the participants from seeing the tactile stimulation and the experimenter. The brush stokes were administered by a well-trained experimenter on the left palm (in the center, equidistant from the bottom of the third finger and the wrist) or left forearm (on the volar side, equidistant from the wrist and elbow) [63] in a proximal-to-distal direction at a velocity of approximately 3 cm/s (CT-optimal gentle stroking touch velocity) [31]. The participants' fingers were affixed with medical tape to avoid being touched by the brush during the palm stimulation. In addition, the corresponding stimulus positions were covered with a plastic film with a window of 30 mm × 80 mm to maintain a constant area of stimulation at both skin sites. The participants' hand (forearm) was fixed on a high-precision, digital scale during the experiment to prevent the movement of the hand (forearm) from causing fluctuations in the display on the digital scale. Three desired stroking forces (1N, 1.7N, 3N) were achieved by the downward force of the brush application. The experimenter controlled the force by observing the display on the digital scale (**Fig. 4.1**). The experimenter controlled the error to remain below 0.15 N to the greatest extent possible. Hence, the tactile stimuli were divided into three types according to the forces.

The visual stimuli consisted of 60 facial expression images (20 unpleasant, 20 neutral, 20 pleasant images) and 60 scene images (20 unpleasant, 20 neutral, 20 pleasant images), which were selected in Experiment 1. Each image was presented three times and combined with three stroking forces of tactile stimulations to form stimulus pairs. All participants took part in two sessions (palm, forearm), and there were three blocks (facial expressions, scenes, nonvisual stimuli) in each session. In total, each individual underwent 4 blocks of visuo-tactile stimulation and 2 blocks of simple tactile stimulation (control group) on separate days in a random order. While viewing images displaying unpleasant, neutral, or pleasant facial expressions (or scenes) on a computer screen, participants received concomitant gentle brush strokes on the left palm (or left forearm) during the visuo-tactile stimulation. In contrast, participants only underwent gentle brush strokes on the left palm (or left forearm) during the simple tactile stimulation. Each block consisted of 120 visuo-tactile stimulus pairs (or tactile stimuli) and lasted approximately 40 minutes. Before each stimulus, participants viewed a fixation cross for 3 s. A cue tone appeared at the beginning of the stimulation to help the experimenter perform the gentle brush strokes. Each visuo-tactile stimulus pair (or tactile stimulus) was presented for 3 s. Following each stimulus, a visual analogue scale (VAS) ranging from -10 (unpleasant) to a neutral (0) midpoint to 10 (pleasant) was presented until the participant rated the pleasantness of the brushing experience using a keyboard (**Fig. 2**). All the visual stimuli and rating scales were presented using e-Prime software. Therefore, a 2 × 3 × 3 factorial experiment was designed, with the factors being 2 skin sites (palm, forearm), 3 stroking forces (1N, 1.7N, 3N), and 3 visual types (unpleasant, neutral, pleasant) based on the visual modalities of the facial expressions and scenes.

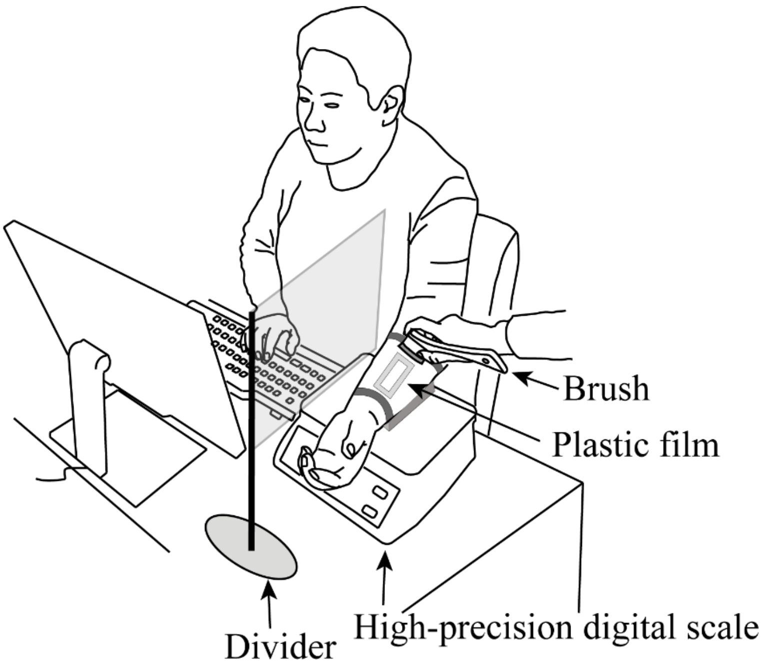

Figure 5.1. Illustration of the experimental procedure (forearm stimulation). The participant's forearm was fixed on the high-precision digital scale and a divider was used to shield the participants from seeing the tactile stimulation and the experimenter. The plastic film with a window (30mm × 80 mm) was attached to the corresponding stimulation area so that the skin area exposed to brush stimulation keep constant. The experimenter conducted the stimuli using a soft brush, and exerted three downward desired forces to the brush by observing the display of the high-precision digital scale. While viewing visual stimulation on a computer

screen, the participants received concomitant tactile stimulation on the left forearm and rate the pleasantness of tactile stimulation using a keyboard.

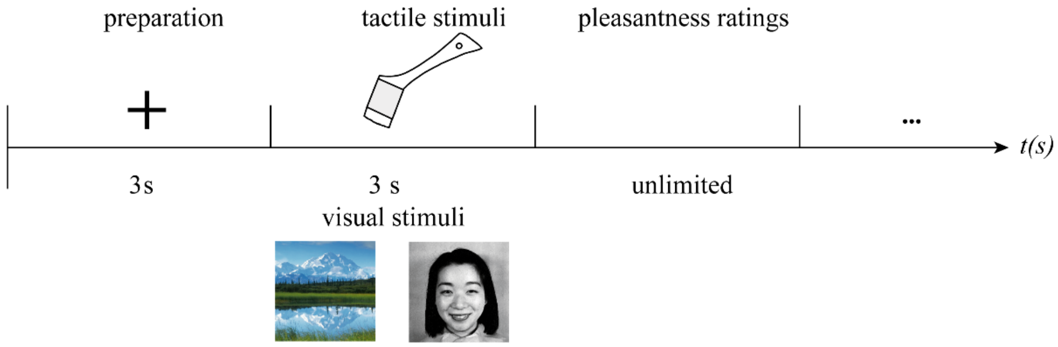

Figure 5.2. Flowchart of experimental trial procedure. At the start of each trial, participants viewed a block fixation cross on a white background displayed for 3 s. Participants were instructed to prepare for visuo-tactile stimuli during this time. At the very onset of a participant's inspiration, participants received gentle brush strokes on the left palm (or left forearm) while viewing concomitant images of unpleasant, neutral, or pleasant facial expressions (or scenes) displayed for 3 s on a computer screen. After the visuo-tactile stimulation, a visual-analogue scale prompted participants to rate the pleasantness of the tactile stimulation (unpleasant – pleasant) for an unlimited time. Once participants had completed these ratings, the next trial began.

Statistical analysis. All statistical data were presented as means ± standard error of the mean (±SEM) and analyzed using SPSS (SPSS Statistics, Version 17; IBM, Armonk, NY). Significance was set at the $p < 0.05$ level, with up to three significant figures. The mean pleasantness scores from the visual modalities of facial expressions and scenes were entered into separate ANOVA analyses to split the data into groups of facial expression and scene factors. Hence, the mean tactile pleasantness data were submitted to a 2 × 3 × 3 repeated-measures ANOVA with 3 within-subject factors: skin site (palm, forearm), stroking force (1N, 1.7N, 3N) and visual type (unpleasant, neutral, pleasant) based on the visual modalities of facial expressions and scenes. The descriptive statistics were analyzed, and a full factorial model was used to explore the factors and the factor interactions. If the sphericity was violated according to Mauchly's sphericity test, the Greenhouse-Geisser (G-G) correction was used to correct the degrees of freedom, and P-values were then recalculated. Then, post hoc tests were performed with paired-samples t-tests with a Bonferroni correction. Furthermore, a 2 × 2 × 3 repeated measures ANOVA with the within-subject factors of skin site (palm, forearm), context modality (facial expression, scene) and visual type (unpleasant, neutral, pleasant) on the difference-scores (visual context – control) of gentle touch revealed significant main effects and interaction effects, and Bonferroni correction was used for low-level multiple comparisons. Moreover, separate paired-sample t-tests were conducted at each visual type in context of facial expressions and scenes to assess whether the difference-scores statistically differed between the palm and forearm.

5.3 Results

The tactile pleasantness data were analyzed by conducting a repeated measures ANOVA to reveal significant differences in the perception of gentle touch for the different skin sites, stroking forces, and visual types with the different visual modalities. For the context modality of facial expressions (**Fig. 4.3A, C**), there were significant main effects of stroking forces ($F_{1.063, 14.876} = 5.917$, $p = 0.027$) and visual types ($F_{1.093, 15.302} = 14.517$, $p = 0.001$) on tactile pleasantness ratings, showing that tactile pleasantness was rated as more pleasant when accompanied by viewing a pleasant (mean ± SEM = 3.286 ± 0.564) facial expression compared to viewing a neutral (3.082 ± 0.530) or unpleasant (2.501 ± 0.556) facial expression. No significant main effect of skin site (palm, forearm) was found ($F_{1, 14} = 0.283$, $p = 0.603$), suggesting similar tactile pleasantness ratings for both skin sites. Bonferroni post hoc tests showed that brush strokes with a force of 1N (3.325 ± 0.567) were rated as significantly more pleasant than brush strokes with a force of 1.7N (3.039 ± 0.544) or 3N (2.505 ± 0.566) in terms of tactile pleasantness ratings, but there was no significant difference between the pleasantness associated with the 1.7N and 3N brush strokes. There was significant interaction effect between visual types and stroking forces ($F_{2, 13} = 4.633$, $p = 0.030$). The remaining possible two-way interactions (visual type × stroking force, stroking force × skin site) and the three-way interactions (visual type × skin site × stroking force) were not significant.

Similarly, for the context modality of scenes (**Fig. 4.3B, D**), a significant main effect of visual type ($F_{1.105, 15.469} = 13.849$, $p = 0.002$) confirmed that tactile pleasantness was rated as more significantly pleasant when accompanied by viewing a pleasant (mean ± SEM = 3.636 ± 0.509) scene image compared to viewing a neutral (2.737 ± 0.529) or unpleasant (2.552 ± 0.553) image. The main effects of skin sites and stroking forces on tactile pleasantness ratings were not significant (all $p > 0.05$, ns), which suggested that there was no significant difference in the perception of gentle touch for either skin site (palm, forearm) or any of the three stroking forces (1N, 1.7N, 3N). All possible two-way interactions and the three-way interactions were not significant.

Furthermore, a 2 × 2 × 3 repeated measures ANOVA with the within-subject factors of skin site (palm, forearm), context modality (facial expression, scene) and visual type (unpleasant, neutral, pleasant) on the difference-scores (visual context – control) of gentle touch was conducted. A significant main effect was only found for visual type ($F_{1.083, 15.160} = 0.001$). No significant main effect of skin site ($p = 0.879$) was found, indicating that the scores between the palm and forearm were not significantly different. Although a significant effect of context modality was also not found ($p = 0.908$), a two-way interaction effect between context modality and visual type was found ($F_{2, 13}$ = 7.220, p = 0.008). Hence, low-level multiple comparisons were deemed necessary to uncover the influences of different visual types on the difference-scores in the visual contexts of facial expressions and scenes. The context modality of facial expression showed that unpleasant facial expressions had a significantly negative impact on tactile pleasantness ratings compared to the impact of the neutral (p = 0.007) or pleasant (p = 0.005) facial expressions (**Fig. 4.4A**). In contrast, the context modality of scene demonstrated a significantly positive impact of pleasant scene images on tactile pleasantness ratings compared to the impact of unpleasant (p = 0.010) or neutral (p = 0.004) scene images (**Fig. 4.4B**). At last, the paired samples t-tests revealed that there were no significant differences between the difference-scores of the palm and forearm at each visual type in context of facial expressions and scenes.

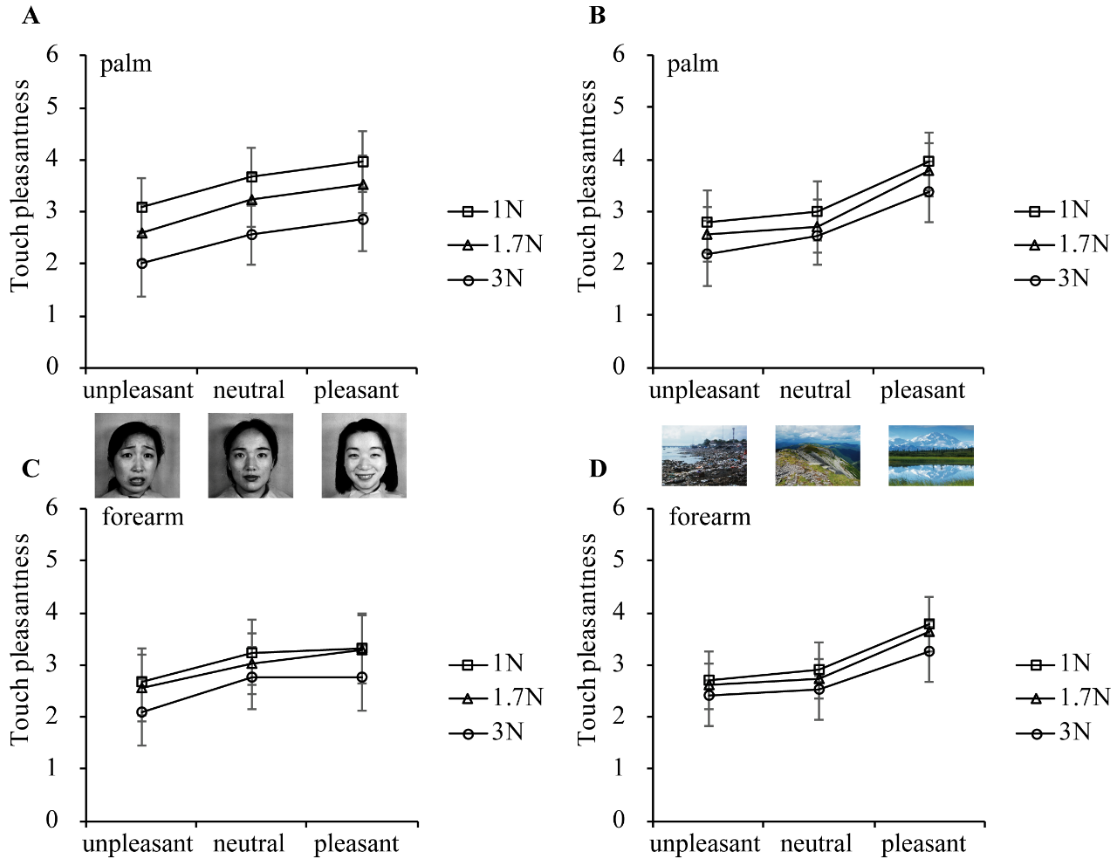

Figure 5.3. Mean pleasantness ratings with different stroking forces over skin sites accompanied by viewing visual stimuli. Tactile pleasantness ratings on the palm were altered by concomitant viewing of facial expression (A) or scene (B) images. Tactile pleasantness ratings on the forearm were also altered by concomitant viewing of facial expression (C) or scene (D) images. Tactile stimuli were most pleasant when accompanied by a pleasant face/scene compared to neutral or unpleasant images. In addition, compared to the visual context of scene, the visual context of facial expression increased the differences between the effects of the three stroking forces on the perception of gentle touch. Error bars correspond to ± SEM.

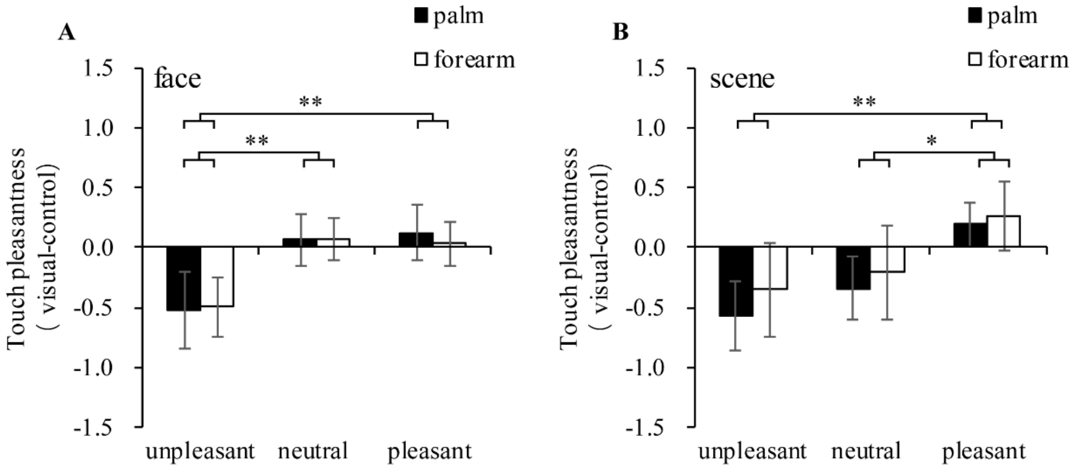

Figure 5.4. Mean difference-scores (visual context – control) based on the visual context. **(A)** In the context of facial expressions, unpleasant facial expressions had a significantly negative impact on tactile pleasantness ratings compared to the impacts of the neutral ($p = 0.007$) and pleasant ($p = 0.005$) facial expressions. **(B)** The effects of the pleasant scene images on tactile pleasantness ratings were significantly different from the effects of the neutral ($p = 0.010$) and unpleasant ($p = 0.004$) images. There were no significant differences between the difference-scores of the palm and forearm at each visual type in context of facial expressions and scenes. Error bars correspond to ± SEM. $^*p < 0.05$.

5.4 Discussion

In this study, we investigated the effect of visual contexts on tactile pleasantness ratings by stroking a soft brush on different skin sites with three stroking forces. The findings of the current study showed that the visual contexts of facial expressions and scenes altered tactile pleasantness ratings (**Fig. 3**). This result is in line with the hypothesis that tactile stimuli are rated as significantly more pleasant when accompanied by viewing a pleasant facial expression (or scene) and least pleasant when accompanied by an unpleasant image. Interestingly, the significant main effect of stroking forces (1N, 1.7N, 3N) was found on the perception of gentle touch in the visual context of facial expressions but not in the scene visual context. The majority of previous studies have shown that the perception of gentle touch varies across skin sites [31, 63]. However, no significant main effect of skin site on the difference-scores was found (**Fig. 4**), suggesting that the visual context, whether a facial expression or scene, had the same effects on the perception of tactile stimulations on the palm and forearm.

Previous studies have shown that the firing frequency of CT afferents preferentially responds to gentle touch with low indentation forces [19, 43]. This may be attributed to the fact that the low indentation forces can convey positive information from touchers, which contributes to affiliative behaviors and social interactions. Thus, it also indicated that stroking force plays an important role in people's social behaviors. Our results showed that the visual context of facial expression increased the differences between the effects of the three stroking forces on the perception of gentle touch compared to the visual context of scene. Ellingsen, Wessberg [93] showed that human touch was more strongly affected by the concomitant facial expression than machine touch, which indicated that both top-down and cross-model factors are involved in the perception of gentle touch. In addition, it has been reported that the identity of the toucher also alters tactile pleasantness ratings [129]. Facial expressions have more social components than scene images, so participants were more likely to associate facial expressions with the provider of tactile stimuli. By adding a social context to the factor of stroking forces, the influences of the three stroking forces on tactile pleasantness ratings were more significantly distinct.

Previous studies have shown that unmyelinated, small-diameter, lower-threshold mechanoreceptive afferents (C-LTMRs), also called CT afferents, transmit elaborate information into affective touch (e.g., gentle touch) [19, 30]. It is widely accepted that CT afferents that transmit pleasant tactile signals are not found in glabrous skin [37]. A microneurographical study [31] showed that the firing frequency of CT correlates well with pleasantness ratings over a range of stroking velocities but not with myelinated affects. These findings support the interpretation that CT afferents play a vital role in affective touch. In addition, the idea that CT afferents are exclusively presenting in hairy skin also leads to differences in tactile pleasantness ratings across different skin sites. However, an important finding of the current study is that the visual contexts had the same effects on tactile pleasantness ratings from glabrous and hairy skin. This demonstrates that the impact of visual context on the perception of gentle touch is more likely to rely on top-down processes. Ellingsen, Wessberg [93] found that touch experience on the left forearm was altered by viewing facial expressions. Specifically, tactile stimuli were most pleasant while viewing a concomitant happy face and least pleasant when accompanied by an angry face. Recently, an fMRI study [130] revealed that a subjectively disgusting olfactory environment could decrease posterior insular activity, which significantly reduced the tactile pleasantness ratings. Hence, these findings showed that the perception of gentle touch depends not only on all available sensory ascending input but also on top-down mechanisms to integrate contextual information from multisensory and prior experiences.

The current study replicates and extends findings of the influences of the visual context on the perception of gentle touch and highlights the same effects of visual contexts on the tactile pleasantness ratings from the glabrous skin of the palm and the hairy skin of the forearm. In line with previous findings, the results of this study suggest that top-down and cross-model factors are involved in the perception of gentle touch. Future experiments using fMRI approaches aimed to directly record cerebral cortex activation to investigate the perception of gentle touch on glabrous and hairy skin with different visual contexts are needed.

6. Conclusion and Future Challenges

6.1 Conclusion of the Dissertation

In the present dissertation, we implemented four psychological experiments to highlight the important role of intrinsic factors, physical characteristics, and contextual information. First, we investigated how stroking area affects the perception of affective touch between the glabrous skin of the palm and the hairy skin of the forearm. Second, we investigated how stroking hardness affects the perception of affective touch, which was given by using four different hardness of brushes at three different forces to either palm or forearm. Third, we investigated the effects of visual contexts (facial expressions, scenes) with different visual types (unpleasant, neutral, pleasant) on affective touch pleasantness across different skin sites. Fourth, we investigated whether visual stimulus size and viewpoint of observation affect the perception of affective touch across human skin. The findings are summarized below.

1) The skin is our largest sensory organ, which transmits temperature, pain, itching and tactile information to the central nervous system. These input channels can be further classified as providing spatial and temporal sensory functions, identifying and providing basic information for controlling and guiding exploratory tactile behavior, and emotional functions. We used two different hardness of brushes to stroke the glabrous skin of the palm and the hairy skin of the forearm. Meanwhile, a series of plastic films with different areas of windows exposed the skin to the moving brush and assured maintenance of a different spatial relationship between the brush and the body part. The current study demonstrated that stroking area have an effect on the perception of affective touch at certain different stroking areas and the stimulus is perceived to be more intense as the area of stimulation increases.

2) Previous studies have shown that sensory factors such as hardness, temperature, force and velocity, contribute to pleasantness ratings of affective touch. Here, we investigated how stroking hardness affects the perception of affective touch. Affective tactile stimulation was given with four different hardness of brushes at three different forces, which were presented to either palm or forearm. The current study suggested that pleasantness ratings over the skin resulted in a preference for light, soft stroking, which was rated as more pleasant when compared to heavy, hard stroking and show that the hairy skin of the forearm is more susceptible to stroking hardness than the glabrous of the palm in terms of the perception of pleasantness. These findings of the current study extend the growing literature related to the effect of stroking characteristics on pleasantness ratings.
3) Human touch is an essential factor in social interaction, and this factor is often accompanied by visual context to contribute to social interaction. It has been widely reported that visual context affects tactile discrimination. Although visuo-tactile integration related to emotional perception has received detailed investigation in recent years, little is known about whether the size of visual stimulus or viewpoint of observation affects the perception of tactile pleasantness. The present study aims to investigate the hedonic aspects of tactile perception in different visual sizes and viewpoints of observation via brush stroking across skin sites. The current results showed that viewpoint of observation affects the perception of affective touch and tactile stimuli accompanied by viewing visual stimulation from front view were rated as more significantly pleasant than from side view. However, there were no effects of visual size on pleasantness ratings of affective touch.
4) Social touch exists in our lives in a variety of forms, ranging from a daily hug to a sensual caress. The most likely reason for the great contribution of touch to

interpersonal communication is that touch can be pleasant. The majority of previous behavioral studies of gentle touch have focused purely on how the visual contexts alter the perception of gentle touch, but it is still unclear how visual contexts affect the perception of gentle touch of different types of skin, such as the skin on the palm (glabrous skin) and the skin on the forearm (hairy skin). In addition, although many studies have recently emerged to investigate how the visual context of facial expression influences gentle touch experiences, visual context is not only limited to facial expressions but also includes external environments such as scenes. However, it remains unclear how other visual contexts, such as scenes, influence the perception of gentle touch and whether the influence differs from that of facial expressions in terms of gentle touch experience. Here, we investigated how visual types (unpleasant, neutral, pleasant) of visual contexts affect tactile pleasantness ratings by stroking a soft brush on two different skin sites with three stroking forces. The current study replicates and extends findings of the influences of the visual context on the perception of gentle touch and highlights the same effects of visual contexts on the tactile pleasantness ratings from the glabrous skin of the palm and the hairy skin of the forearm. We also found that the visual context of facial expression increased the differences between the effects of the three stroking forces on the perception of gentle touch compared to the visual context of the scene.

6.2 Future Challenges

Touch plays a vital role in social communication and physiological development and creates an emotional bond for interpersonal interactions. Although interpersonal touch communicates distinct emotions, it is mainly considered to convey positive emotional messages, such as pleasantness, encouragement and consolation. The appraisal of perceived touch is not only related to the physical factors of the tactile stimuli, such as temperature, softness, force and velocity, but also to intrinsic factors such as oxytocin, mechanisms and multisensory context.

The current study demonstrates that stroking area have an effect on the perception of affective touch at certain different stroking areas and the stimulus is perceived to be more intense as the area of stimulation increases. Subsequently, these findings of the current study extend the growing literature related to the effect of stroking characteristics on pleasantness ratings and show that the hairy skin of the forearm is more susceptible to stroking hardness than the glabrous skin of the palm. However, despite their different innervations, there were many similarities in perception between the forearm and the palm, which needs further examination in future studies. In addition, our experiment only investigated two stroking sites on the palm and forearm; therefore, there are limitations in explaining the differential effects between hairy and glabrous skin. The experiment was also conducted as a behavioral one, making it difficult to attribute the affective feelings of hairless skin to the top-down mechanism. Hence, further studies are needed to incorporate more stroking sites into the experimental design and to extend fMRI approaches to the experiments to better investigate the top-down mechanism. Meanwhile, future experiments using fMRI approaches aimed to directly record cerebral cortex activation to investigate the perception of gentle touch on glabrous and hairy skin with different visual contexts are needed.

Publications

Journal Papers

1. Jiabin Yu, Jiajia Yang, Yinghua Yu, Qiong Wu, Satoshi Takahashi,Yoshimichi Ejima, and Jinglong Wu, "Stroking Hardness Changes the Perception of Affective Touch Pleasantness across Different Skin Sites", *Heliyon* (2019).
2. Wu Wang, Jiajia Yang, Yinghua Yu, Qiong Wu, Jiabin Yu, Satoshi Takahashi, Yoshimichi Ejima, and Jinglong Wu, "Tactile angle discriminability improvement: roles of training time intervals and different types of training tasks", *Journal of neurophysiology* (2019).

Book Chapters

3. Jiabin Yu, Zhiwei Wu, Jiajia Yang and Jinglong Wu, "MRI-compatible haptic stimuli delivery systems for investigating neural substrates of touch", *Improving the Quality of Life for Dementia Patients through Progressive Detection, Treatment, and Care*. Hershey, PA, USA: IGI Global, pp.236-248 (2016).

International Conference Proceedings

4. Jiabin Yu, Qiong Wu, Jiajia Yang, Satoshi Takahashi, Yoshimichi Ejima, and Jinglong Wu, "A Study of Shape Discrimination for Tactile Guide Maps", *2017 IEEE International Conference on Mechatronics and Automation (ICMA2017)*, pp.565-570 (2017).
5. Jiabin Yu, Jiajia Yang, Qiong Wu, Satoshi Takahashi, Yoshimichi Ejima, and Jinglong Wu, "Influence of temporal and spatial properties of stroking tactile stimuli on soft touch perception", *The 21st Annual Meeting for The Association for the Scientific Study of Consciousness (ASSC 21*), pp.49-50 (2017).

6. Wu Wang, Jiajia Yang, Yinghua Yu, Qiong Wu, Qingqing Li, Jiabin Yu, Satoshi Takahashi, Yoshimichi Ejima, and Jinglong Wu, “Tactile Training Improvement of Same-orientation but Not Different-orientation Discrimination”, *2019 IEEE International Conference on Mechatronics and Automation (ICMA2019)*, pp.2240-2244 (2019).

National conference Presentation (In Japan)

7. 余家斌，楊家家，于英花，呉瓊，李青青，王武，高橋智，江島義道，呉景龍, 視覚文脈がジェントルタッチに与える影響に関する行動学的研究, 日本生体医工学会中国四国支部大会，No.Ⅰ-3,pp.14 (2018).
8. 李青青，呉瓊，呉鳳侠，余家斌，高橋智，呉景龍，江島義道: 視覚二重課題遂行時の聴覚刺激による促進効果の検討, 日本生体医工学会中国四国支部大会，Ⅰ-2, pp.13, (2018)

Appendix

Japanese Version of Experiment Participation Reports

実験参加報告書

(実験者(記入)→実験参加者(記入:実験日)→実験者(受取)→GL→高橋)

【実験者 記入欄】

実験タイトル：

実験者：

実施年月日：　　　　年　　　月　　　日

実験時間：　　　：　　　～　　　：　　　（実験説明，休憩含む）

実験場所

実験項目（内容は簡単に，実験数に応じて記入）

実験１：

実験２：

実験３：

実験４：

実験５：

【実験参加者 記入欄】（表面，裏面とも記入し，署名する）

○現在の状態について，次の７段階で最も当てはまるスケールの数字に○印をしてください．

↓項目	当てはまらない		少し当てはまる		かなりあてはまる		非常に当てはまる
まぶたが重いと感じる	1	2	3	4	5	6	7
眠い	1	2	3	4	5	6	7
緊張している	1	2	3	4	5	6	7
どきどきしている	1	2	3	4	5	6	7
くつろいだ気分だ	1	2	3	4	5	6	7
ゆったりした気分だ	1	2	3	4	5	6	7
思考が鈍っている	1	2	3	4	5	6	7
認知の集中ができにくい	1	2	3	4	5	6	7
活力がみなぎっている	1	2	3	4	5	6	7
積極的な気分だ	1	2	3	4	5	6	7

やる気が出ない	1	2	3	4	5	6	7
何かすることに気乗りがしない	1	2	3	4	5	6	7
昨日は十分に睡眠をとった	1	2	3	4	5	6	7
昨日今日は暴飲暴食，深酒はしていない	1	2	3	4	5	6	7
健康状態は良好だ	1	2	3	4	5	6	7
実験中に不安に感じることがあった	1	2	3	4	5	6	7
次回も実験に参加したい	1	2	3	4	5	6	7
実験１の方法は理解できた	1	2	3	4	5	6	7
実験２の方法は理解できた	1	2	3	4	5	6	7
実験３の方法は理解できた	1	2	3	4	5	6	7
実験４の方法は理解できた	1	2	3	4	5	6	7
実験５の方法は理解できた	1	2	3	4	5	6	7
(以下必要に応じて実験者が追加)							
	1	2	3	4	5	6	7
	1	2	3	4	5	6	7
	1	2	3	4	5	6	7
↑項目	当てはまらない		少し当てはまる		かなりあてはまる		非常に当てはまる

実験について，感想・コメントを１言(以上)書いてください.

【実験参加者 署名】

実験年月日：　＿＿＿＿年＿＿月＿＿日

署名(自署)：　＿＿＿＿＿＿＿＿＿＿

同意書への記入：　有　　無

Acknowledgements

I am especially grateful to Prof. Jinglong Wu, my supervisor, for patiently teaching me and adding to that a contagious enthusiasm for science, humor, and generosity that has made being your doctoral student no less than great. Your skillful teaching and faith in my abilities have made experiments, quirky statistics and science pure fun. Beyond the university, Professor Wu has also kindly helped me, a foreigner in Japan, with everyday life.

I also would like to thank Prof. Eiji Tomita, Akihiko Horibe, Yoshimichi Eijiama and Associate Professor Satoshi Takahashi, who provided valuable advice for data analysis and oral presentation.

I also want to express my sincere gratitude to Dr. Jiajia Yang and Yinghua Yu, who provided valuable advice for writing the dissertation, kindly manuscript review and encouragement.

I also thank the students and staff in the Wu lab. Without their cooperation, I cannot imagine how I could have finished my experiments. I sincerely thank all those who contributed to my experiment, my paper, and dissertation. Finally, I would like to thank my parents, older sisters and my girlfriend for supporting me spirituality during my doctoral journey.

References

1. Gallace, A. and C. Spence, *The science of interpersonal touch: an overview.* Neurosci Biobehav Rev, 2010. **34**(2): p. 246-59.
2. Eaton, M., I.L. Mitchellbonair, and E. Friedmann, *The Effect of Touch on Nutritional Intake of Chronic Organic Brain-Syndrome Patients.* Journals of Gerontology, 1986. **41**(5): p. 611-616.
3. Whitcher, S.J. and J.D. Fisher, *Multidimensional reaction to therapeutic touch in a hospital setting.* J Pers Soc Psychol, 1979. **37**(1): p. 87-96.
4. Ditzen, B., et al., *Effects of different kinds of couple interaction on cortisol and heart rate responses to stress in women.* Psychoneuroendocrinology, 2007. **32**(5): p. 565-74.
5. Glynn, L.M., N. Christenfeld, and W. Gerin, *Gender, social support, and cardiovascular responses to stress.* Psychosom Med, 1999. **61**(2): p. 234-42.
6. Jones, S.E. and A.E. Yarbrough, *A naturalistic study of the meanings of touch.* Communications Monographs, 1985. **52**(1): p. 19-56.
7. Diamond, A. and D. Amso, *Contributions of neuroscience to our understanding of cognitive development.* Current Directions in Psychological Science, 2008. **17**(2): p. 136-141.
8. Harlow, H.F. and S.J. Suomi, *Nature of love--simplified.* Am Psychol, 1970. **25**(2): p. 161-8.
9. Crusco, A.H. and C.G. Wetzel, *The Midas touch: The effects of interpersonal touch on restaurant tipping.* Personality and Social Psychology Bulletin, 1984. **10**(4): p. 512-517.
10. Morrison, I., L.S. Loken, and H. Olausson, *The skin as a social organ.* Experimental Brain Research, 2010. **204**(3): p. 305-314.
11. Hornik, J., *Tactile stimulation and consumer response.* Journal of Consumer Research, 1992. **19**(3): p. 449-458.
12. Joule, R.V. and N. Gueguen, *Touch, compliance, and awareness of tactile contact.* Perceptual and Motor Skills, 2007. **104**(2): p. 581-588.
13. Field, T., *Touch*. 2014: MIT press.
14. Gray, L., L. Watt, and E.M. Blass, *Skin-to-skin contact is analgesic in healthy newborns.* Pediatrics, 2000. **105**(1).
15. Coan, J.A., H.S. Schaefer, and R.J. Davidson, *Lending a hand: Social regulation of the neural response to threat.* Psychological Science, 2006. **17**(12): p. 1032-1039.
16. Hertenstein, M.J., et al., *Touch communicates distinct emotions.* Emotion, 2006. **6**(3): p. 528-33.
17. Hertenstein, M.J., et al., *The communication of emotion via touch.* Emotion, 2009. **9**(4): p. 566-73.
18. Elfenbein, H.A. and N. Ambady, *Is there an in-group advantage in emotion recognition?* 2002.
19. McGlone, F., et al., *Discriminative touch and emotional touch.* Canadian Journal of Experimental Psychology-Revue Canadienne De Psychologie Experimentale, 2007. **61**(3): p. 173-183.
20. Zimmerman, A., L. Bai, and D.D. Ginty, *The gentle touch receptors of mammalian skin.* Science, 2014. **346**(6212): p. 950-954.
21. Vallbo, A.B. and R.S. Johansson, *Properties of Cutaneous Mechanoreceptors in the Human Hand Related to Touch Sensation.* Human Neurobiology, 1984. **3**(1): p. 3-14.
22. Johnson, K.O., *The roles and functions of cutaneous mechanoreceptors.* Current Opinion in Neurobiology, 2001. **11**(4): p. 455-461.

23. Iggo, A. and H. Ogawa, *Correlative physiological and morphological studies of rapidly adapting mechanoreceptors in cat's glabrous skin.* J Physiol, 1977. **266**(2): p. 275-96.
24. Janig, W. and B. Rath, *Electrodermal reflexes in the cat's paws elicited by natural stimulation of skin.* Pflugers Arch, 1977. **369**(1): p. 27-32.
25. Johansson, R.S., *Tactile sensibility in the human hand: receptive field characteristics of mechanoreceptive units in the glabrous skin area.* J Physiol, 1978. **281**: p. 101-25.
26. Iggo, A. and A.R. Muir, *The structure and function of a slowly adapting touch corpuscle in hairy skin.* J Physiol, 1969. **200**(3): p. 763-96.
27. Woodbury, C.J., et al., *Identity of myelinated cutaneous sensory neurons projecting to nocireceptive laminae following nerve injury in adult mice.* J Comp Neurol, 2008. **508**(3): p. 500-9.
28. Li, L., et al., *The functional organization of cutaneous low-threshold mechanosensory neurons.* Cell, 2011. **147**(7): p. 1615-27.
29. Biemesderfer, D., et al., *The pilo-Ruffini complex: a non-sinus hair and associated slowly-adapting mechanoreceptor in primate facial skin.* Brain research, 1978. **142**(2): p. 197-222.
30. Olausson, H., et al., *Unmyelinated tactile afferents signal touch and project to insular cortex.* Nature Neuroscience, 2002. **5**(9): p. 900-904.
31. Loken, L.S., et al., *Coding of pleasant touch by unmyelinated afferents in humans.* Nat Neurosci, 2009. **12**(5): p. 547-8.
32. Liljencrantz, J. and H. Olausson, *Tactile C fibers and their contributions to pleasant sensations and to tactile allodynia.* Front Behav Neurosci, 2014. **8**: p. 37.
33. Zotterman, Y., *Touch, pain and tickling: an electro-physiological investigation on cutaneous sensory nerves.* J Physiol, 1939. **95**(1): p. 1-28.
34. Iggo, A. and H.H. Kornhuber, *A quantitative study of C-mechanoreceptors in hairy skin of the cat.* J Physiol, 1977. **271**(2): p. 549-65.
35. Kumazawa, T. and E.R. Perl, *Primate cutaneous sensory units with unmyelinated (C) afferent fibers.* J Neurophysiol, 1977. **40**(6): p. 1325-38.
36. Nordin, M., *Low-threshold mechanoreceptive and nociceptive units with unmyelinated (C) fibres in the human supraorbital nerve.* J Physiol, 1990. **426**: p. 229-40.
37. Vallbo, A.B., H. Olausson, and J. Wessberg, *Unmyelinated afferents constitute a second system coding tactile stimuli of the human hairy skin.* J Neurophysiol, 1999. **81**(6): p. 2753-63.
38. Iggo, A., *Cutaneous mechanoreceptors with afferent C fibres.* J Physiol, 1960. **152**: p. 337-53.
39. Bessou, P., et al., *Dynamic properties of mechanoreceptors with unmyelinated (C) fibers.* J Neurophysiol, 1971. **34**(1): p. 116-31.
40. Wiklund Fernström, K., *Physiological properties of unmyelinated low-threshold tactile (CT) afferents in the human hairy skin*. 2004.
41. Vallbo, A., et al., *A System of Unmyelinated Afferents for Innocuous Mechanoreception in the Human Skin.* Brain Research, 1993. **628**(1-2): p. 301-304.
42. Olausson, H., et al., *The neurophysiology of unmyelinated tactile afferents.* Neuroscience and Biobehavioral Reviews, 2010. **34**(2): p. 185-191.
43. Wessberg, J., et al., *Receptive field properties of unmyelinated tactile afferents in the human skin.* J Neurophysiol, 2003. **89**(3): p. 1567-75.
44. Ackerley, R., et al., *Quantifying the sensory and emotional perception of touch: differences between glabrous and hairy skin.* Frontiers in Behavioral Neuroscience, 2014. **8**.
45. Schultz, S.K., *Principles of neural science, 4th edition.* American Journal of Psychiatry, 2001. **158**(4): p. 662-662.

46. Maeda, K., et al., *Topography of the secondary somatosensory cortex in humans: a magnetoencephalo-graphic study.* Neuroreport, 1999. **10**(2): p. 301-306.
47. Schneider, R.J., D.P. Friedman, and M. Mishkin, *A Modality-Specific Somatosensory Area within the Insula of the Rhesus-Monkey.* Brain Research, 1993. **621**(1): p. 116-120.
48. Mesulam, M.M., *From sensation to cognition.* Brain, 1998. **121**: p. 1013-1052.
49. Maldjian, J.A., et al., *The sensory somatotopic map of the human hand demonstrated at 4 Tesla.* Neuroimage, 1999. **10**(1): p. 55-62.
50. Ruben, J., et al., *Somatotopic organization of human secondary somatosensory cortex.* Cerebral Cortex, 2001. **11**(5): p. 463-473.
51. Light, A.R. and H.H. Willcockson, *Spinal laminae I-II neurons in rat recorded in vivo in whole cell, tight seal configuration: Properties and opioid responses.* Journal of Neurophysiology, 1999. **82**(6): p. 3316-3326.
52. Brown, A.G. and R.E. Fyffe, *Form and function of dorsal horn neurones with axons ascending the dorsal columns in cat.* J Physiol, 1981. **321**: p. 31-47.
53. Dostrovsky, J.O. and A.D. Craig, *Cooling-specific spinothalamic neurons in the monkey.* J Neurophysiol, 1996. **76**(6): p. 3656-65.
54. Craig, A.D., *How do you feel? Interoception: the sense of the physiological condition of the body.* Nature Reviews Neuroscience, 2002. **3**(8): p. 655-666.
55. Craig, A., *Interoception and emotion: a neuroanatomical perspective.* Handbook of emotions, 2008. **3**(602): p. 272-88.
56. Bjornsdotter, M., et al., *Somatotopic organization of gentle touch processing in the posterior insular cortex.* J Neurosci, 2009. **29**(29): p. 9314-20.
57. McGlone, F., et al., *Touching and feeling: differences in pleasant touch processing between glabrous and hairy skin in humans.* Eur J Neurosci, 2012. **35**(11): p. 1782-8.
58. Lucas, M.V., et al., *Dissociating the Neural Correlates of Experiencing and Imagining Affective Touch.* Cereb Cortex, 2015. **25**(9): p. 2623-30.
59. Zimmerman, A., L. Bai, and D.D. Ginty, *The gentle touch receptors of mammalian skin.* Science, 2014. **346**(6212): p. 950-4.
60. McGlone, F., J. Wessberg, and H. Olausson, *Discriminative and affective touch: sensing and feeling.* Neuron, 2014. **82**(4): p. 737-55.
61. Vallbo, A., et al., *A system of unmyelinated afferents for innocuous mechanoreception in the human skin.* Brain Res, 1993. **628**(1-2): p. 301-4.
62. Vallbo, A.B., et al., *Receptive field characteristics of tactile units with myelinated afferents in hairy skin of human subjects.* J Physiol, 1995. **483 (Pt 3)**: p. 783-95.
63. Ackerley, R., et al., *Touch perceptions across skin sites: differences between sensitivity, direction discrimination and pleasantness.* Front Behav Neurosci, 2014. **8**: p. 54.
64. Rolls, E.T., et al., *Representations of pleasant and painful touch in the human orbitofrontal and cingulate cortices.* Cereb Cortex, 2003. **13**(3): p. 308-17.
65. Schepers, R.J. and M. Ringkamp, *Thermoreceptors and thermosensitive afferents.* Neuroscience and Biobehavioral Reviews, 2010. **34**(2): p. 177-184.
66. Ackerley, R., et al., *Human C-Tactile Afferents Are Tuned to the Temperature of a Skin-Stroking Caress.* Journal of Neuroscience, 2014. **34**(8): p. 2879-2883.
67. Ackerley, R., et al., *Human C-tactile afferents are tuned to the temperature of a skin-stroking caress.* J Neurosci, 2014. **34**(8): p. 2879-83.
68. Watanabe, N., et al., *Effect of gentle cutaneous stimulation on heat-induced autonomic response and subjective pain intensity in healthy humans.* J Physiol Sci, 2012. **62**(4): p. 343-50.
69. Klocker, A., et al., *Physical Factors Influencing Pleasant Touch during Tactile Exploration.* Plos One, 2013. **8**(11).

70. Mountcastle, V.B., et al., *Neural basis of the sense of flutter-vibration.* Science, 1967. **155**(3762): p. 597-600.
71. Loken, L.S., M. Evert, and J. Wessberg, *Pleasantness of touch in human glabrous and hairy skin: order effects on affective ratings.* Brain Res, 2011. **1417**: p. 9-15.
72. Vallbo, A.B. and R.S. Johansson, *Properties of cutaneous mechanoreceptors in the human hand related to touch sensation.* Hum Neurobiol, 1984. **3**(1): p. 3-14.
73. Bensmaia, S.J., *Tactile intensity and population codes.* Behav Brain Res, 2008. **190**(2): p. 165-73.
74. Olausson, H., et al., *Unmyelinated tactile afferents signal touch and project to insular cortex.* Nat Neurosci, 2002. **5**(9): p. 900-4.
75. Olausson, H., et al., *The neurophysiology of unmyelinated tactile afferents.* Neurosci Biobehav Rev, 2010. **34**(2): p. 185-91.
76. Perini, I., H. Olausson, and I. Morrison, *Seeking pleasant touch: neural correlates of behavioral preferences for skin stroking.* Front Behav Neurosci, 2015. **9**: p. 8.
77. Sakamoto, M. and J. Watanabe, *Exploring Tactile Perceptual Dimensions Using Materials Associated with Sensory Vocabulary.* Frontiers in Psychology, 2017. **8**.
78. Guest, S., et al., *Physics and Tactile Perception of Fluid-Covered Surfaces.* Journal of Texture Studies, 2012. **43**(1): p. 77-93.
79. Matthews, J., G. Berry, and P. Armitage, *Statistical methods in medical research*. 2002, Oxford: Blackwell Science.
80. Blischke, W.R., J.W. Bush, and R.M. Kaplan, *Successive intervals analysis of preference measures in a health status index.* Health Serv Res, 1975. **10**(2): p. 181-98.
81. Edwards, A.L., *The scaling of stimuli by the method of successive intervals.* Journal of Applied Psychology, 1952. **36**(2): p. 118.
82. Fairhurst, M.T., L. Loken, and T. Grossmann, *Physiological and behavioral responses reveal 9-month-old infants' sensitivity to pleasant touch.* Psychol Sci, 2014. **25**(5): p. 1124-31.
83. Morrison, I., et al., *Reduced C-afferent fibre density affects perceived pleasantness and empathy for touch.* Brain, 2011. **134**(Pt 4): p. 1116-26.
84. Gordon, I., et al., *Brain mechanisms for processing affective touch.* Human Brain Mapping, 2013. **34**(4): p. 914-922.
85. Voos, A.C., K.A. Pelphrey, and M.D. Kaiser, *Autistic traits are associated with diminished neural response to affective touch.* Soc Cogn Affect Neurosci, 2013. **8**(4): p. 378-86.
86. Klocker, A., et al., *Physical Factors Influencing Pleasant Touch during Passive Fingertip Stimulation.* Plos One, 2014. **9**(7).
87. Ackerley, R., et al., *Quantifying the sensory and emotional perception of touch: differences between glabrous and hairy skin.* Front Behav Neurosci, 2014. **8**: p. 34.
88. Provitera, V., et al., *Myelinated nerve endings in human skin.* Muscle & Nerve, 2007. **35**(6): p. 767-775.
89. Guest, S., et al., *The development and validation of sensory and emotional scales of touch perception.* Atten Percept Psychophys, 2011. **73**(2): p. 531-50.
90. Morrison, I., M. Bjornsdotter, and H. Olausson, *Vicarious responses to social touch in posterior insular cortex are tuned to pleasant caressing speeds.* J Neurosci, 2011. **31**(26): p. 9554-62.
91. Kennett, S., M. Taylor-Clarke, and P. Haggard, *Noninformative vision improves the spatial resolution of touch in humans.* Current Biology, 2001. **11**(15): p. 1188-1191.
92. Cardini, F., et al., *Rapid enhancement of touch from non-informative vision of the hand.* Neuropsychologia, 2012. **50**(8): p. 1954-1960.

93. Ellingsen, D.M., et al., *In touch with your emotions: Oxytocin and touch change social impressions while others' facial expressions can alter touch.* Psychoneuroendocrinology, 2014. **39**: p. 11-20.
94. Bjornsdotter, M., I. Morrison, and H. Olausson, *Feeling good: on the role of C fiber mediated touch in interoception.* Experimental Brain Research, 2010. **207**(3-4): p. 149-155.
95. Nordin, M., *Low-Threshold Mechanoreceptive and Nociceptive Units with Unmyelinated (C) Fibers in the Human Supraorbital Nerve.* Journal of Physiology-London, 1990. **426**: p. 229-240.
96. Lloyd, D.M., F.P. McGlone, and G. Yosipovitch, *Somatosensory pleasure circuit: from skin to brain and back.* Exp Dermatol, 2015. **24**(5): p. 321-4.
97. Pessoa, L., *On the relationship between emotion and cognition.* Nature Reviews Neuroscience, 2008. **9**(2): p. 148-158.
98. McCabe, C., et al., *Cognitive influences on the affective representation of touch and the sight of touch in the human brain.* Social Cognitive and Affective Neuroscience, 2008. **3**(2): p. 97-108.
99. von Mohr, M., L.P. Kirsch, and A. Fotopoulou, *The soothing function of touch: affective touch reduces feelings of social exclusion.* Scientific Reports, 2017. **7**.
100. Ellingsen, D.M., et al., *The Neurobiology Shaping Affective Touch: Expectation, Motivation, and Meaning in the Multisensory Context.* Front Psychol, 2015. **6**: p. 1986.
101. Schreuder, E., et al., *Emotional Responses to Multisensory Environmental Stimuli: A Conceptual Framework and Literature Review.* Sage Open, 2016. **6**(1).
102. Crucianelli, L., et al., *Bodily pleasure matters: velocity of touch modulates body ownership during the rubber hand illusion.* Front Psychol, 2013. **4**: p. 703.
103. van Stralen, H.E., et al., *Affective touch modulates the rubber hand illusion.* Cognition, 2014. **131**(1): p. 147-58.
104. Lloyd, D.M., et al., *Pleasant touch moderates the subjective but not objective aspects of body perception.* Front Behav Neurosci, 2013. **7**: p. 207.
105. Crucianelli, L., et al., *Interoceptive ingredients of body ownership: Affective touch and cardiac awareness in the rubber hand illusion.* Cortex, 2018. **104**: p. 180-192.
106. Gallagher, S., *Philosophical conceptions of the self: implications for cognitive science.* Trends in Cognitive Sciences, 2000. **4**(1): p. 14-21.
107. Tsakiris, M. and P. Haggard, *The rubber hand illusion revisited: Visuotactile integration and self-attribution.* Journal of Experimental Psychology-Human Perception and Performance, 2005. **31**(1): p. 80-91.
108. Botvinick, M. and J. Cohen, *Rubber hands 'feel' touch that eyes see.* Nature, 1998. **391**(6669): p. 756-756.
109. Ehrsson, H.H., *The experimental induction of out-of-body experiences.* Science, 2007. **317**(5841): p. 1048-1048.
110. Lenggenhager, B., et al., *Video ergo sum: Manipulating bodily self-consciousness.* Science, 2007. **317**(5841): p. 1096-1099.
111. Meehan, S.K. and W.R. Staines, *Task-Relevance and Temporal Synchrony Between Tactile and Visual Stimuli Modulates Cortical Activity and Motor Performance During Sensory-Guided Movement.* Human Brain Mapping, 2009. **30**(2): p. 484-496.
112. Dionne, J.K., et al., *Crossmodal Influences in Somatosensory Cortex: Interaction of Vision and Touch.* Human Brain Mapping, 2010. **31**(1): p. 14-25.
113. Macaluso, E. and J. Driver, *Spatial attention and crossmodal interactions between vision and touch.* Neuropsychologia, 2001. **39**(12): p. 1304-1316.
114. Macaluso, E., C.D. Frith, and J. Driver, *Modulation of human visual cortex by crossmodal spatial attention.* Science, 2000. **289**(5482): p. 1206-1208.

115. Hertenstein, M.J., et al., *The communicative functions of touch in humans, nonhuman primates, and rats: A review and synthesis of the empirical research.* Genetic Social and General Psychology Monographs, 2006. **132**(1): p. 5-94.
116. Feldman, R., M. Singer, and O. Zagoory, *Touch attenuates infants' physiological reactivity to stress.* Developmental Science, 2010. **13**(2): p. 271-278.
117. Feldman, R., et al., *Testing a family intervention hypothesis: the contribution of mother-infant skin-to-skin contact (kangaroo care) to family interaction, proximity, and touch.* J Fam Psychol, 2003. **17**(1): p. 94-107.
118. Barnett, L., *Keep in touch: The importance of touch in infant development.* Infant Observation, 2005. **8**(2): p. 115-123.
119. Ellingsen, D.M., et al., *The Neurobiology Shaping Affective Touch: Expectation, Motivation, and Meaning in the Multisensory Context.* Frontiers in Psychology, 2016. **6**.
120. Ravaja, N., et al., *Feeling Touched: Emotional Modulation of Somatosensory Potentials to Interpersonal Touch.* Scientific Reports, 2017. **7**.
121. Liu, Q., et al., *Molecular genetic visualization of a rare subset of unmyelinated sensory neurons that may detect gentle touch.* Nature Neuroscience, 2007. **10**(8): p. 946-948.
122. Ackerley, R., et al., *Touch perceptions across skin sites: differences between sensitivity, direction discrimination and pleasantness.* Frontiers in Behavioral Neuroscience, 2014. **8**.
123. Kirsch, L.P., et al., *Reading the mind in the touch: Neurophysiological specificity in the communication of emotions by touch.* Neuropsychologia, 2018. **116**: p. 136-149.
124. Olausson, H.W., et al., *Unmyelinated tactile afferents have opposite effects on insular and somatosensory cortical processing.* Neuroscience Letters, 2008. **436**(2): p. 128-132.
125. Croy, I., et al., *Olfactory modulation of affective touch processing - A neurophysiological investigation.* Neuroimage, 2016. **135**: p. 135-141.
126. Lamm, C., G. Silani, and T. Singer, *Distinct neural networks underlying empathy for pleasant and unpleasant touch.* Cortex, 2015. **70**: p. 79-89.
127. Silani, G., et al., *Right Supramarginal Gyrus Is Crucial to Overcome Emotional Egocentricity Bias in Social Judgments.* Journal of Neuroscience, 2013. **33**(39): p. 15466-15476.
128. Lyons, M.J., et al. *The Japanese female facial expression (JAFFE) database*. in *Proceedings of third international conference on automatic face and gesture recognition*. 1998.
129. Gazzola, V., et al., *Primary somatosensory cortex discriminates affective significance in social touch.* Proceedings of the National Academy of Sciences of the United States of America, 2012. **109**(25): p. E1657-E1666.
130. Croy, I., et al., *Olfactory modulation of affective touch processing - A neurophysiological investigation.* Neuroimage, 2016. **135**: p. 135-41.