Illusion of Wetness by Dynamic Touch

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***Abstract*—Humans perceive wetness on contact with a dry-cold material; however, the magnitude of wetness that can be perceived using dynamic touch remains unclear. This study assessed how the type of touch, namely hand movement (either statically or dynamically) and pressing force (either low or high pressure), affect the perception of wetness. The participants judged the magnitude of perceived wetness after four types of touch of four stimuli comprising four fabrics of varying water content and surface temperatures. Overall, the perceived wetness was differed between static and dynamic touch independent of pressure and the participants scored the dry-cold stimulus as relatively dry for dynamic touch. Furthermore, cluster analysis revealed individual differences in the recognition of wetness in dynamic touch conditions. These results revealed the variability in the mechanisms used by humans to perceive wetness. Additionally, we discussed the optimal methods to reproduce the wetness perception using this illusion.**

***Index Terms*—Wetness, coldness, friction, pressure, cross-modal interaction.**

I. Introduction

Wetness is a feeling that an object contains moisture. This perception is important for human health and safety. A human wearing wet clothing is at risk for reduced body temperature and damaged health. Therefore, upon sensing wetness, humans feel discomfort [1]–[4] and avoid these fabrics. Furthermore, because the surface friction changes when an object contains moisture, the wetness results in an adjustment of grip force [5]–[8]. Recent research efforts have been directed toward developing a method to reproduce haptic sensations; however, studies on the reproduction of wetness, which is essential, as mentioned above, are limited. The feedback of this feeling has the potential to provide realistic material recognition and accurate adjustment of grip force in remote-control robotics and neuroprostheses [9]. It can also improve the feeling of immersion by representing atmospheric conditions in virtual reality contexts [10].

The present study investigated methods to reliably reproduce the wetness perception, as an understanding of the mechanisms that underlie the perception of haptic sensation are important for haptic reproduction. We summarize the current literature on the mechanisms of perceive wetness. Some studies have proposed that the feeling of wet (moist)-dry is one of the perceptual dimensions of haptic textures [11]–[15]. However, humans are not equipped with skin receptors to detect this [16]. Instead, we perceive wetness using a combination of thermal (i.e., heat transfer) and tactile (i.e., mechanical pressure and friction) cues [9], [17], whereas the wetness, temperature, softness, and roughness have been found to be different perceptual dimensions [11]–[15]. In addition, the wetness perception may be affected by the type of contact; that is, dynamic or static touch. Dynamic touch is defined when a contact surface moves relatively along the object surface from the initial contact position; in contrast, the contact area does not move in static touch.

As an example of the effect of pressure in wetness perception, higher mechanical pressure (127 Pa versus 236 Pa) on the skin significantly increases the perceived wetness for both static and dynamic touches [18], [19]. The study [20], which used clothes for evaluation, showed that a higher mechanical pressure on the skin resulting from tight-fitting garment, which limits skin-clothing interaction, significantly reduces the perception of sweat-induced wetness, than a loose garment, which allows free interaction during physical exercise. In the case of dynamic touch, the sensations of roughness, friction, and stickiness are also important [17], [19], [21]–[23]. These tactile cues affect the wetness perception so that the threshold required for the detection of wetness by dynamic touch is smaller than that for static touch [21]. Furthermore, body parts seem to affect wetness perception; for example, the back of the torso is relatively sensitive to the wetness [24], [25]. Differences in perceived wetness according to body parts may relate to differences in thermal and tactile sensations due to receptor density and skin thickness.

Interestingly, a dry-cold stimulus can evoke a wetness perception rather than dryness [22], [25]–[30] (Fig. 1). In static touch research, some physical evidence suggests that temperature conditions with a similar drop in skin temperature such as that experienced during contact with a wetted object can cause an illusion of wetness [28]–[30]. In contrast, increasing the skin temperature can suppress the perceived wetness: both dry and wets surfaces do not lead to wetness perception when they are warmed [29], [31]. Bergmann Tiest *et al.* [22] suggested that the illusion of wetness does not depend on the type of touch employed, (i.e., static or dynamic) in contrast to the study about actual wetness [2], [20], [21]. This illusory perception decreases when the pressure is strong by passive touch (10000 Pa versus 7000 Pa) [27]. These findings of illusory wetness are not only clues to clarify the mechanism of wetness perception but are also a useful method for haptic feedback devices to reproduce the perception.

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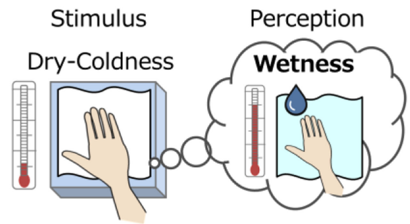

Fig. 1. Concept about the illusion of wetness. Human perceives wetness from dry-cold fabrics [29].

The present study focused on the illusion of wetness caused by cold-dry and warmed-wetted fabrics, especially for dynamic touch. In contrast to the results of previous study indicating that the illusion does not depend on the type of touch [22], we believed that the type of touch affects the illusion of wetness for three reasons. The first is the wetness threshold in dynamic touch. As mentioned, tactile cues have some impact on the perception of wetness in dynamic touch and the threshold of wetness by dynamic touch is smaller than for static touch [21]. Thus, humans appear to more sensitively discriminate wetness from dryness using tactile information when dynamic (versus static) touch is used. The second is the effect of thermal sense. Regarding thermal information, although the skin more rapidly decreases in temperature when a cold object is touched dynamically, research has shown that thermal sensations are suppressed in dynamic touch [32], [33]. Therefore, the illusion of wetness perceived by contact with a cold object may be more difficult to evoke during dynamic touch. The third reason is the effect of pressure. The pressing force may be an important factor in wetness perception of dry-cold stimulus in dynamic touch. When the pressing force is small, the friction between the skin and material is limited. Thus, when the pressing force is weak, thermal cues from a dry-cold stimulus may be more dominantly used to perceive wetness because of the limited ability to detect tactile cues (e.g., the sensation of friction and roughness). This suggests that a decrease in temperature but also a pressure are the causes of perceived wetness in dynamic touch.

The present study, therefore, examined how the type of touch affected the illusion of wetness by focusing on hand movement and pressing force. We hypothesized that the magnitude of the perceived wetness evoked from a dry-cold stimulus would vary depending on the use of static versus dynamic touch. We used fabrics to conduct a psychophysical experiment and analyzed the effect of various physical parameters associated with touch (e.g., temperature, pressure, and friction) on the wetness perception.

II. Psychophysical Experiment

The participants were asked to judge the magnitude of the wetness of a piece of fabric for four variations of touch (i.e., static and dynamic touch with low and high pressure). In this experiment, pressing contact by the palm of the hand was defined as static touch and a tracing touch to one direction as dynamic touch. In addition to the changes in the type of touch, the drop in skin temperature and wetness of the fabric varied in four ways (Table I). Using this approach, we evaluated whether contact with a dry-cold fabric would produce the same drop in skin temperature as that for contact with a wet fabric and whether such contact would produce the wetness perception. We also investigated the counter condition, in which the stimulus was a warm wet fabric. We hypothesized that the way the fabric was touched (i.e., statically versus dynamically) would affect the perceived wetness.

TABLE I
Experimental Conditions and Temperatures where the Upper Part of the Cell Shows the Name of Experimental Conditions and the Lower Part Shows the Setting Temperature. For Example, the Upper Right Cell Shows the 'Dry-Cold' Condition in Which the Cloth Doesn't Hold Water and the Temperature is Set at 18 °C to Increase the Drop in Skin Temperature

		Drop in skin temperature	
		Small	Large
Water	Without	Dry	Dry-Cold
		25°C	18°C
	With	Wet-Warm	Wet
		30°C	25°C

A. Participants

Twenty-one paid volunteer students (females, aged between 18 and 21 years) participated in this psychophysical experiment. The participants had no specialized knowledge about this experiment and provided written informed consent before the experiment began. The experimental protocol was approved by the Nara Women's University and was performed in accordance with the ethical standards outlined by the Declaration of Helsinki.

B. Stimulus and the Types of Touch

The experimental setup is shown in Fig. 2. We used a polyester circular interlock knitted fabric (2.83-3.28g, 13 × 13 cm) as the stimulation material. To control the surface temperature of the stimulus, the fabric was placed on a cool plate (SCP-85, asOne Co., Ltd.) (Fig. 2(a)), containing a 10 × 10 cm Peltier element. A 12.5 × 10 cm piece of aluminum was positioned on the Peltier to expand the area capable of controlling the fabric's temperature. The fabric was fixed on the cool plate by twelve magnets. The cool plate was then placed on a three-axis force plate (TF-4060, Tec Gihan Co., Ltd.) so that force could be measured during the touch portion of the experiments (Fig. 2 (a)). The force data were output as csv files.

The participants sat at a table on which the experimental equipment had been placed (Fig. 2(b)) and were instructed to use their right hands. Before touching a stimulus, the participants were instructed to place their right hands on a hotplate (NHP-M30N, New Japan Chemical Co, Ltd.) set to 32 °C for 1 minute to control for variability in initial skin temperatures. A cover over the equipment prevented the participants from seeing the fabric and they were asked to monitor the display showing the measured exerted force (located in front of them) to control the pressure applied during the touching stage of the

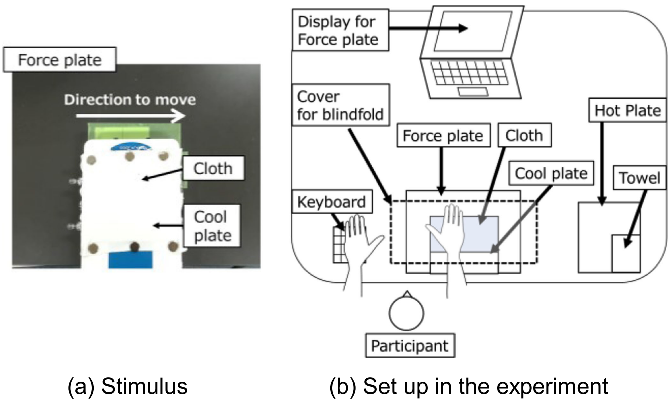

Fig. 2. Experimental apparatus. A cool plate is placed under the fabric to control the temperature and the force plate is used to measure the pressing force. The participants touched the fabric stimulus through the cover with their right hand. The participants used their left hand on the keyboard to score the impression of wetness after the contact. (a) Stimulus. (b) Set up in the experiment.

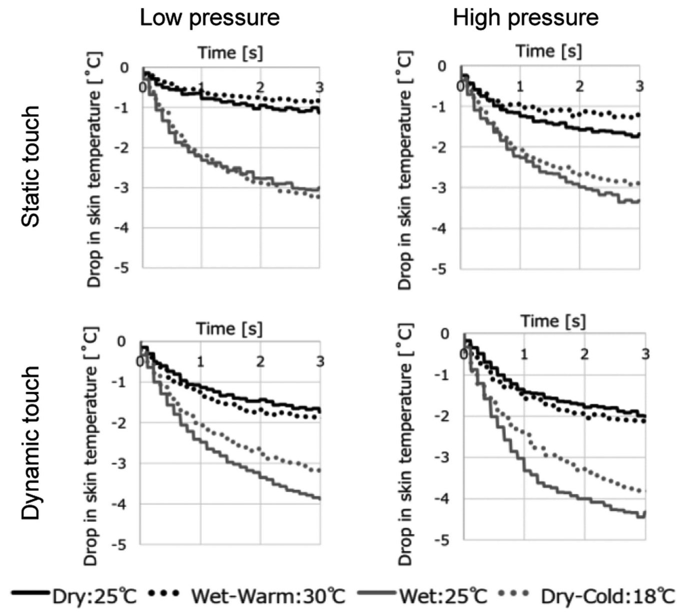

Fig. 3. Drops in skin temperature. We measured the skin temperature for 3 seconds after contact with stimuli by the first author's hand. The graphs indicate the average of five measurements.

experiment. The types of touch conditions during this experiment were varied by hand movement (namely, static and dynamic) and pressure (low [< 1 N, or approximately 140 Pa] versus high [> 3 N, approximately 430 Pa]). In other words, the participants were asked to touch the fabric using the following four variations: static touch with low pressure, static touch with high pressure, dynamic touch with low pressure, and dynamic touch with high pressure. For the static touch condition, the participants were instructed to press the thenar region of the palm onto the fabric for 3 seconds without moving. For the dynamic touch condition, the participants were asked to trace the fabric from the left to the right side (~12.5 cm in length) for 3 seconds; i.e., a velocity of tracing of 4.2 cm/s.

C. *Experimental Conditions*

In this psychophysical experiment, room temperature and humidity were maintained at 26 ± 2 °C and 50 ± 8% RH, respectively.

The participants were instructed to touch fabrics that differed in temperature and water content: Dry (D), Wet (W), Dry-Cold (DC), and Wet-Warm (WW) (Table I). We aimed to investigate the cues associated with a perceived wetness by comparing these experimental conditions with and without water and large and small drop in skin temperature.

To control the water condition, the fabrics used in the experiments were left in the experimental room for more than one hour. The fabrics used in the Wet and Warm-Wet conditions contained water by sandwiching them between highly hygroscopic sponges (relative humidity [RH], 49 ± 6%). The fabrics used in the wet conditions contained 1.76–2.64 g water, as measured using a digital scale (0.01 g accuracy) (HT-120, A&D Co., Ltd.). The water content of the fabrics was calculated by comparing post-experimental dry and wet fabric weights, resulting in the range of 60–80% by weight. The water content of the fabrics used in the Dry and Dry-Cold conditions was below 0.7%.

We set the surface temperature of the fabric for the Dry-Cold condition to make the drop in skin temperature after contact similar to that of the Wet condition to induce an illusory wetness perception, as shown in our previous study [29]. Furthermore, we set the surface temperature of the Wet-Warm condition to make the drop in skin temperature similar to that of the Dry condition. The Dry-Cold and Wet-Warm conditions were adopted based on the static touch condition at low pressure, as described in our previous study, regardless of the type of touch or pressure.

To determine the optimal cool plate temperature setting, we used a Thermistor (P1703, Alpha Technics Inc., diameter and length of the sensing-part were 0.5 mm and 4 mm, respectively) with tape affixed to the thenar to measure the contact temperature between the first author's hand and the fabrics used in each experimental condition that occurred three seconds after contact. We defined the decrease of contact temperature that occurred three seconds after contact as 'drop in skin temperature.' An Arduino UNO microcontroller was used for voltage readings of the Thermistor. To remove noise obtained during the readings, the last 50 values were averaged and smoothed. The voltages were converted to temperature in the Arduino UNO and sent to the computer by serial communication within 10 milliseconds. The room temperature and humidity were 27 ± 0.8 °C and 49 ± 6% RH, respectively.

Fig. 3 shows the stimulus-induced drop in skin temperature, averaged across five measurements, of the finally determined temperature setting. The cool plate was set to 25 °C for the Dry and Wet conditions and to 30 °C and 18 °C, respectively, for the Wet-Warm and Dry-Cold conditions. During the dynamic touch condition, we observed that the drop in skin temperature was greater for all stimuli than that for static touch. We applied the temperature settings obtained from the measurement of one participant to the other participants of that experiment. While we expected the drop in temperature to vary across participants, we assumed that the natural tendency of skin temperature

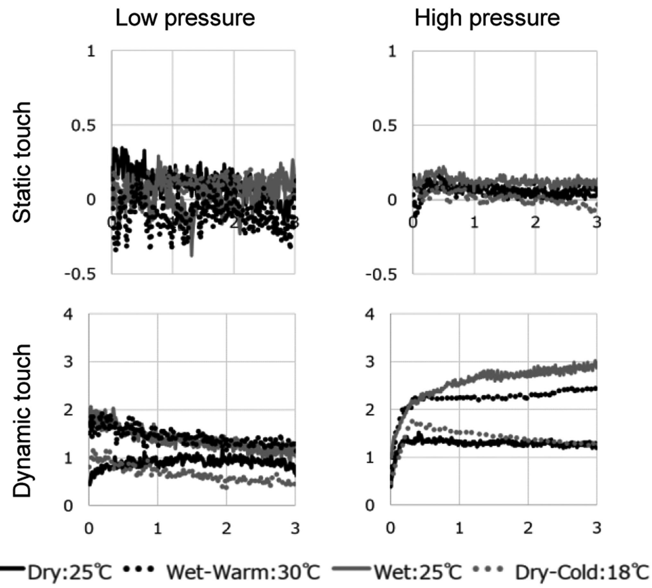

Fig. 4. Friction coefficients. The first author touched the stimuli and measured the tangential and vertical forces. The graphs show the calculated friction coefficient from those forces based on the average of five results.

decreases across all stimuli would not depend on skin characteristics (e.g., the thickness of the epidermal skin layer) if initial skin temperatures were similar across participants.

To examine the mechanical characteristics, the first author measured the tangential and horizontal forces exerted on the force plate located underneath the fabrics. Measurements were obtained at 1-millisecond intervals for the entire 3-second duration of the touch experiments. The friction coefficients calculated from the measured forces are shown in Fig. 4. To remove measurement noise, we averaged the last 10 measurement values. The friction coefficient was calculated as the difference between measures obtained at the initial stimulus contact and those obtained during 3 seconds. In the dynamic touch condition, the friction coefficient of the wet stimulus tended to be larger than that of the dry stimulus.

D. Experimental Design

Before the experiment, the participants touched the Wet and Dry conditions to confirm that they could perceive the difference in wetness between those conditions. Next, they practiced each touch while viewing the force plate display so that their touch was constant throughout the experiment. The participants scored the magnitude of the perceived wetness on a scale ranging from 0 to 6. Scores of “0” and “6” indicated complete dryness and extreme wetness, respectively. Prior to each touch set, the participants touched the Wet condition as practiced and were asked to establish the perceived wetness score of “6”. Each experiment consisted of four fabric conditions, four kinds of touch, and three repetitions, resulting in 48 total evaluations. Each experiment was divided into four sets of each touch, yielding a total of 12 trials. The set order and stimulus presentations were as a balanced design both within and across participants.

A typical experiment was performed as follows. First, a stimulus was placed on the cool plate for one minute to control its surface temperature; prior to participant contact, the temperature of the fabric was confirmed to have sufficiently changed. During this time, the participant’s skin temperature was adjusted via a brief contact with the hotplate. After one minute, the participant would hear a sound cue prompting them to touch the experimental stimulus with their right hand via the instructed type of contact for 3 seconds. After 3 seconds of contact, a second sound cue was played. The participants were then required to score the magnitude of the perceived wetness using a keyboard positioned by their left hand. After responding, the participants disengaged their right hand from the stimulus and removed moisture using a dry towel. The participants then repositioned their hands on the hotplate and waited for the next trial to begin. Each experimental set was separated by a 5-minute break.

E. Analysis

Using a seven-point rating scale, the participants scored the perceived wetness three times for each condition. The median of these three evaluations was used as the participants’ wetness score for each condition.

To statistically investigate the interaction effects by analysis of variance (ANOVA) using acquired nonparametric data, we computed the Aligned Rank Transform (ART) [34], [35] package using R, a free software package for statistics. The ART computes a separate aligned ranked response variable for each effect of the user-specified model; we then performed a classic ANOVA for each of the aligned ranked responses. We conducted a three-way ANOVA of the ART-treated data using stimuli (four levels: D, WW, DC, W), touch (two levels: static and dynamic), and pressure (two levels: low and high) as factors. Next, post hoc pairwise comparisons of the principal effect were performed by the Tukey test and cross-factor pairwise comparisons using Wilcoxon rank sum tests were performed as post hoc comparisons by the Holm-Bonferroni method.

We carried out a power analysis using the free software GPower [36] to confirm that the number of participants was adequate. The total sample size was 12 for three-way ANOVA for an effect size, significance level, and power of 0.3, 0.05, and 0.8, respectively. Therefore, the 21 participants included in this study were sufficient for the analysis.

Furthermore, we focused on individual differences in the results of the dynamic touch condition (see the next chapter). We grouped the participants according to the similarity of their results for Dry-Cold and Wet-Warm fabrics in dynamic touch with high pressure conditions. The grouping was conducted using k-means clustering function of the *KMeans* library for Python. We selected the number of clusters based on the elbow method (values of the sum of squares of errors within the cluster). The other parameters for the K-means function were the initial setting values.

After the grouping, we compared the tendencies of the participants’ responses by group mainly focusing on the differences between static and dynamic touches. We also conducted a three-way ANOVA for each group as described above. There

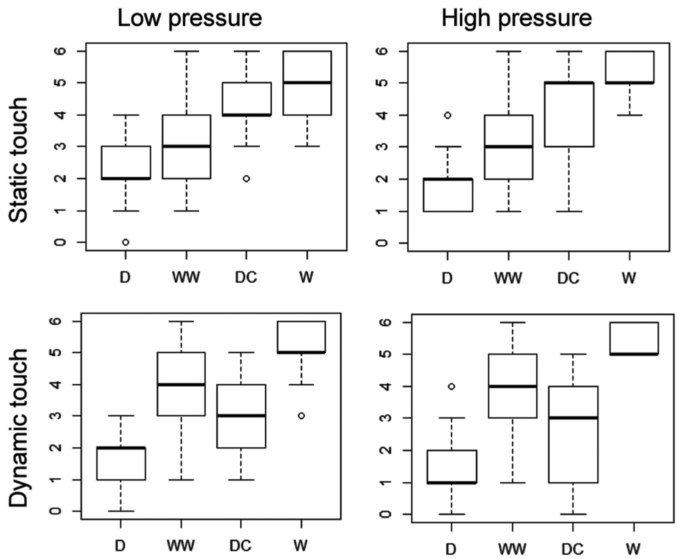

Fig. 5. Results of the analysis of all participant scores. The vertical axis represents the magnitude of perceived wetness. D, WW, DC, and W on the horizontal axis represent the Dry, Wet-Warm, Dry-Cold, and Wet conditions, respectively.

was the potential that the number of participants in each group was less than the adequate sample number (12); however, the ANOVA of each group was useful to investigate the difference in recognition of wetness between groups.

III. Results

Fig. 5 shows the boxplots of the values of the perceived wetness. The scores of wetness were highest in the order of Wet, Dry-Cold, Wet-Warm, and Dry for the static touch conditions, regardless of pressure. This order differed from that of the dynamic touch conditions, in which the order of Dry-Cold and Wet-Warm was reversed. The ANOVA showed an interaction effect between the stimuli and touch ($F(3,300) = 17.2$, $p < 0.01$). There was no significant difference (n.s.) between the stimuli and pressure ($F(3, 300) = 0.46$, $p = 0.7$). The participants significantly evaluated the fabrics of Dry and Wet conditions as dry and wet, respectively, in each of the four touch and pressure conditions. In the case of Dry-Cold and Wet-Warm fabrics, the participants evaluated Dry-Cold as wet significantly more often than the Wet-Warm fabrics in the static touch conditions ($V(41) = 595$, $p < 0.01$), while Wet-Warm was identified as wet significantly more often than was Dry-Cold in the dynamic touch conditions ($V(41) = 186$, $p = 0.012$).

We also found that the widths between the lowest and highest quartile of the boxplot diagrams for Dry-Cold stimulation; i.e., the individual differences in the results in the dynamic touch condition are wider than those for static touch. The widths for Wet-Warm stimuli in all four condition are also relatively wider than that those for the Dry and Wet conditions. To further investigate these individual differences, we conducted cluster analysis using the results of Dry-Cold and Wet-Warm stimuli in the dynamic touch conditions. Because there was no significant difference between the low and high pressures, we used data from the high-pressure conditions.

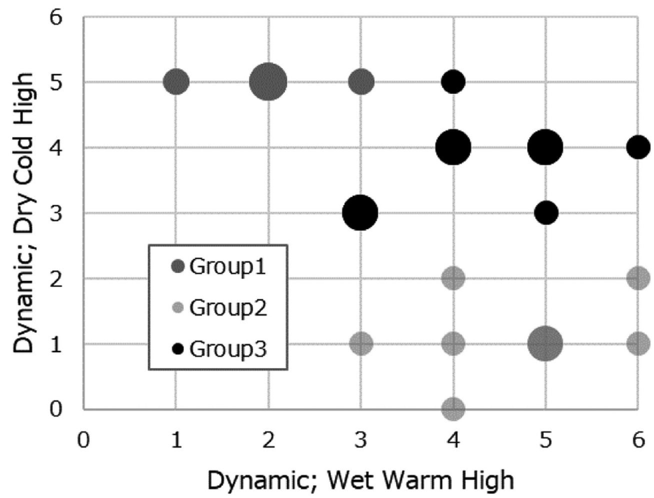

Fig. 6. Grouping of all participant. The larger circle represents the same evaluation by multiple participants.

Fig. 6 shows the results of clustering for three clusters. There are four, eight, and nine participants in groups 1, 2, and 3, respectively. Group 1 (dark gray dots) included participants who evaluated the Dry-Cold and Wet-Warm stimuli are relatively wet and dry, respectively, while the participants in Group 2 (light gray dots) evaluated the Dry-Cold and Wet-Warm stimuli are relatively dry and wet, respectively. The participants in group 3 (black dots) evaluated both stimuli as relatively wet.

Fig. 7 shows the boxplots of the data from each of these group. These graphs also represent the difference of the participants' response between groups. The ANOVA of each group showed that the main effect of stimuli for Group 1 (($F(3,45) = 50.6$, $p < 0.01$), and interaction effects between the stimuli and touch for Groups 2 ($F(3,105) = 12.5$, $p < 0.01$) and 3 ($F(3,120) = 22.8$, $p < 0.01$). The participants in Group 1 evaluated the Dry-Cold and Wet stimuli as wet (n.s. between the Dry-Cold and Wet, $t(15) = -0.7$, $p = 0.90$) and the Wet-Warm and Dry stimuli as dry (n.s. between the Wet-Warm and Dry, $t(15) = -0.26$, $p = 0.99$), regardless the touch type and pressure. There were differences between static and dynamic touch in Groups 2 and 3. The participants in Group 2 evaluated both Wet-Warm and Dry-Cold stimuli as relatively wet in static touch conditions (n.s. between the Wet-Warm and Dry-Cold, $(15) = 52.5$, $p > 0.99$) and Dry-Cold stimulus drier than Wet-Warm in dynamic touch ($V(15) = 4.5$, $p < 0.01$). Furthermore, the Dry stimulus in static touch scored wetter than that in dynamic touch ($V(15) = 102$, $p < 0.01$). The results of Group 3 are similar to those of Group 1 for the static touch conditions: there was no statistically significant difference between the Dry and Wet-Warm stimuli ($V(17) = 23$, $p = 0.19$) and, although there was a significant difference between the Dry-Cold and Wet stimuli ($V(17) = 6$, $p = 0.03$), the difference in the median wetness score between them was less than one. However, the scores for the Dry-Cold and Wet-Warm stimuli in the static touch condition were reversed under dynamic touch conditions: Dry-Cold was higher than Wet-Warm for static touch ($V(17) = 120$, $p < 0.01$) but vice versa for dynamic touch ($V(17) = 16$, $p = 0.02$).

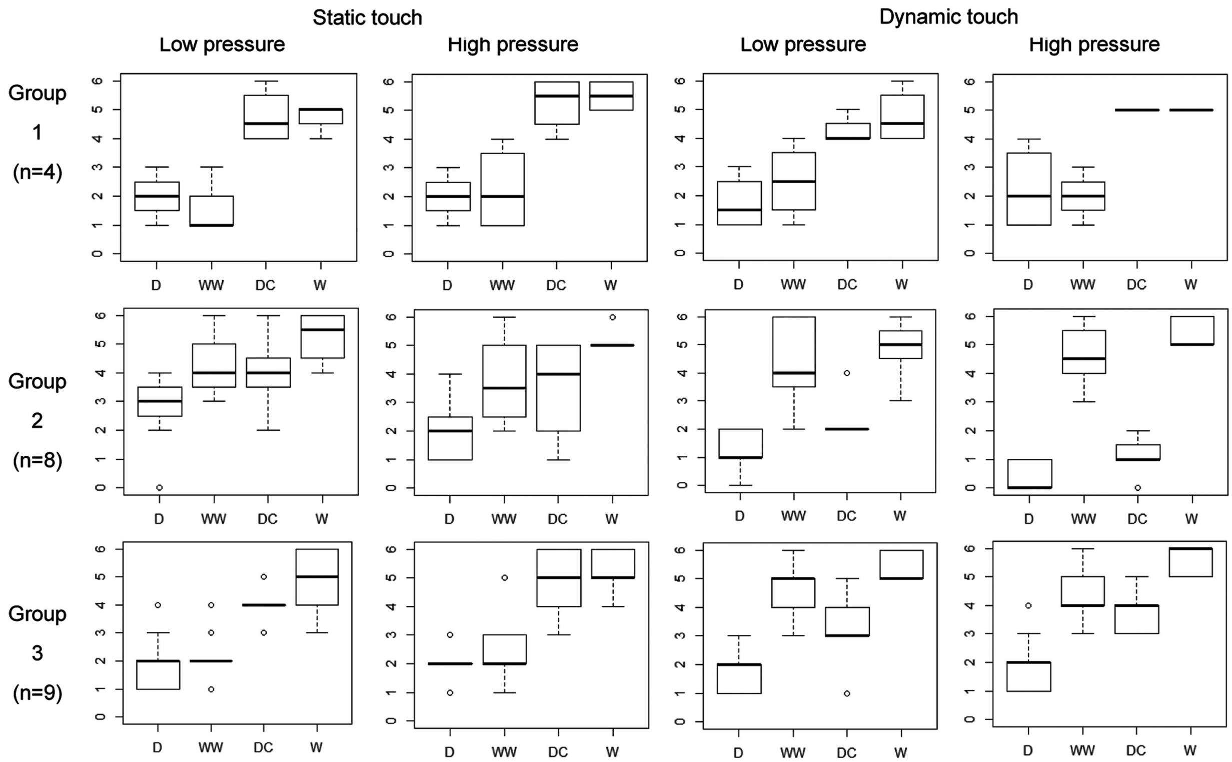

Fig. 7. Results of each group score. Rows represent the results of three groups. Columns represent the results of the four types of touch: static or dynamic, and low or high pressure. For example, the bottom right cell shows the result of Group 3 with by dynamic touch under the high-pressure condition. The vertical and horizontal axes of all graphs are the same as Fig. 5.

IV. Discussion

A. Wetness Illusion by Dynamic Touch

We hypothesized that the magnitude of the perceived wetness evoked by a Dry-Cold stimulus would differ between static and dynamic touch conditions. Furthermore, we thought that the pressure of dynamic touch might affect the perceived material wetness. We found that the perceived magnitude of wetness reported for the Dry-Cold and Wet-Warm stimuli differed based on the type of touch and that there were individual differences among participants. The first result corresponds with those of previous studies reporting that the threshold of wetness increases for dynamic touch in cases of actual wetted material [21]. Our results also showed that pressure did not have a significant effect on the magnitude of the perceived wetness. Previous studies using both wetted and dry materials have reported pressure to affect the wetness perception [18], [19], [20], [27]. The reasons for the discordant results may be due to differences in the experimental setups such as pressure conditions and body parts between this and previous studies. For example, the difference between the high- and low-pressure conditions of this study, which were approximately below 140 Pa and above 430 Pa, respectively, was smaller than that of the earlier study [27], which was 10000 Pa versus 7000 Pa. Moreover, participants touched the fabrics by their palms in our experiment; in the previous studies, stimuli were applied on the upper back [18], at the ventral aspect of the forearm [19], and the participants wore the garment [20]. In the study [20], tactile cues other than pressure, like the interactions between the fabric and sweat-induced skin (e.g., limited tactile interactions or allowed free interaction condition), can impact the perceived wetness. We should further consider the impact of the pressure on perceived wetness for future work.

Furthermore, the grouping results suggest that there are three methods for the recognition of wetness. Based on the wetness scores (Fig. 7), participants in Group 1 judged the static Wet-Warm stimulus "dryness" and the dynamic Dry-Cold stimulus as "wetness" (Fig. 7) regardless of the type of touch. Thus, we assumed that participants in this group gave priority to material coldness when perceiving wetness; nevertheless, the friction coefficient of the wetted stimulus increased enough for participants to discriminate them in the dynamic touch condition (Fig. 4).

In Group 2, the wetness illusion occurred only for the Dry-Cold stimuli and static touch condition (Fig. 7). The participants correctly judged the water content in the dynamic touch condition. These results imply that the participants in Group 2 used tactile information such as friction and roughness to judge the magnitude of wetness, especially in the dynamic touch condition. Furthermore, the wetness score for the Dry stimulus in the static touch condition was relatively high compared to that in the other touch conditions or groups. Therefore, the participants in Group 2 prioritized tactile information for the perception of wetness such that the wetness sensitivity was worse in static conditions than that in dynamic ones.

In Group 3, the wetness illusion was the same as that in Group 1 for the static touch condition but the participants judged the Wet-Warm stimuli as wetted in the dynamic touch

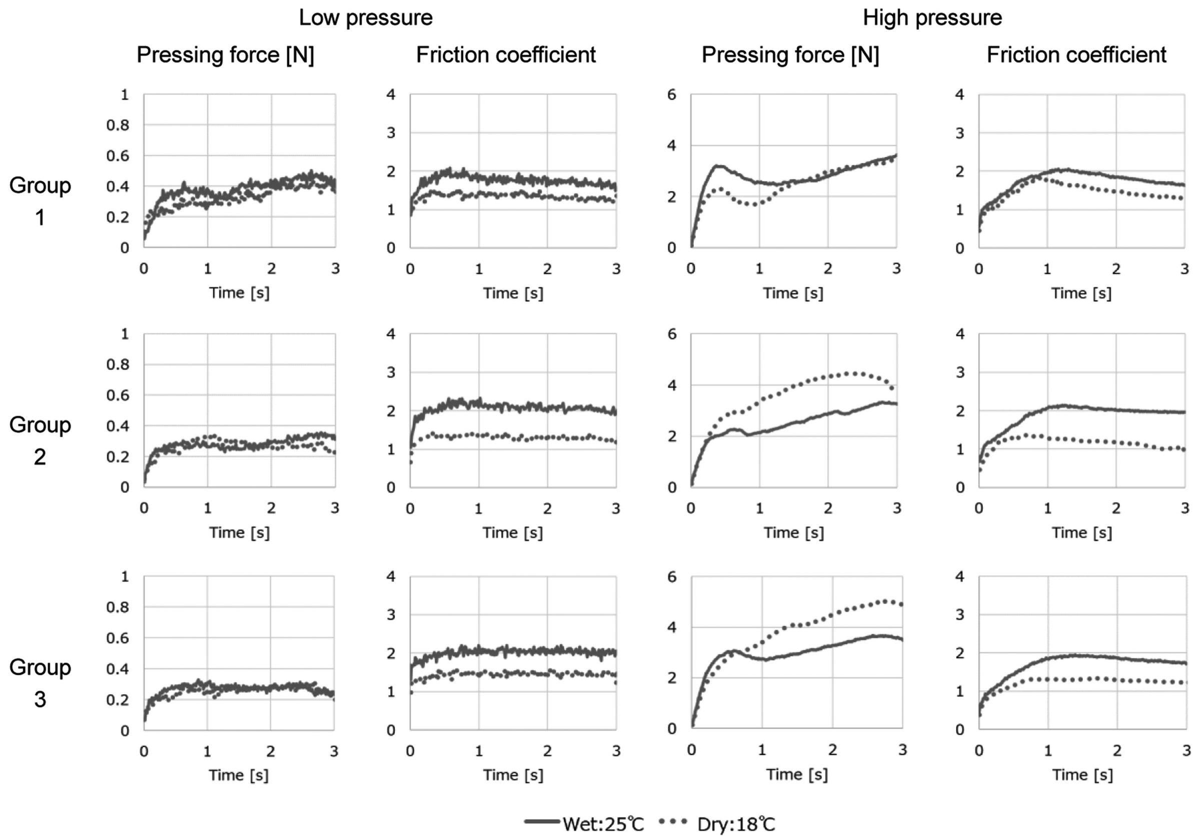

Fig. 8. Differences of force in the dynamic touch. Rows and columns represent the results of three groups and the pressure conditions, respectively. The left and right side of each cell represent the results of pressing force and friction coefficient, respectively.

conditions (Fig. 7). Furthermore, the score for the Dry-Cold stimulus in the dynamic touch condition was lower than that for the static touch condition and scores for the Wet-Warm and Dry-Cold stimuli were reversed under static and dynamic touch conditions. Therefore, the participants in Group 3 likely perceived the wetness through coldness (i.e., a decrease in skin temperature) in the static touch condition and through friction or roughness in the dynamic touch condition.

There are three possible causes for the individual differences. First, there might be individual differences in the integration processing even of the same physical stimuli. If this is the case, then the key factor determining the recognition of wetness would differ for each group. This would hold true in Group 1, which had higher scores for the Dry-Cold stimulus than those of the other groups for the dynamic touch condition, indicating that the participants likely gave priority to coldness when perceiving wetness. If there are individual differences in the integration process, the wetness perception may not be a cognition but rather an acquired recognition. Another possibility is the effect of hand movement. Some participants may have been so focused on moving their hand that they did not perceive the coldness of the fabric in dynamic touch condition. However, this hypothesis could not explain the large wetness scores for the Wet-Warm stimuli among the Group 2 participants for the static touch condition; the participants in this group judged the wetness of Wet-Warm stimuli based on the tactile sensations, not on temperature, without hand movement. The third possibility is a difference in the input of the physical stimuli. If the individual differences arose from variability in the physical input, skin friction might diverge across the groups.

To further investigate this third hypothesis, we analyzed the friction measurements across every trial in the psychophysical experiment (Fig. 8). Specifically, we focused on the Wet (solid line) and Dry-Cold (dotted line) stimuli, analyzing friction coefficients and pressures obtained from interactions with these stimuli on the force plate (Fig. 8). This analysis revealed that the difference in friction coefficient between the Dry-Cold and Wet stimuli in Group 1 tended to be smaller for both pressures than those in the other groups. This was particularly true for the friction coefficient of the Dry-Cold stimulus, which was higher than that in the other groups for the dynamic touch condition. As the physical property of the fabric was the same across all trials, these results might be due to differences in the microstructure of the skin (e.g., softness and unevenness). In other words, because friction was low when participants in Group 2 and 3 traced the Dry-Cold stimulus (due to the microstructure of the skin), these groups scored the Dry-Cold stimulus lower than did Group 1 based on coldness. However, additional studies are required to verify this hypothesis.

As such, we postulate that the cause of individual differences in the dynamic touch condition was due to variation in integration processing or in the input of the physical stimuli.

We expect that understanding of the difference in recognition of wetness between participants will be clues to clarify the mechanism of wetness perception.

B. Applications and Limitations

One of the aims of this study was to reproduce the wetness perception under conditions of both dynamic and static touch. To realize this aim, we suggest the following methods. In the static touch condition, our study and previous studies [26]–[30] found that the perceived wetness could be created by controlling the surface temperature. Moreover, most of the individuals who participated in this study were able to perceive the wetness from the Dry-Cold stimulus to the palm in the static touch condition. Thus, the perceived wetness can be reproduced in the static touch condition when the stimulus temperature is colder. This result is valuable for the application of telerobotics and neuroprostheses that require the grasping object with appropriate pressure. It will also allow the application of the wetness illusion to reproduce feeling of wetness or comfort when wearing fabrics in the context of virtual fitting technology.

However, in the dynamic touch condition, fewer participants reported the illusion of wetness when they traced the Dry-Cold stimulus compared to those in the static touch condition. Therefore, to reproduce the perceived wetness in the dynamic touch condition, we suggest that both tactile sensations and temperature be manipulated. In other words, both tactile and thermal feedback are required to provide realistic material recognition, which is usually done by hand during dynamic touch. The importance of tactile information in wetness perception may affect the illusion in other body parts. Because the density of mechanoreceptors and thermal receptors differ depending on body parts, the strength of the wetness illusion may also differ. For example, the wetness illusion may occur more strongly on the back of the torso than that on the palm; although their thermal sensitivities are similar [37], the back is less sensitive to tactile stimuli [38]. Differences in skin temperature due to body part, gender [39], and age could also affect the thermal sensation and wetness. Furthermore, if tactile information affects the illusion of wetness, the type of material with which the skin contacts; e.g., the fabric in this study, may also affect the illusion in dynamic touch conditions. These hypotheses will be investigated in future studies. Clarification of these points will allow the further application of the wetness illusion to reproduce feelings of wetness and comfort.

It should be noted that since the temperature of the Wet-Warm and Dry-Cold stimuli in our experiment were controlled, they are considered ‘artificial’ stimuli. However, in daily life, humans perceive wetness from ‘natural’ stimuli, from substances containing some liquid before touch and garments containing sweat produced by skin. An example of the former type of stimulation is laundry. When dried laundry is cooled by cold air conditioning (Dry-Cold) or wet laundry is warmed by a dryer (Wet-Warm), accurate judgement by only static contact with the hand, is difficult. However, if we trace the surface, by dynamic touch, we can differentiate between these conditions. In this way, the ‘natural’ experience of wetness in daily life aligns with our results obtained from ‘artificial’ stimuli. On the contrary, some instances of fabric with sweaty skin experienced in daily life are not in line with our results. Fukazawa and Havenith [1] found that the feeling of thermal comfort changed depending on wetness induced by the fabric, but without observing a concomitant reduction in skin temperature. This is similar to our condition with Wet-Warm stimuli, although, the result differed from our present study in which most participants did not perceive wetness from Wet-Warm stimuli by static touch. We estimate that tactile interaction between fabric and skin (e.g., friction and weight) during exercise led to wetness perception in the previous research [1]. Therefore, our results are applicable to instances of daily life when humans touch object surface containing water; although, our results from ‘artificial’ stimuli included some exceptions such as the sweat-induced situation.

V. Conclusion

We evaluated the illusion of perceived wetness when stimuli of varying water content and temperature were touched both statically and dynamically. We observed a difference in the wetness illusion between static and dynamic touches in which the participants scored the dry-cold stimulus as relatively dry when the material was touched dynamically. Furthermore, the recognition of wetness in dynamic touch conditions differed across individuals. The participants could be categorized into three groups based on their methods of judging wetness; namely, based on thermal sense, tactile sense, and either thermal or tactile sense depending on which was more effective according to the touch condition. The results were independent of the touch pressure. These results revealed the variability in the mechanisms used by humans to perceive wetness. We also described how to reproduce a wet perception in different touch conditions.

References

[1] T. Fukazawa and G. Havenith, “Differences in comfort perception in relation to local and whole body skin wettedness,” *Eur. J. Appl. Physiol.*, vol. 106, no. 1, pp. 15–24, 2009.

[2] T. Koshiba and T. Tamura, “Factors governing the wet sensation of human skin,” *J. Jpn. Res. Assoc. Textile End-Uses*, vol. 36, pp. 119–124, 1995.

[3] M. Yamakawa and S. Isaji, “Factors affecting the clamminess,” *J. Textile Eng.*, vol. 37, no. 12, pp. 492–500, 1984.

[4] K. H. Chau, K. P. Maggie Tang, and C. W. Kan, “Subjective wet perception assessment of fabrics with different drying time,” *Roy. Soc.*, Aug. 2018, Art. no. 180798, doi: 10.1098/rsos.180798.

[5] P. Saels, J. L. Thonnard, C. Detrembleur, and A. M. Smith, “Impact of the surface slipperiness of grasped objects on their subsequent acceleration,” *Neuropsychologia*, vol. 37, no. 6, pp. 751–756, 1999.

[6] T. André, V. Lévesque, V. Hayward, P. Lefèvre, and J.-L. Thonnard, “Effect of skin hydration on the dynamics of fingertip gripping contact,” *J. Roy. Soc. Interface*, vol. 8, pp. 1574–1583, 2011, doi:10.1098/rsif.2011.0086.

[7] A. M. Smith, G. Cadoret, and D. St-Amour, “Scopolamine increases prehensile force during object manipulation by reducing palmar sweating and decreasing skin friction,” *Express Brain Res.*, vol. 114, no. 3, pp. 578–583, 1997.

[8] T. André, P. Lefèvre, and J.-L. Thonnard, “Fingertip moisture is optimally modulated during object manipulation,” *J. Neurophysiol.*, vol. 103, pp. 402–408, 2009.

[9] D. Filingeri and R. Ackerley, "The biology of skin wetness perception and its implications in manual function and for reproducing complex somatosensory signals in neuroprosthetics," *Neuroscience*, vol. 117, no. 4, pp. 1761–1775, 2017.

[10] R. L. Peiris, L. Chan, and K. Minamizawa, "LiquidReality: Wetness sensations on the face for virtual reality," in *Proc. Int. Conf. Human Haptics Sens. Touch Enabled Comput. Appl., Part 2*, 2018, pp. 366–378.

[11] R. Ackerley, K. Saar, F. McGlon, and H. B. Wasling, "Quantifying the sensory and emotional perception of touch: Differences between glabrous and hairy skin," *Frontiers Behav. Neurosci.*, vol. 8, no. 34, Art. no. 34, 2014.

[12] S. Guest *et al.*, "The development and validation of sensory and emotional scales of touch perception," *Attention Perception Psychophys.*, vol. 73, no. 2, pp. 531–550, 2011.

[13] H. Shirado and T. Maeno, "Modeling of texture perception mechanism for tactile display and sensor," *Trans. Virtual Reality Soc. Jpn.*, vol. 9, no. 3, pp. 235–240, 2004.

[14] K. Tamura, K. Oyama, and H. Yamada, "Study on feeling evaluation applied to material recognition," in *Proc. JSME Dyn. Des. Conf.*, 2000, no. 709, pp. 77–80.

[15] Y. Tanaka, M. Tanaka, and S. Chonan, "Development of a sensor system for measuring tactile sensation," in *Proc. IEEE Sensors*, 2006, pp. 554–557.

[16] R. P. Clark and O. C. Edholm, "Man and his thermal environment, " *J. Neurophysiol.*, vol. 113, pp. 402–408, 2010, doi:10.1152/jn.00901.2009.

[17] D. Filingeri, D. Fournet, S. Hodder, and G. Havenith, "Why wet feels wet? A neurophysio-logical model of human cutaneous wetness sensitivity," *J. Neurophysiol.*, vol. 112, no. 6, pp. s1457–1469, 2014.

[18] M. Raccuglia, S. Hodder, and G. Havenith, "Human wetness perception in relation to textile water absorption parameters under static skin contact.," *Textile Res. J.*, vol. 87, no. 20, pp. 2449–2463, 2017.

[19] M. Raccuglia *et al.*, "Human wetness perception of fabrics under dynamic skin contact," *Textile Res. J.*, vol. 88, no. 19, pp. 2155–2168, 2018.

[20] D. Filingeri, D. Fournet, S. Hodder, and G. Havenith, "Tactile cues significantly modulate the perception of sweat-induced skin wetness independently of the level of physical skin wetness," *J. Neurophysiol.*, vol. 113, no. 10, pp. 3462–3473, 2015.

[21] W. M. Bergmann Tiest, N. D. Kosters, A. M. L. Kappers, and H. A. M. Daanen, "Haptic perception of wetness," *Acta Psychologica*, vol. 141, no. 2, pp. 159–163, 2012.

[22] W. M. Bergmann Tiest, N. D. Kosters, A. M. L. Kappers, H. A. M. Daanen, "Phase change materials and the perception of wetness," *Ergonomics*, vol. 55, no. 4, pp. 508–512, 2012.

[23] X. Chen, C. J. Barnes, T. H. C. Childs, B. Henson, F. Shao, "Materials' tactile testing and characterisation for consumer products' affective packaging design," *Mater. Des.*, vol. 30, no. 10, pp. 4299–4310, 2009.

[24] R. Ackerley, H. Olausson, J. Wessberg, F. McGlone, "Wetness perception across body sites," *Neurosci. Lett.*, vol. 522, no. 1, pp. 73–77, 2012.

[25] D. Filingeri, D. Fournet, S. Hodder, G. Havenith, "Body mapping of cutaneous wetness perception across the human torso during thermo-neutral and warm environmental exposures," *J. Appl. Physiol.*, vol. 117, no. 8, pp. 887–897, 2014.

[26] D. Filingeri, B. Redortier, S. Hodder, G. Havenith, "The role of decreasing contact temperatures and skin cooling in the perception of skin wetness," *Neuroscience*, vol. 551, pp. 65–69, 2013.

[27] D. Filingeri, B. Redortier, S. Hodde, G. Havenith, "Thermal and tactile interactions in the perception of local skin wetness at rest and during exercise in thermo-neutral and warm environments," *Neuroscience*, vol. 258, pp. 121–130, 2014.

[28] H. A. M. Daanen, "Method and system for alerting the occurrence of wetness," European Patent 2268247, 2009.

[29] M. Shibahara and K. Sato, "Illusion of moisture sensation of a cloth by thermal control," *Jpn. Res. Assoc. Textile End-Uses*, vol. 56, no. 12, pp. 951–958, 2015.

[30] M. Shibahara and K. Sato, "Illusion of wet sensation by controlling temperature and soft-ness of dry cloth," in *Proc. Int. Conf. Human Haptic Sens. Touch Enabled Comput. Appl., Part 1*, 2016, pp. 371–379.

[31] D. Filingeri, B. Redortier, S. Hodder, and G. Havenith, "Warm temperature stimulus suppresses the perception of skin wetness during initial contact with a wet surface," *Skin Res. Technol.*, vol. 21, no. 1, pp. 9–14, 2015.

[32] G. H. Van Doorn, V. Dubaj, D. B. Wuillemin, B. L. Richardson, and M. A. Symmons, "Cognitive load can explain differences in active and passive touch," in *Proc. Int. Conf. Human Haptic Sens. Touch Enabled Comput. Appl.*, 2012, pp. 91–102.

[33] B. G. Green, "Temperature perception on the hand during static versus dynamic contact with a surface," *Attention, Perception, Psychophys.*, vol. 71, no. 5, pp. 1185–1196, 2009.

[34] J. J. Higgins and S. Tashtoush, "An aligned rank transform test for interaction," *Nonlinear World*, vol. 1, no. 2, pp. 201–211, 1994.

[35] J. O. Wobbrock, L. Findlater, D. Gergle, and J. J. Higgins, "The aligned rank transform for nonparametric factorial analyses using only ANOVA procedures," in *Proc. Int. Conf. Human Factors Comput. Syst.*, 2011, pp. 143–146.

[36] F. Faul, E. Erdfelder, A. G. Lang, and A. Buchner, " G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences," *Behav. Res. Methods*, vol. 39, no. 2, pp. 175–191, 2007.

[37] J. C. Stevens and K. K. Choo, "Temperature sensitivity of the body surface over the life span," *Somatosensory Motor Res.*, vol. 15, pp. 13–28, 1998.

[38] S. Weinstein, "Intensive and extensive aspects of tactile sensitivity as a function of body part, sex and laterality," in *Proc. 1st Int. Symp. Skin Senses*, 1968, pp. 195–222.

[39] H. Kim, C. Richardson, J. Roberts, L. Gren, and J. L. Lyon, "Cold hands, warm heart," *The Lancet*, vol. 351, no. 9114, p. 1492, 1998.

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