COMMUNICATIONS IN
DEVELOPMENT AND ASSEMBLING OF TEXTILE PRODUCTS

Influence of environmental temperature on the hand-feel perception of textiles

Lars Claussen[1], Kimberly Lim[1], Julia Wilfling[1], Alex Lloyd[1], Daniel Ruiz[2], George Havenith[1,*]

[1] *Environmental Ergonomics Research Centre, Loughborough School of Design and Creative Arts, Loughborough University, Loughborough, UK*
[2]*adidas Innovation, adidas AG, Herzogenaurach, Germany*
*Corresponding author *E-mail address:* g.havenith@lboro.ac.uk

INFO

CDAPT, ISSN 2701-939X
Peer reviewed article
2023, Vol. 4, No. 1, pp. 95-109
DOI 10.25367/cdatp.2023.4.p95-109
Received: 30 November 2022
Accepted: 24 January 2022
Available online: 25 March 2023

ABSTRACT

The present study investigated the effect of environmental temperature on the hand-feel perception of textiles. Participants were exposed to three different climate conditions (10 °C/20 °C/ 30 °C, RH 65 %) to simulate cool, mild, and warm environments. Hand-feel attributes, comfort, and preferences of a wide range of textiles were rated by the participants. Participants' body responses to the different temperatures were controlled by monitoring participants' aural temperature, mean skin temperature, hand temperature, tactile sensitivity, and environmental perception. Fabric weight was measured to monitor changes in textile properties induced by the different environmental conditions. The outcomes of the study suggest that the environmental temperature led to significant changes in participants' aural temperature, mean skin temperature, hand temperature, tactile sensitivity, and environmental perception, affecting the hand-feel perception of the different textiles. Thus, the present study provides insight for practitioners to develop more comfortable textiles for specific environmental temperatures by establishing a basis for understanding how environmental temperature, body responses, and hand feel perception interact.

Keywords
textiles,
temperature,
hand-feel,
touch,
fabric hand,
perception,
tactile sensitivity,
haptic,
comfort

1 Introduction

Perception of clothing/textiles and their related comfort needs to be considered in the interplay of clothing, environment, and body. One factor is affecting the other [1]. Therefore, changes in environmental conditions, like in the case of the present study the environmental temperature, are affecting the human body and also the textile itself. For example, in the heat, the human body starts sweating, and the properties of the textile can change, as shown by Naebe et al. [2] for the objective hand-feel measurement, which consequently leads to a changing perception of the textile [3, 4]. The present study applied this holistic clothing-environment-body view from the clothing/textile perception to the hand-feel perception of textiles.

Textile hand-feel is seen as one component of clothing comfort next to the physiological and psychological components [5, 6]. Textile hand-feel can be defined as the sensations caused by a textile in contact with the skin [5, 7–9]. The sensations induced by textile-skin contact are categorised into four types of sensorial properties which can influence each other. Sensorial properties like smoothness, roughness, prickliness, stickiness, scratchiness, softness, and stiffness are related to the mechanical properties of the fabric [9]. Skin contact with a textile can lead to the sensation of a temperature change, described as a warm or cold touch. Moisture-related sensations include clamminess, dampness, wetness, stickiness, and clingy sensations. The pressure of the fabric refers to sensations like lightness, heaviness, softness, and stiffness [10, 11]. Similarities exist between the descriptors used for hand-feel, environment and body. For example, a warm or cold sensation is typically used to describe the environmental temperature, and a sweaty body can feel wet or sticky.

Physiology can explain how the environmental temperature potentially influences the textile hand-feel perception. As part of thermoregulation, the body either increases the blood flow to the skin (vasodilation) or reduces the blood flow to the skin (vasoconstriction). The first cools the body with an increased skin temperature, while the second reduces the skin temperature and prevents heat loss. This process particularly impacts extremities such as hands [12, 13]. Several studies have shown that skin temperature affects tactile sensitivity. Especially a reduction in skin temperature leads to a deterioration of tactile sensitivity. Within the studies, the effect of skin temperature on tactile sensitivity varied with the mode of tactile stimulation, quality of the stimulus, and type of threshold determination [14–22].

While the hand-feel itself, or more specifically the tactile sensitivity, is influenced by the environmental temperature, only limited research has investigated how the environmental temperature influences the perception of textile hand-feel. Liao et al. [23] investigated the influence of temperature and humidity acclimatisation on textile hand-feel perception. 226 participants from six East-Asian cities with different climates assessed fabrics in a chamber with constant climate conditions. It was found that the climate to which the participants were habitually acclimatised affected their smoothness and warmth perception. While this study shows that the climatic environment in which the participants live affects the hand-feel rating, it does not show how the actual environmental temperature during the experiment affects the hand-feel rating, as this was kept constant. Similar to the present study, Gwosdow et al. [24] studied the influence of skin friction on the perception of fabric texture and pleasantness in a hot-dry, hot-humid and neutral environment. Increasing the temperature and humidity led to higher skin wetness, associated with a higher force needed to pull fabrics over the participants' skin. The higher skin wetness and friction in warm-humid environments were connected with a less pleasant and more rough perception of the tested fabrics. The superficial perception rating used in Gwosdow et al.'s study does not deliver detailed insight into textile hand-feel perception changes. The study focused mainly on skin friction and used a passive forearm-feel evaluation method (fabrics pulled across the participant's forearm). In the present study, an active hand-feel evaluation method is used. Gwosdow et al.'s. study was also limited to mild and warm temperature conditions. During controlled wear trials, Stanton et al. [25] showed that the environmental climate influenced the prickle and discomfort scores of woollen long-sleeved t-shirts.

Studies have shown that environmental temperature influences tactile sensitivity. How this affects the textile hand-feel perception is not fully understood yet and is relevant for developing clothing/textiles made for specific climates. Appling a clothing-environment-body view, the present study investigates if and how the perception of hand-feel attributes, comfort, and preferences of a wide range of textiles changes in cool (10 °C, RH 65 %), mild (20 °C, RH 65 %), and warm (30 °C, RH 65 %) environments while monitoring participants' aural temperature, mean skin temperature, hand temperature, tactile sensitivity, environmental perception and fabric weight.

2 Method

2.1 Materials

A major sports clothing company supplied textile fabrics with a wide range of characteristics designed for different seasons. The textiles had different fabric structures and thicknesses and were made from different materials. The specifications of the textiles are given in Table 1. Textile 2 (polyester fleece) and textile 5 (wool fabric) represent fabrics for cooler seasons, while textile 7 (thin polyester single jersey) is a typical example of fabric for warmer seasons.

Table 1: Specifications of the textiles used.

Textile	Material composition [%]	Structure	Weight [g m^{-2}]	Thickness [mm]
1	100 % Polyester	Single jersey	145.9	0.83
2	100 % Polyester	Double layer, Face side: Brushed fleece Skin side: Single jersey	157.9	2.13
3	100 % Cotton	Double knit, Face side: Single jersey Skin side: Waffle	303.5	1.93
4	100 % Polyester	Interlock	123.1	0.64
5	100 % Wool	Flat knit	342.8	2.34
6	80.5 % Polyester 14.6 % Cotton 4.9 % Elastane	Single jersey	233.5	0.84
7	100 % Polyester	Single jersey	75.5	0.36

Table 2: Fabric structure of the face (upper row) and skin side (lower row) of the textiles used. The pictures represent a fabric width of 10 mm.

Textile 1	Textile 2	Textile 3	Textile 4	Textile 5	Textile 6	Textile 7

2.2 Research design and analysis

To investigate how the environmental temperature affects the hand-feel perception of textiles, three study sessions in cool (10 °C, RH 65 %), warm (30 °C, RH 65 %), and mild (20 °C, RH 65 %) temperature conditions were conducted in a climate-controlled chamber. The textiles were acclimated two hours before the experiment, and the participants were acclimated for 30 minutes at seated rest. Changes in the fabric weight, body responses, environmental perception, and textile hand-feel perception were measured during the experiment. Participants were asked to wear clothing in which they felt comfortable during the sessions, but did not cover their hands.

After the two hours acclimation of the textiles, the fabric weight was measured at the respective environmental temperature following BS EN 12127:1998 [26]. The fabric weight was monitored to identify potential effects on the textile properties due to temperature changes and, related to this, absolute humidity changes in the environment.

Through physiological measurements and perception ratings it was monitored how the body reacts to changes in environmental temperature. iButtons placed at the chest, left upper arm, left anterior thigh, and left shin measured the mean skin temperature of the participants every minute from the start of the acclimation till the end of the session according to Ramanathan's 4-point mean skin temperature protocol [27]. The participant's aural temperature was measured at the start of the acclimation period, after the acclimation period and at the end of the session using a Braun Welch Allyn Thermoscan Pro4000. These three-time points will be referred to as 'Pre', 'Post' and 'End' in the graphs of the present manuscript. Hand temperature was measured by infrared thermal imaging at the same three points in time. Following recommendations from the literature, a FLIR T620 camera was set up and calibrated using an Omega Black Point Blackbody Calibrator BB702 [28, 29]. Using the FLIR tools program, the temperatures at the palm, proximal little finger, distal little finger, thump, proximal index finger and distal index finger of the right and left hand were extracted from the thermal images. The participants' tactile sensitivity was measured in the same areas of the hands after the 30 min acclimation period using an Aesthesio Precision Tactile Sensory Evaluator 20-piece kit of Von Frey filaments. The cutaneous sensation threshold, measured as the minimum tactile force applied necessary to evoke a sensation, was determined following the 4,2, and 1 stepping algorithm by Dyck et al. [30]. The environmental perception was assessed following ASHRAE standard 55 by asking participants to rate their thermal sensation, thermal preference, comfort and satisfaction on 7-point Likert scales [31].

After acclimation and the physiological measurements, the participants evaluated hand-feel attributes and comfort of the face side of seven textiles and selected their preferred textile for the respective session. The hand-feel evaluation followed the guidelines given in AATCC EP5 [32]. Participants sat behind a shield, so they were blinded and could only feel the textile samples. The textiles were presented in a randomised order to avoid any order effects. For the hand-feel evaluation, participants performed the touch-stroke, rotating cupped/squeeze, and pinch method with their hands as described in AATCC EP5. The following seven hand-feel attributes were evaluated during the study on a 7-point Likert scale with bipolar attributes at both extreme ends: Warm-cool, rough-smooth, hard-soft, stiff-flexible, thin-thick, dry-damp, and light-heavy. The comfort of the textiles was evaluated on a comfort affective labelled magnitude (CALM) scale [33]. At the end of each session, participants were asked to choose their preferred textile to wear in the designated condition.

Statistical analysis was performed to determine if there is a significant difference in the physiological measurements and perception ratings between the three sessions (10 °C, 20 °C, 30 °C) post acclimation. For the aural, mean skin, and hand temperatures, a one-way repeated measures ANOVA was performed with post-hoc tests. A Friedman's test was used to determine differences in the hand-feel attribute rating, CALM scores, thermal assessment ratings, and tactile sensitivity between the three sessions. The Chi-square goodness of fit test was used to test whether there was a significant preference for one or more fabrics in the preference vote. A significance threshold of $p < .05$ was set for all statistical tests.

2.3 Sample

A convenience sample of ten participants was recruited from the Loughborough University student cohort. The sample size followed the recommendations for controlled clothing physiology trials [34–36]. The participants had a mean age of 24.5 (SD = 2) and were all right-handed. Six females and four males participated in the study. The inclusion criteria for the study were that the participants are healthy, non-smokers, and aged between 18 and 35. Due to the nature of the study, it was emphasised that the participants had no skin abnormalities in the palm and finger areas, such as rashes and calluses, and had no hand sensation impairments. Loughborough University's Human Participants sub-committee granted ethical approval for the study (Project ID: 8583), and participants gave informed consent.

3 Results

In all three temperature conditions, the fabric weight of all textiles stayed constant. No significant difference could be found, and the standard deviation was at a maximum of 1.42 g m^{-2} (textile 5, 30 °C). This suggests that the textile properties are only affected to a limited extent by the changes in the environmental temperature. The fabric weight, for example, facilitates the assessment of moisture absorbed from the environment into the textiles.

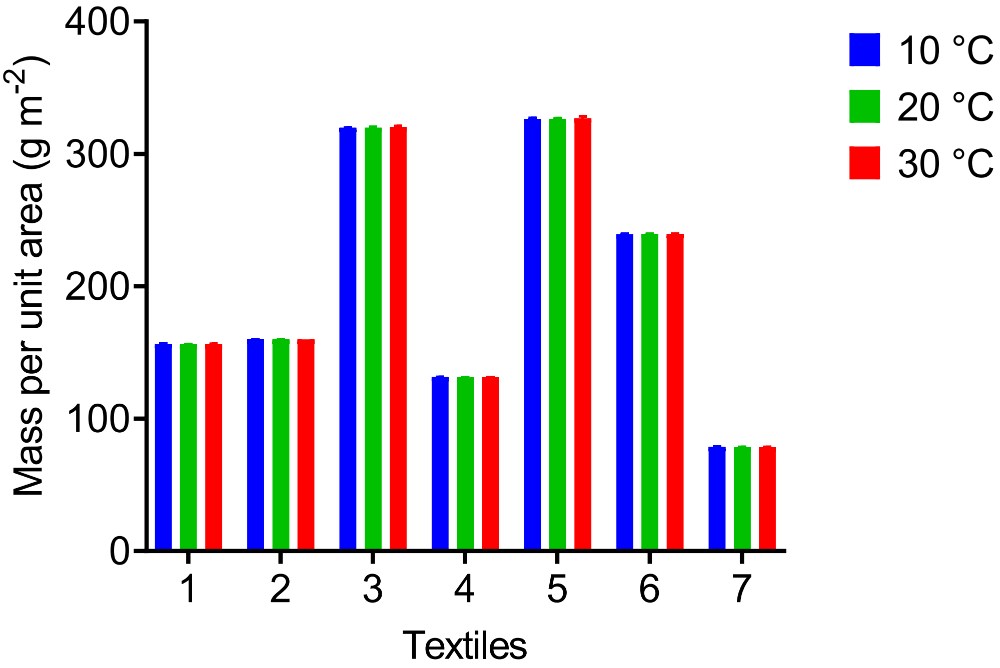

Fig. 1: Fabric weight of textiles 1 - 7 at 10 °C, 20 °C, and 30 °C; The graph shows the mean with SD.

In contrast to the textiles, the participants' bodies showed clear reactions to the changes in environmental temperature. Throughout the individual sessions, the three measured temperatures, aural (Fig. 2 a), mean skin (Fig. 2 b), and hand temperature (Fig. 3), followed the expected trends. In the warm condition, the three temperatures increase; in the cool, they decline; and in the mild condition, they stay relatively stable. For the hand temperature, it was interesting to observe that the closer the measured points were to the centre of the hand, the warmer they were, and the farther away the measured points were, the cooler they were. A repeated measure ANOVA showed that there is a significant difference in the temperature measurements between the three sessions (10 °C, 20 °C, 30 °C) post acclimation. For the aural temperature, a post hoc test showed that the aural temperature was significantly higher in the warm environment than in the neutral environment. The mean skin temperature at minute 30 (start of post acclimation) differed significantly between the three sessions, increasing from cool to neutral to warm. There was a significant difference in hand temperature between the three sessions after acclimation for both the right and left hand in all six hand locations. Again the hand temperature increased from cool to neutral to warm.

The global picture that arose from the absolute values of the tactile sensitivity test measured by the Von Frey Filaments was that a higher tactile force was required to elicit a sensation in the cool condition than in the other two conditions, meaning that the participant's hands were less sensitive in the cold. Statistical tests partially confirmed this picture, especially for the right hand, which was less sensitive than the left hand. A red asterisk in Fig. 4 indicates significant differences between the three sessions identified by a Friedman test. Based on pairwise comparisons, the significant difference was most frequently found between the sessions at 10 °C and 30 °C. Exceptions are the right palm, right proximal little finger, left proximal little finger, and right distal index finger. For the latter two, no difference was found in the pairwise comparison. For the right palm, there was next to a difference between the sensitivity at 10 °C and 30 °C also, a difference between 20 °C and 30 °C. The right proximal little finger's sensitivity differed between 10 °C and 30 °C, and between 10 °C and 20 °C. Further, the variation in hand sensitivity was much higher in the cool condition than in the mild and warm conditions, which matches the variations in hand temperature.

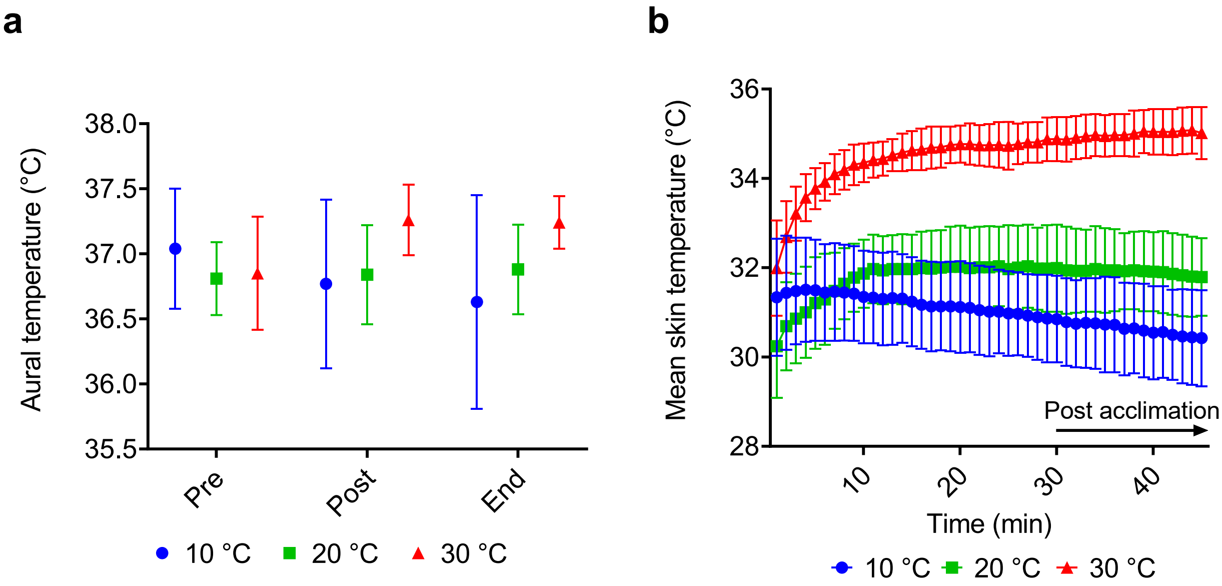

Fig. 2: (a) Aural temperature at 10 °C, 20 °C, and 30 °C for the points of time pre- and post-acclimation and at the end of the session; (b) Mean skin temperature 10 °C, 20 °C, and 30 °C recorded every minute of the sessions; Graphs show the mean with SD.

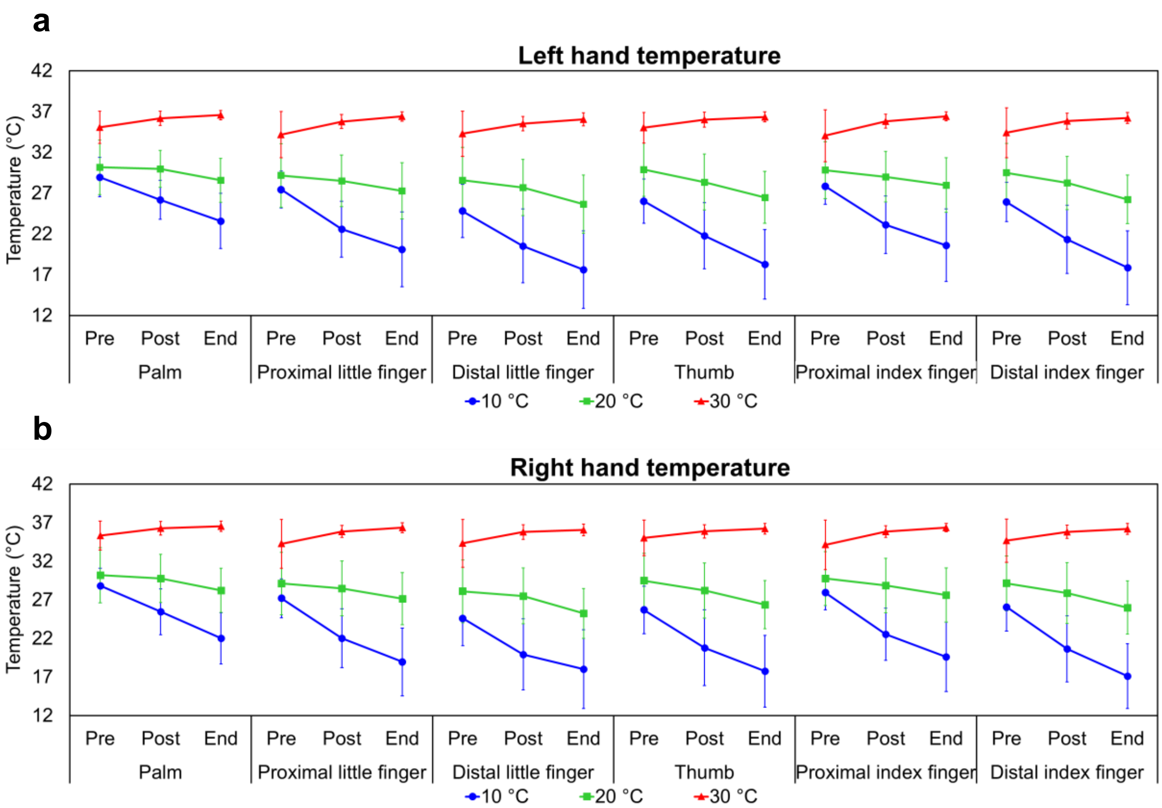

Fig. 3: (a) Left hand temperature and (b) right hand temperature at 10 °C, 20 °C, and 30 °C for the points of time pre- and post-acclimation and at the end of the session; The hand temperature is displayed for the palm, proximal little finger, distal little finger, thump, proximal index finger and distal index finger; Graph shows the mean with SD.

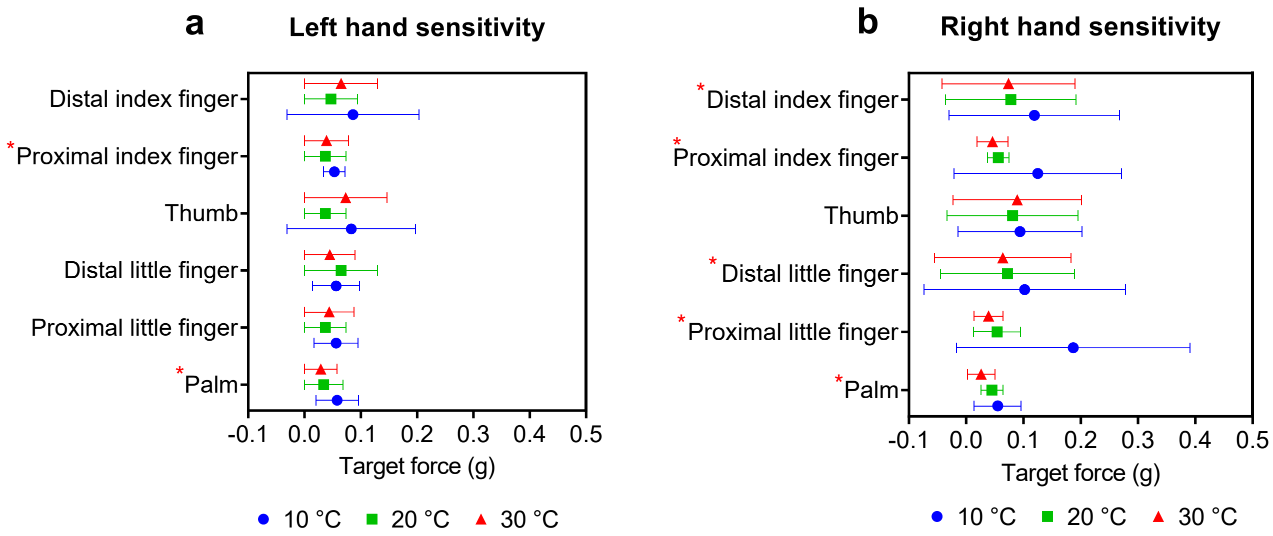

Fig. 4: (a) Left hand sensitivity and (b) right hand sensitivity post acclimation at 10 °C, 20 °C, and 30 °C measured by Von Frey Filaments. The hand sensitivity is displayed for the palm, proximal little finger, distal little finger, thump, proximal index finger and distal index finger; Graphs show the mean with SD.

Participants' perceptions of the environmental conditions during the three sessions differed substantially. For the 20 °C sessions, the median of the thermal sensation rating was 'neutral', the thermal preference was 'no change', the participants felt 'comfortable', and the participants were satisfied with the environmental conditions. Changing the ambient temperature to 30 °C resulted in median ratings that went more towards the extremes of the scale. According to the median ratings, participants felt 'warm' and would prefer a 'slightly cooler' environment. Resulting in a 'slightly uncomfortable' and 'slightly dissatisfied' environmental assessment, the worst assessment of all three sessions. At 10 °C, the environmental conditions were perceived as 'slightly cool', and the participants would prefer a 'slightly warmer' environment. The comfort and satisfaction assessment median rating was between 'neutral' and 'slightly comfortable/satisfied'. A Friedman test confirmed that the environmental assessment differed significantly between all three sessions. The details of the pairwise comparison are shown in Fig. 5 by asterisks.

The hand-feel attribute rating of the seven textiles during the three sessions is displayed in Fig. 6. To better illustrate variations in the hand-feel attribute rating between the three sessions, Fig. 7 shows the mean difference between the rating at 20 °C, which was taken as a standard, and the rating at 10 °C and 30 °C. As the rating was done on a 7-point Likert scale, the highest possible variations are ± 6. It stands out in Fig. 6 that the hand-feel attribute rating for the textiles varied strongly, which reflects the diversity of the selected textiles. The rating also corresponds to the objective hand-feel measurements of the textiles conducted in previous studies (Wilfling, unpublished results). Although there were significant differences in the textile attribute rating between the sessions, it is difficult to establish a general trend of how the environmental temperature influences the hand-feel attribute rating. Statistical differences are indicated in Fig. 6 by asterisks. Most frequently, significant differences between the session were found for the attributes thin-thick (5 of 7 textiles), followed by stiff-flexible (3 of 7 textiles), warm-cool and hard-soft (2 of 7 textiles), and light-heavy (1 of 7 textiles). There was no significant difference for all textiles for the attributes dry-damp and smooth-rough. A paired comparison showed that the significant difference was most frequent between the sessions at 10 °C and 30 °C. The inconsistent trend in the effect of temperature on the attribute rating can also be seen in Fig. 7. While the mean rating at 10 °C and 30 °C vary from the rating at 20 °C, there is no clear direction in which the ratings deviate. Generally, there is a limited variation from the 20 °C rating. The mean 10 °C ratings deviated at most by 0.9. This was the case for attribute smooth-rough for textile 2 and light-heavy for textile 5. For the mean 30 °C ratings, the maximum deviation was 1.5, as found in textile 6 for the attribute warm-cool.

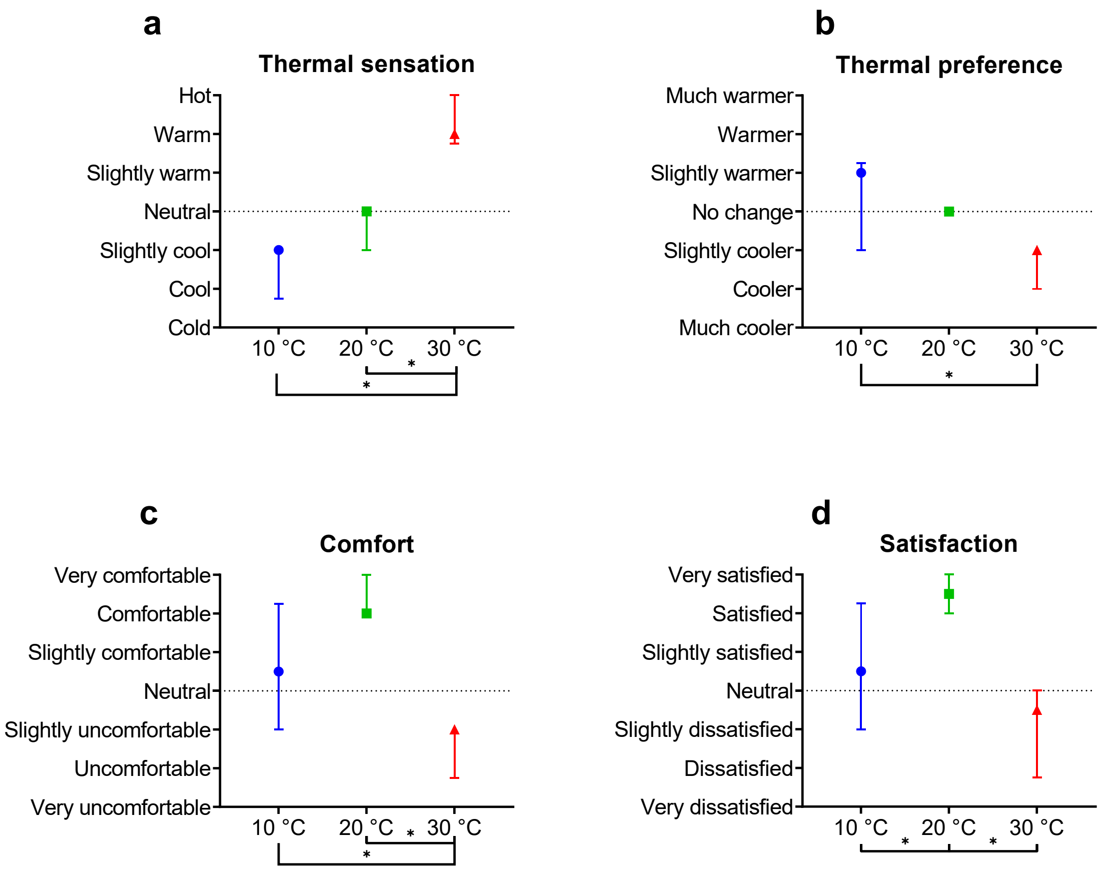

Fig. 5: Environmental perception of (a) Thermal sensation, (b) Thermal preference, (c) Comfort, and (d) Satisfaction at 10 °C, 20 °C, and 30 °C; Asterisks demonstrate significant differences based on a pairwise comparison; Graphs show the median with interquartile range.

The textile comfort rating (Fig. 8 a) reflected the season the textiles were designed for. The thicker fabrics 2, 5, and 3 were rated as comfortable in cool conditions and rated as uncomfortable in warm conditions. On the other side of the scale, the thinnest textile, 7, was rated the most comfortable in warm conditions and the most uncomfortable in cool conditions. The most comfortable textile in the mild condition was textile 6. Textile 4 was the only textile that was perceived as comfortable in all three conditions. The comfort rating also significantly differed between the three conditions for textiles 2, 5, 6, and 7. The significant difference mainly occurred when comparing the rating at 10 °C with the rating at 20 °C or 30 °C.

The results of the comfort vote were reflected in the preference rating. Textiles 2 and 5 were the preferred textiles at 10 °C. Textile 6 was most preferred, followed by both textile 4 and 7 at 20 °C. For 30 °C, textiles 7 and 4 were the preferred ones with equal votes. A chi-square test confirmed that the textiles described above were significantly preferred in the respective conditions over the other textiles.

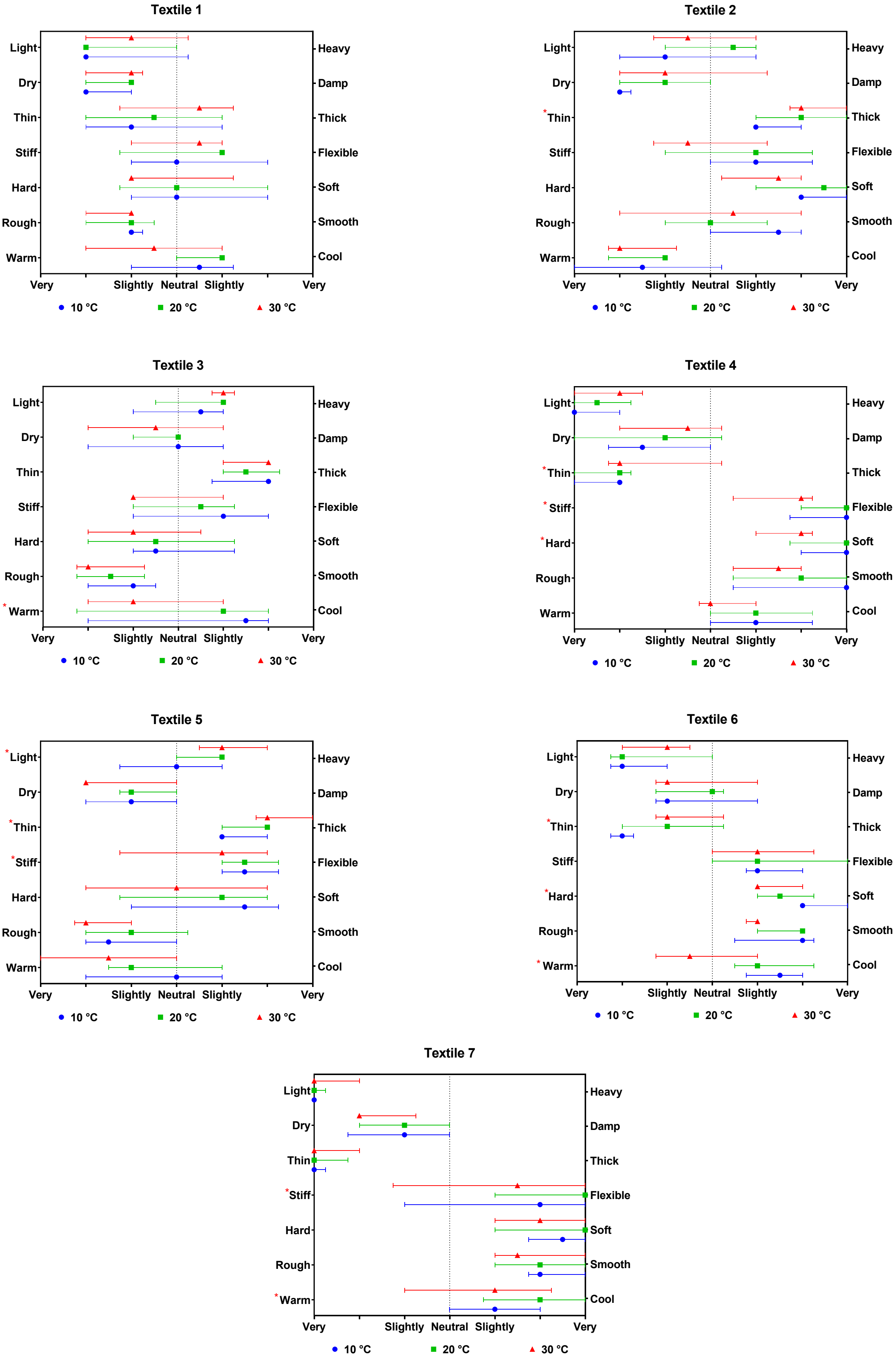

Fig. 5: Hand-feel attribute rating of textiles 1 - 7 at 10 °C, 20 °C, and 30 °C; The graphs show the median with interquartile range.

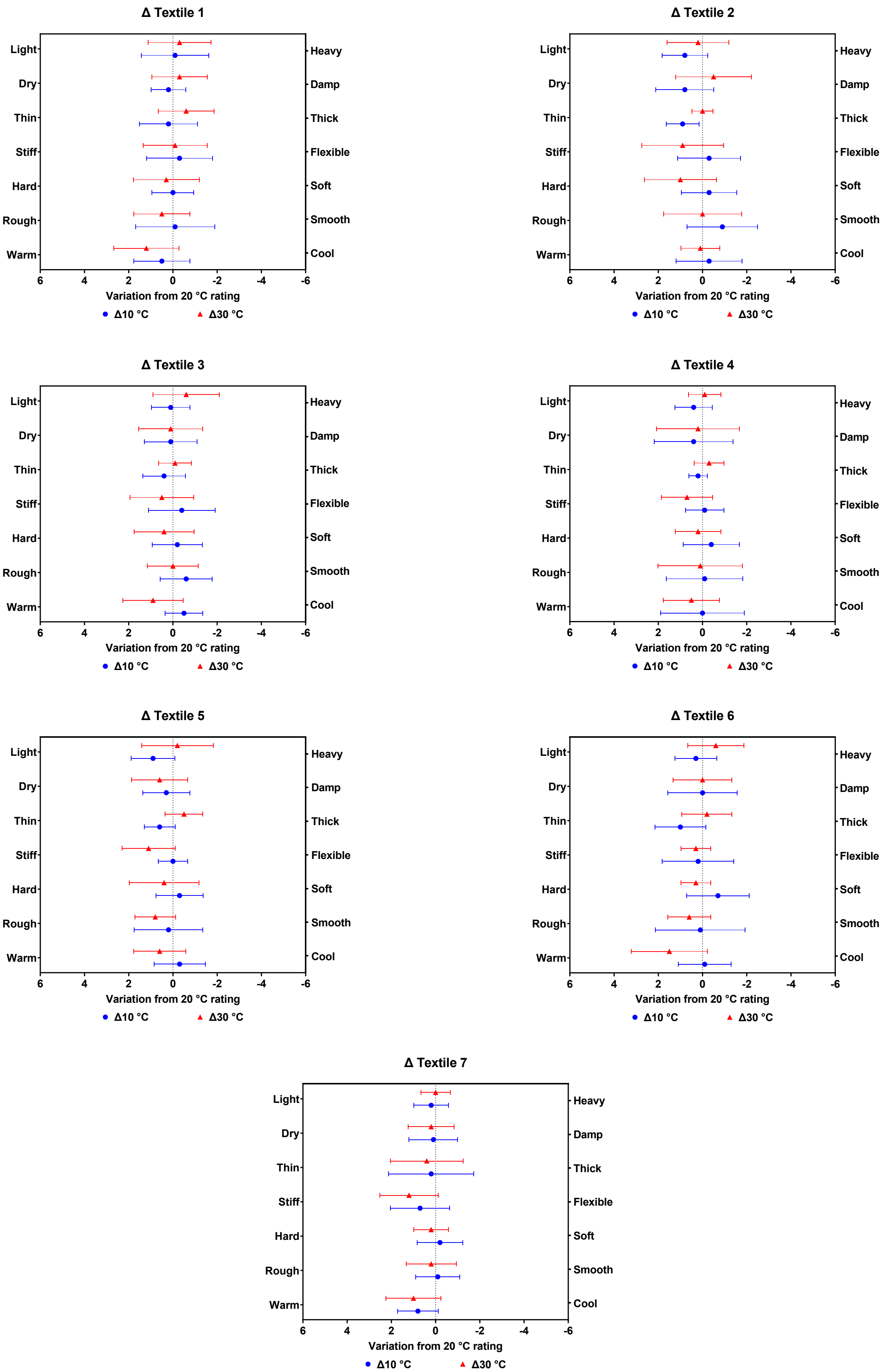

Fig. 6: Variation of the hand-feel attribute ratings of textiles 1 - 7 at 10 °C, and 30 °C from the 20 °C ratings; The graphs show the mean with SD.

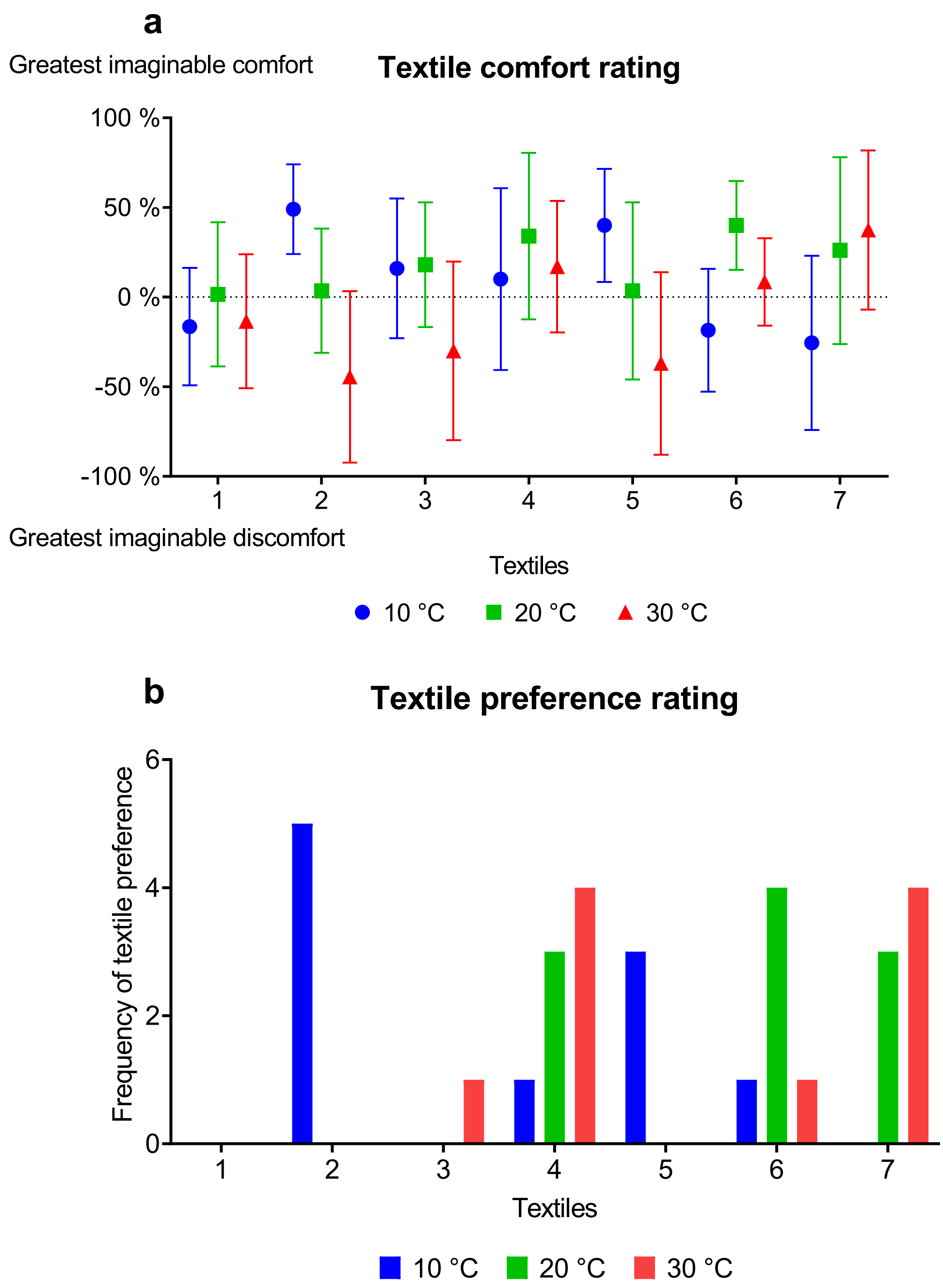

Fig. 7: (a) Comfort rating (CALM Score) of textiles 1 – 7 at 10 °C, 20 °C, and 30 °C; The graph shows the mean with SD; (b) Frequency of preferences for textiles 1 – 7 at 10 °C, 20 °C, and 30 °C; The graph shows the absolute number of preference votes.

4 Discussion

Based on the results of physiological measurements and a textile hand-feel assessment conducted at cool (10 °C, RH 65 %), warm (30 °C, RH 65 %), and mild (20 °C, RH 65 %) temperature conditions, it will be discussed how the environmental temperature affects the textile hand-feel perception and related body reactions.

As expected, the aural, mean body and hand temperature increased in the warm, decreased in the cool, and stayed rather constant in the mild conditions during the acclimation period and experiment. Interestingly, while the aural and mean skin temperatures started for the three conditions nearly from the same temperature, the mean hand temperatures deviated almost immediately upon entering the climatic chamber, showing a consistent pattern during the 30 minutes acclimation period across hand sites.

Along with hand and skin temperature, tactile sensitivity differed between the three sessions. It can generally be stated that in the cool session, hands were less sensitive. Although not for all hand areas, a statistical difference was found. Previous studies confirm that at a hand skin temperature below the range of 25 °C to 20 °C first changes in sensitivity occur. During the experiment's cool session, participants' hand skin temperature reached this range. Severe loss of tactile sensitivity is apparent at hand temperatures below 10 °C [13, 19, 21]. Due to the safety and comfort of the participants, these temperatures were not targeted in the present study. The left and non-dominant hand seemed more sensitive and had slightly higher hand temperatures than the participants' right hand. However, no statistically significant difference was found between the left and right hand tactile sensitivity and temperature. Other studies suggest such a difference in sensitivity between the right and left hand, with the left hand being more sensitive [37]. Using nylon filaments to measure tactile sensitivity in different climates can represent a potential source of error [38], as the climate can influence the filaments' properties. Potentially the filaments get stiffer in cold and softer in warm conditions, meaning that less target force would be needed in the cold and more target force in the warmth to evoke a sensation. An effect that would be contrary to the outcomes of the present study, where more target force was needed in the cold and less in the warmth to evoke a sensation. Moreover, Andrews [38] showed that relative humidity significantly affects the accuracy of von Frey filaments, but this was kept constant in the present study. Only a small effect of temperature, on the accuracy of von Frey filaments was observed [38] implying that the use of the Von Frey filaments in the present study with only changes in temperature was warranted. Next to the conducted physiological measurements, it was also assessed how the participants perceived the cool, mild, and warm conditions. The perception of the three sessions differed significantly from each other.

While physiological measurements and environmental perception showed a clear picture aligned with the literature, this is not the case for the textile hand-feel perception. Significant differences in the attribute rating were present, but the differences in the attribute ratings varied from textile to textile. It can be concluded that environmental temperature influences the hand-feel attribute rating, but no general conclusions can be drawn about how environmental temperature affects attribute perception. This is in contrast to previous literature, which found that the roughness sensation increased with the environmental temperature [23, 24]. Even if Fig. 7 shows a slight shift of the sensation towards a rougher sensation in the warm condition and a smoother sensation in the cool condition, the present study showed no significant differences in the roughness–smoothness ratings for any of the seven textiles between the three temperature conditions. There are many possible explanations for this contradiction with previous studies. Most importantly, the study design and research question were different in all three studies. Gwosdow et al. [24] used a passive forearm-feel assessment where fabrics were pulled over the participant's forearm. In the present study, participants actively touched the textiles with their hands. Different regions of the body have different sensitivities to the perception of roughness, and the sensation of textiles may differ when touched actively or passively [23, 39]. Other vital aspects are the scales and descriptors used to evaluate the fabrics. For example, Gwosdow et al. [24] used a visual analogue scale, whereas the present study and Liao et al. [23] used a 7-point Likert scale. The descriptors are slightly different in all three studies. It is not very meaningful to compare the hand-feel rating obtained from two different scales. This can be seen by comparing the rating from the present study with the rating from a previous study using the same textiles but different scales [40]. Textile selection is another issue that could explain the differences in roughness perception between the three studies. This study used fabrics designed for sportswear, which were mainly synthetic. Gwosdow et al. [24] used only natural materials, which tend to be rougher than synthetic fabrics. Liao et al. [23] used a wide range of fabrics. Turning to the actual research question of this study, which is how environmental temperature affects the perception of textile hand feel, it is clear that it differs slightly from the other two studies. Gwosdow et al. [24] investigated the interaction between skin friction, skin wetness, textile perception, temperature and humidity. Higher skin wetness and friction in warm-humid environments were associated with a less pleasant and rougher perception of the fabrics tested. Humidity and skin wetness, which were not the focus of this study, could explain the differences in perceived roughness [41, 42]. Liao et al. [23] studied the influence of temperature and humidity acclimatisation on the perception of the hand feel of textiles. The climatic conditions during the experiment were the same for each participant, suggesting that the place of residence and the local climate influenced the participants' roughness perception. For the present study, the acclimatisation of the participants was the same. However, participant selection is an important factor that could explain the differences in roughness perception between studies. For example, it is known that participants from different cultural backgrounds rate differently on Likert scales [43]. Therefore, comparisons of subjective ratings between subjects in the UK and East Asia have limitations. Explanations for the differences in roughness perception between the three studies are manifold. Following the clothing-environment-body approach, further research into the influence of humidity on the hand-feel of textiles is suggested. The influence of the temperature on the comfort rating was obvious and plausible. The textiles 2, 5, 6, and 7 that can be assigned to a specific season were rated significantly different on the comfort scale in cool, mild, and warm environments. Thicker fabrics were perceived as more comfortable in the cool, and thinner fabrics were perceived as more comfortable in a warm environment. The attribute thin–thick also had a statistically significant difference in most textiles between the three sessions. The comfort perception of the textile hand-feel differs in different environmental temperatures, and textiles can be designed to provoke a certain comfort sensation in a specific environmental temperature. The insights from the comfort rating are also reflected in the preference vote. Textiles designed for specific environmental conditions, like fleece for cool conditions, were also preferred in these conditions.

So far, this paper has focused on the influence of environmental temperature on the hand-feel perception of textiles. The following section will discuss whether there are any differences between females and males in the hand-feel perception of textiles when exposed to three different environmental temperatures. Previous studies have suggested that there are sex differences in sensory perception [44–46]. A Mann-Whitney U test was performed to determine differences between females and males in the hand-feel attribute ratings, CALM scores, thermal assessment ratings, and tactile sensitivity. An unpaired t-test was performed for aural, mean skin and hand temperatures. The results of the statistical analysis suggest that there are no differences between males and females in the textile perception ratings and physiological measurements performed in this study. Thus, this study confirmed previous research using the same textiles, which found no differences in the hand-feel ratings of textiles between males and females [40]. It should be noted that the present study was not designed to identify differences in hand-feel perception between males and females. For example, the sample size and selection of textiles may have influenced the statistical analysis results.

5 Conclusions

Based on a hand-feel assessment of textiles and monitoring participants' body responses while participants were exposed to three different environmental temperatures (10 °C/20 °C/30 °C, RH 65 %), it can be concluded that environmental temperature led to significant changes in participants' aural temperature, mean skin temperature, hand temperature, tactile sensitivity, and environmental perception, affecting the hand-feel perception of the different textiles. While the perception of the hand-feel attributes changed with the environmental temperature, no consistent effects were observed across textiles, and thus no general conclusions can be drawn about how environmental temperature affects attribute perception. Textiles designed for specific seasons, such as thick fleece fabrics for the cold or very thin fabrics for the warmth, are preferred and perceived as more comfortable in the respective environment they are intended for. Thus, the present study not only builds a foundation to understand how environmental temperature, body responses, and hand-feel perception interact but also delivers insights for practitioners to develop more comfortable textiles for specific environmental temperatures. While the study monitored various body responses that might be affected by the environmental temperature, the skin wetness of the hands was not monitored. It is suggested that skin wetness is potentially relevant for the hand-feel perception and should be considered in future studies [24, 41, 42]. The present study focused on environmental temperature; investigating the influence of humidity or humidity and temperature combined could also be interesting.

Author Contributions

L. Claussen: conceptualisation, methodology, formal analysis, data curation, visualisation, writing – original draft preparation; K. Lim: conceptualisation, methodology, formal analysis, investigation, data curation, visualization; J. Wilfling: Methodology; A. Lloyd: Methodology, writing – review and editing; D. Ruiz: Resources; G. Havenith: Methodology, writing – review and editing, supervision. All authors have read and agreed to the published version of the manuscript.

Acknowledgements

We thank Hirotsugu Sato (adidas AG) for inspiring us to do this research.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Hollies, N. R. S.; Custer, A. G.; Morin, C. J.; Howard, M. E. A Human Perception Analysis Approach to Clothing Comfort. *Text. Res. J.*, **1979**, *49* (10), 557–564. https://doi.org/10.1177/004051757904901001.
2. Naebe, M.; Yu, Y.; McGregor, B. A.; Tester, D.; Wang, X. The Effect of Humidity and Temperature on Wool ComfortMeter Assessment of Single Jersey Wool Fabrics. *Text. Res. J.*, **2013**, *83* (1), 83–89. https://doi.org/10.1177/0040517512441988.
3. Fourt, L.; Hollies, N. R. S. Clothing Comfort and Function. *Cloth. Comf. Funct.*, **1970**.
4. Mecheels, J. *Körper, Klima, Kleidung : Grundzüge Der Bekleidungsphysiologie*; Schiele & Schön, 1991.
5. Bartels, V. T. Physiological Comfort of Sportswear. In *Textiles in Sport*; Elsevier Ltd., 2005; pp 177–203. https://doi.org/10.1533/9781845690885.3.177.
6. Slater, K. *Human Comfort*, Volume 2.; Thomas, C.C.: Springfield, Ill., USA, 1985.
7. Bishop, D. P. Fabrics: Sensory and Mechanical Properties. *Text. Prog.*, **1996**, *26* (3), 1–62. https://doi.org/10.1080/00405169608688866.
8. Claussen, L.; Lloyd, A.; Ruiz, D.; Havenith, G. Experts' Views on Sports Clothing Quality. *Int. J. Fash. Des. Technol. Educ.*, **2021**, 1–12. https://doi.org/10.1080/17543266.2021.2011432.
9. Kamalha, E.; Zeng, Y.; Mwasiagi, J. I.; Kyatuheire, S. The Comfort Dimension; a Review of Perception in Clothing. *J. Sens. Stud.*, **2013**, *28* (6), 423–444. https://doi.org/10.1111/joss.12070.
10. Bartels, V. T. Contact Sensations of Medical Textiles on the Skin. In *Handbook of Medical Textiles*; Elsevier Inc., 2011; pp 221–247. https://doi.org/10.1533/9780857093691.2.221.
11. Das, A.; Alagirusamy, R. Improving Tactile Comfort in Fabrics and Clothing. In *Improving Comfort in Clothing*; Elsevier, 2011; pp 216–244. https://doi.org/10.1533/9780857090645.2.216.
12. Cheung, S. S. Responses of the Hands and Feet to Cold Exposure. *Temperature*, **2015**, *2* (1), 105–120. https://doi.org/10.1080/23328940.2015.1008890.
13. Havenith, G.; Heus, R.; Daanen, H. A. M. The Hand in the Cold, Performance and Risk. *Arctic Med. Res.*, **1995**, *54*, 37–47.
14. A. GESCHEIDER, G.; THORPE, J. M.; GOODARZ, J.; BOLANOWSKI, S. J. The Effects of Skin Temperature on the Detection and Discrimination of Tactile Stimulation. *Somatosens. Mot. Res.*, **1997**, *14* (3), 181–188. https://doi.org/10.1080/08990229771042.
15. Bolanowski Jr, S. J.; Verrillo, R. T. Temperature and Criterion Effects in a Somatosensory Subsystem: A Neurophysiological and Psychophysical Study. *J. Neurophysiol.*, **1982**, *48* (3), 836–855.
16. Bolanowski, S. J.; Gescheider, G. A.; Verrillo, R. T.; Checkosky, C. M. Four Channels Mediate the Mechanical Aspects of Touch. *J. Acoust. Soc. Am.*, **1988**, *84* (5), 1680–1694. https://doi.org/10.1121/1.397184.
17. Green, B. G. The Effect of Skin Temperature on Vibrotactile Sensitivity. *Percept. Psychophys.*, **1977**, *21* (3), 243–248. https://doi.org/10.3758/BF03214234.
18. Green, B. G. The Effect of Skin Temperature on the Perception of Roughness. *Sens. Process*, **1979**, *3*, 327–333.
19. Morton, R.; Provins, K. A. Finger Numbness after Acute Local Exposure to Cold. *J. Appl. Physiol.*, **1960**, *15* (1), 149–154. https://doi.org/10.1152/jappl.1960.15.1.149.
20. Provins, K. A.; Morton, R. Tactile Discrimination and Skin Temperature. *J. Appl. Physiol.*, **1960**, *15* (1), 155–160. https://doi.org/10.1152/jappl.1960.15.1.155.
21. Stevens, J. C.; Green, B. G.; Krimsley, A. S. Punctate Pressure Sensitivity: Effects of Skin Temperature. *Sens. Processes*, **1977**, *1* (3), 238–243.
22. Verrillo, R. T.; Bolanowski, S. J. The Effects of Skin Temperature on the Psychophysical Responses to Vibration on Glabrous and Hairy Skin. *J. Acoust. Soc. Am.*, **1986**, *80* (2), 528–532. https://doi.org/10.1121/1.394047.
23. Liao, X.; Li, Y.; Hu, J.; Ding, X.; Zhang, X.; Ying, B.; Takatera, M.; Sukigara, S.; Pan, F.; Sun, Y.; et al. Effects

of Contact Method and Acclimation on Temperature and Humidity in Touch Perception. *Text. Res. J.*, **2018**, *88* (14), 1605–1615. https://doi.org/10.1177/0040517517705628.
24. Gwosdow, A. R.; Stevens, J. C.; Berglund, L. G.; Stolwijk, J. A. J. Skin Friction and Fabric Sensations in Neutral and Warm Environments. *Text. Res. J.*, **1986**, *56* (9), 574–580. https://doi.org/10.1177/004051758605600909.
25. Stanton, J. H.; Speijers, J.; Naylor, G. R.; Pieruzzini, S.; Beilby, J.; Barsden, E.; Clarke, A. Skin Comfort of Base Layer Knitted Garments. Part 1: Description and Evaluation of Wearer Test Protocol. *Text. Res. J.*, **2014**, *84* (13), 1385–1399. https://doi.org/10.1177/0040517514521114.
26. British Standards Institution. *BS EN 12127:1998, Textiles. Fabrics. Determination of Mass per Unit Area Using Small Samples*; 1998.
27. Ramanathan, N. L. A New Weighting System for Mean Surface Temperature of the Human Body. *J. Appl. Physiol.*, **1964**, *19* (3), 531–533. https://doi.org/10.1152/jappl.1964.19.3.531.
28. Foster, J.; Lloyd, A. B.; Havenith, G. Non-Contact Infrared Assessment of Human Body Temperature: The Journal *Temperature* Toolbox. *Temperature*, **2021**, *8* (4), 306–319. https://doi.org/10.1080/23328940.2021.1899546.
29. Moreira, D. G.; Costello, J. T.; Brito, C. J.; Adamczyk, J. G.; Ammer, K.; Bach, A. J. E.; Costa, C. M. A.; Eglin, C.; Fernandes, A. A.; Fernández-Cuevas, I.; et al. Thermographic Imaging in Sports and Exercise Medicine: A Delphi Study and Consensus Statement on the Measurement of Human Skin Temperature. *J. Therm. Biol.*, **2017**, *69*, 155–162. https://doi.org/10.1016/j.jtherbio.2017.07.006.
30. Dyck, P. J.; O'Brien, P. C.; Kosanke, J. L.; Gillen, D. A.; Karnes, J. L. A 4, 2, and 1 Stepping Algorithm for Quick and Accurate Estimation of Cutaneous Sensation Threshold. *Neurology*, **1993**, *43* (8), 1508–1508. https://doi.org/10.1212/WNL.43.8.1508.
31. ASHRAE. ANSI/ASHRAE Standard 55-2017 : Thermal Environmental Conditions for Human Occupancy. *ASHRAE Inc.*, **2017**, *2017*, 66.
32. American Association of Textile Chemists and Colorists. *AATCC EP5-1996e2(2020), Evaluation Procedure for Fabric Hand*; 2020.
33. Cardello, A. V.; Winterhalter, C.; Schutz, H. G. Predicting the Handle and Comfort of Military Clothing Fabrics from Sensory and Instrumental Data: Development and Application of New Psychophysical Methods. *Text. Res. J.*, **2003**, *73* (3), 221–237. https://doi.org/10.1177/004051750307300306.
34. Havenith, G. Laboratory Assessment of Cold Weather Clothing. In *Textiles for Cold Weather Apparel*; Elsevier Inc., 2009; pp 217–243. https://doi.org/10.1533/9781845697174.2.217.
35. Holmér, I. Human Wear Trials for Cold Weather Protective Clothing Systems. In *Textiles for Cold Weather Apparel*; Elsevier Inc., 2009; pp 256–273. https://doi.org/10.1533/9781845697174.2.256.
36. Parsons, K. Testing and Developing Clothing. In *Human Thermal Environments*; CRC Press, 2014; pp 235–256. https://doi.org/10.1201/b16750-11.
37. Weinstein, S. Intensive and Extensive Aspects of Tactile Sensitivity as a Function of Body Part, Sex, and Laterality; 1968.
38. Andrews, K. The Effect of Changes in Temperature and Humidity on the Accuracy of von Frey Hairs. *J. Neurosci. Methods*, **1993**, *50* (1), 91–93. https://doi.org/10.1016/0165-0270(93)90059-Z.
39. Temel, M.; Johnson, A. A.; Lloyd, A. B. Body Mapping of Skin Friction Coefficient and Tactile Perception during the Dynamic Skin-Textile Interaction. *Ergonomics*, **2022**, 1–16. https://doi.org/10.1080/00140139.2022.2152112.
40. Wilfling, J.; Havenith, G.; Raccuglia, M.; Hodder, S. Can You See the Feel? The Absence of Tactile Cues in Clothing e-Commerce Impairs Consumer Decision Making. *Int. J. Fash. Des. Technol. Educ.*, **2022**, 1–10. https://doi.org/10.1080/17543266.2022.2154396.
41. Li, Y. The Science of Clothing Comfort. *Text. Prog.*, **2001**, *31* (1–2), 1–135. https://doi.org/10.1080/00405160108688951.
42. Raccuglia, M.; Pistak, K.; Heyde, C.; Qu, J.; Mao, N.; Hodder, S.; Havenith, G. Human Wetness Perception of Fabrics under Dynamic Skin Contact. *Text. Res. J.*, **2018**, *88* (19), 2155–2168. https://doi.org/10.1177/0040517517716905.
43. Heine, S. J.; Lehman, D. R.; Peng, K.; Greenholtz, J. What's Wrong with Cross-Cultural Comparisons of Subjective Likert Scales?: The Reference-Group Effect. *J. Pers. Soc. Psychol.*, **2002**, *82* (6), 903–918. https://doi.org/10.1037/0022-3514.82.6.903.
44. Essick, G. K.; McGlone, F.; Dancer, C.; Fabricant, D.; Ragin, Y.; Phillips, N.; Jones, T.; Guest, S. Quantitative Assessment of Pleasant Touch. *Neurosci. Biobehav. Rev.*, **2010**, *34* (2), 192–203. https://doi.org/10.1016/j.neubiorev.2009.02.003.
45. Gescheider, G. A.; Edwards, R. R.; Lackner, E. A.; Bolanowski, S. J.; Verrillo, R. T. The Effects of Aging on Information-Processing Channels in the Sense of Touch: III. Differential Sensitivity to Changes in Stimulus Intensity. *Somatosens. Mot. Res.*, **1996**, *13* (1), 73–80. https://doi.org/10.3109/08990229609028914.
46. Woodward, K. L. The Relationship between Skin Compliance, Age, Gender, and Tactile Discriminative Thresholds in Humans. *Somatosens. Mot. Res.*, **1993**, *10* (1), 63–67. https://doi.org/10.3109/08990229309028824.