Apparent Thermal Motion on the Forearm

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Abstract. The concept of Apparent Tactile Motion (ATM) has been extensively studied in the field of haptics, allowing people to perceive a sense of dynamic motion through tactile stimuli such as vibrations, tapping or mid-air stimuli. However, there is a lack of research on whether a similar perception of motion can be achieved using thermal stimuli. As prior research suggests that particularly the stimuli onset asynchrony (SOA) of two stimuli is a significant contributor to the perception of motion, in this study, we examine different SOAs between two warm stimuli on the forearm in order to induce a sensation of motion. Our results indicate that the sensation of motion can be achieved on the forearm with SOAs close to the signal duration. We further found a negative correlation between SOAs and the perception of speed and report findings of participants' perceptions of motion through drawings. With our study, we strengthen the understanding of dynamic thermal feedback through apparent thermal motion that may lead to the development of lighter and more sustainable wearable thermal devices.

Keywords: Apparent motion · Thermal feedback · Thermal illusion.

1 Introduction

Virtual reality (VR) experiences become increasingly immersive by not only producing high definition visual and auditory content but also stimulating the sense of touch and temperature through haptic interfaces [30]. Growing research further explores the rendering of not only static but dynamic experiences caused by thermal [9] or tactile stimulation [11]. Dynamic tactile feedback allows to create more nuanced tactile and thermal sensations to increase users' sense of immersion and realism in, for instance, multisensory VR experiences that simulate heat, rain, and winds [8] or for achieving dynamic user awareness of objects in the virtual surroundings [29].

The illusionary perception of motion has been examined through sensory phenomena such as the apparent tactile motion (ATM) [2, 31] or the cutaneous rabbit illusion [5]. Both illusions use successive signals to create sensations of motion. While the cutaneous rabbit requires a series of closely positioned actuators, apparent tactile motion can elicit a perception of movement between two or more actuators placed at greater distances from each other, even across hands [22]. ATM generates a continuous sensation on the skin between two stimuli which can potentially result in a reduced number of actuators and may lead to lighter and more energy-efficient wearable haptic interfaces or handheld devices. To achieve ATM between two or more successive tactile signals applied to the skin, it is crucial to determine the right Stimuli Onset Asynchrony (SOA) time. SOA refers to the point in time when the subsequent signal activates, hence, it describes a delay in the actuator's activation. If this time is too large, an individual would perceive two discrete signals. Conversely, if the time is too small, the signals would be perceived as simultaneous. Only when the SOA timing is optimal can a person perceive a continuous motion between two tactile signals. Moreover, the SOA is dependent on the stimulus duration (DOS), hence an increased DOS leads to an increased SOA [24].

Research on apparent tactile motion can already be dated back to the beginning of the 19th century [2, 31]. Previous studies primarily concentrated on utilizing vibrotactile feedback to explore motion sensation. However, as research in the field has expanded, more recent studies have introduced mid-air haptics as another tactile modality to produce motion sensations [26, 21]. To elicit the perception of apparent motion with vibrotactile [2, 31, 22] or mechanical tapping stimulation [13, 15] prior work has shown that particularly stimulus duration (DOS) and SOA timing show a significant effect on the perception of continuous tactile motion. Israr and Poupyrev [10] showed that, in addition, frequency of vibration signals might impact motion perception. In terms of body locations, Chu et al. [4] developed a MotionRing that produces an illusionary motion sensation through an array of vibration motors around the head. Hands as body site were examined by [22], [12] and [7]. Pittera et al. [22] report a successful motion perception between two hands of a participant while participants in [7] perceived motion traveling from hand to the hand of another person. Takeda and colleagues [26] investigated ATM of air stimuli at cheek and ear. Perceiving motion remained achievable even when utilizing different devices with different actuator vibration frequencies, for instance, from a game controller to a smart watch on the wristband [12]. In terms of speed perception, Lacôte and colleagues [15] investigated the discrimination of velocity changes conveyed during apparent tactile motion and found that there was no significant discrimination of speed levels for different SOAs.

Since the prior research has focused specifically on apparent motion illusion induced by tactile stimuli through vibration or pressure [10, 22, 7, 32, 26, 4], only very limited research has explored if motion illusions are achievable with thermal signals as well [6, 3]. As an example, consider the possibility of VR enabling users to experience dynamic sensations such as hot steam or cold wind moving across their bodies. A key challenge compared to tactile stimulation here is that human spatial resolution of thermal perception is rather poor [27, 28], so the question is if people would be able to distinguish different locations of traveling stimuli.

Prior thermal perception studies have investigated the effects of different SOAs and temperatures on thermal motion perception intermanually and on the face [3, 6]. Gongora and colleagues [6] were able to produce a motion sensation with both warm and cold stimuli between two hands of a person. They also found that cold stimuli are more sensitive for motion quality than warm signals. Chen [3] found that participants were able to indicate the correct direction of motion with an accuracy of 70%. Nevertheless, there remains a notable gap in current research regarding the feasibility of generating thermal motion on other body sites, such as the arm (see Figure 1), which is frequently targeted by haptic sleeves [33] or gloves [20]. Ongoing research of such devices make the arms an suitable area for generating motion sensations. For example, haptic and thermal stimuli can travel along the length of the arms, either from distal to proximal or vice versa.

To understand whether and how a motion illusion can be produced with thermal stimuli on the forearm, we conducted an experiment with ten participants and investigated (1) What is the optimal SOA to perceive the motion of a thermal stimulus produced by two Peltier elements on the forearm? Moreover, we are interested in the perception of velocity and ask (2) Does SOA influence the perception of speed for thermal stimulation?

This research contributes to the understanding of motion illusions induced by thermal feedback both for the scientific and engineering community. By exploring the relationship between thermal stimuli and perceived motion, our study contributes to advancing the apparent motion phenomenon beyond the tactile modality.

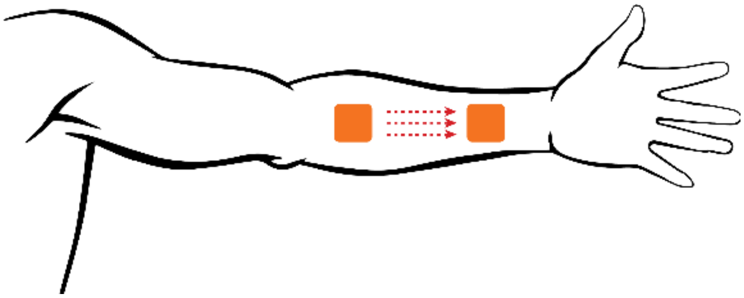


Fig. 1: Is it possible to achieve a sensation of motion across the forearm by modulating the stimulus onset asynchrony of successive thermal signals from two Peltiers attached to the arm?

2 Experiment

2.1 Participants

Ten participants (five female, five male) took part in the experimental study. Their age ranged from 19 to 41 (mean age: 29). Participants were recruited through a public call. No participant reported any abnormalities in their sense of touch or temperature on the forearms used for thermal evaluation. At the beginning of the experiment, participants received general information about the study context and procedure and were asked to sign a consent form. After study completion we handed them a 20€ restaurant gift card. In accordance with the Declaration of Helsinki this study was confirmed by our university's ethics committee.

2.2 Apparatus

To apply the thermal stimuli we used two bracelets each containing a Peltier cell (20x20 mm, CUI Devices CP20251, maximum heat output 80°C) attached to a metal heat sink

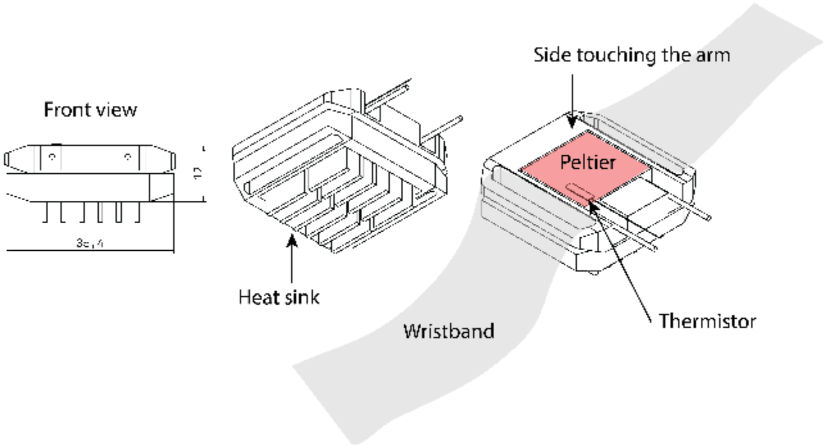


Fig. 2: Custom designed and 3D-printed case for Peltier component and heat sink, holes left and right allow to attach wristband. See in use in Figure 5.

for heat dissipation. A custom designed and 3D printed case (PLA material with heat resistance of ca. 60°C) with elastic wristbands help to attach the module to the arm (see Figure 2). A thermistor (TEWA Sensors LLC, TT6-10KC8-9-25) placed between the skin and the Peltier module measured the temperature applied to the skin. The Peltier cells were controlled with an Arduino Uno microcontroller.

2.3 Procedure and stimuli

Based on [10] we define the concept of motion as a thermal sensation that

a) presents continuous motion,
b) has a clear start and end,
c) is perceived as a single unit that cannot be subdivided, and
d) can move with varying speed.

We presented this definition to the participants. To familiarize participants with the dynamic thermal signals on the arm and check if participants were able to perceive the two distinct spots we provided two test signals to the forearm. One of the signals had a large SOA (i.e., 12s) indicating two discrete signals while one signal produced a hypothetical continuous motion sensation (i.e., 6s).

The signal duration was set to 8s. This DOS was chosen since in our pilot study it took a considerable longer time to perceive a thermal signal on the forearm than compared to the fingertip. For the SOAs, we opted for five intervals centered around the selected duration: 4s, 6s, 8s, 10s, 12s (see Figure 3). The rate of temperature change was at 1.8s/°C, with a target temperature of 39°C which is below the pain threshold [17]. Room temperature was kept at 20°C for every participant. The spacing between Peltiers was 10cm (see Figure 5). We placed the Peltiers centrally on the underside of the forearm which is less hairy and more sensitive compared to the outer side [16]. The overall experiment comprised of 25 trials per participant (5 SOAs x 5 repetitions) (see Figure 4) and lasted approximately 1.5 hours. The order of trials was counterbalanced. The stimuli lasted either 12s (with SOA of 4s), 14s (SOA: 6s), 16s (SOA: 8s), 18s (SOA: 10s), or 20s (SOA: 12s). We allowed a break of a few minutes after a set of five trials.

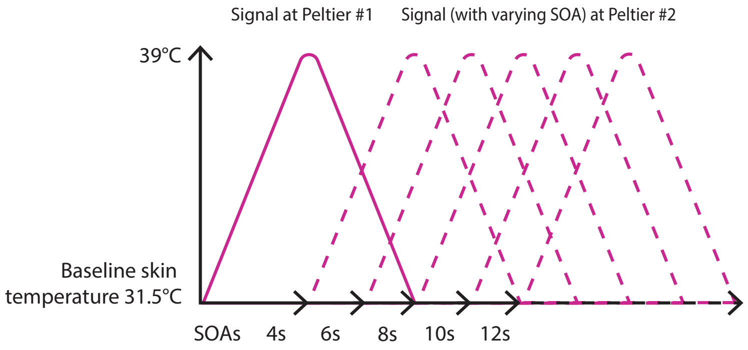


Fig. 3: Different SOAs between first and second thermal signal; each signal lasted for a fixed duration of 8 seconds

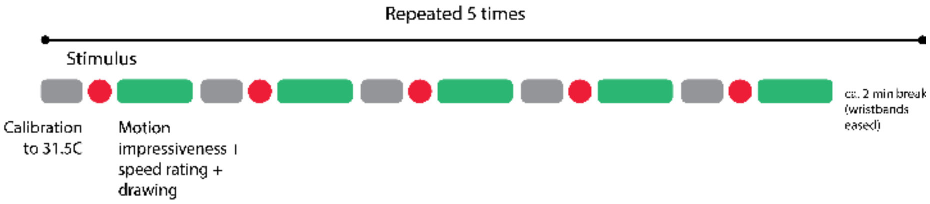


Fig. 4: Study procedure: 1. calibration phase, 2. stimulus (consists of two thermal signals with a different SOA) and 3. participant ratings and drawing plus break

To ensure a perceptual distinction between stimuli it must be ensured that a normal skin temperature is regained [23]. Based on our pilot tests on the arm and hand, we observed that this process takes a considerably higher amount of time on the forearm compared to, for instance, the fingertips (some participants described that heat is “lingering” after a stimulus is applied). This makes it more challenging to repeat trials and display multiple, successive stimuli on the arm. To ensure thermal recovery after each trial, we allowed a time period of 30 seconds for the skin to return to a normal temperature state, allowing thermal recovery. During that time the participant gave their ratings and drew their motion sensation. Secondly, after every set of five trials, the wristband was eased, and participants were instructed to rub their skin where the stimuli were applied. Lastly, before initiating each new trial, we calibrated the Peltiers so that the skin reaches a baseline skin temperature of 31.5°C (normal skin temperature). Following this calibration phase, a sound was played as an indicator of the stimulus to start. After each trial participants were asked to rate the motion impressiveness from 0 to 3:

‘0’ indicated that no motion was felt,

‘1’ that motion was weak or vague,

‘2‘ that motion is definitely present but not so clear, and

‘3‘ indicated impressive and continuous motion from one stimulating point to the other (based on [13]).

In addition, we instructed the participant after each trial to rate the perception of speed from ‘0’ (no motion), ‘1’ (slow), ‘2’ (medium), and ‘3’ (fast). Lastly, we asked the participant to draw their perceptions on a tablet that displayed a forearm (1:1 scale) to indicate further features of the sensation such as intensities or directions. We offered suggestions for visualizing the sensations (e.g. colours or arrows) but allowed the participant to create their drawings freely. Mapping sensations in body outlines is a common research tool that allows to capture complex bodily experiences [1]. This is done by asking participants to visualize their sensations in a body map. Body mapping as a tool can, for instance, assist researchers to make sense of subjective bodily experiences that cannot necessarily be expressed through words or numbers.

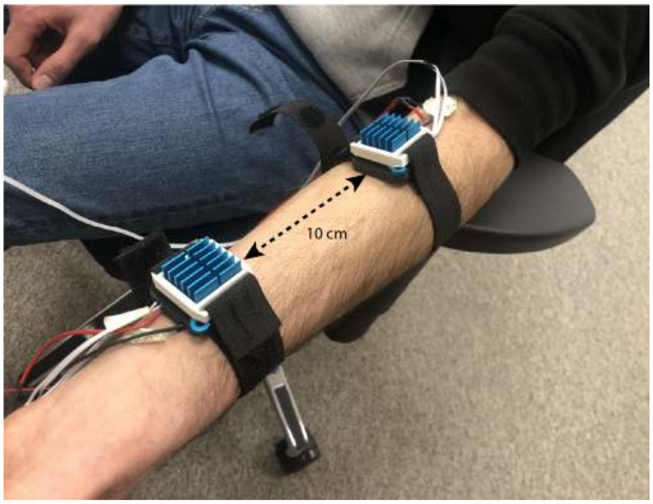


Fig. 5: Study setup of Peltiers attached with a wristband to the forearm

3 Results

3.1 Ratings

We calculated the mean ratings for motion impressiveness and speed (ranging from 0 to 3) for each SOA provided by the participants and conducted a one-way ANOVA test to prove statistical signifance. We used Tukey HSD post hoc test to identify exactly which groups differ from each other. Figure 6 depicts participants' ratings on motion impressiveness and Figure 7 speed as a function of SOA. For continuous motion induced by thermal signals of 8s duration, the optimal SOA value (highest mean for motion impressive) is 6s, with a corresponding mean rating of 2.22 (SD = 1.00), closely followed by 8s (mean impressiveness rating of 1.97; SD = 1.09) and 10s (mean = 1.6; SD = 1.09). SOA of 12s received the worst ratings of 1.04 (SD = 1.19). A quadratic trend line was fitted to the plot ($R^2 = 0.97$). We can theorize that as the values of SOA become smaller than 4s or larger than 12s, participants are likely to perceive a decrease in the continuity of motion. A one-way ANOVA revealed that SOA timings have a significant effect on the motion impressiveness ($F(4, 242) = 7.8$, $p < 0.01$). The post hoc pairwise comparisons using Tukey HSD test (no violation against homogeneity of variances with $p > 0.05$) show that there are significant differences between 4s and 12s, 6s and 12s, 8s and 12s, and 6s and 10s ($p < 0.005$). Taken together, these results suggest that a higher SOA such as 12s cause significantly less impressive motion sensations than the smaller SOAs.

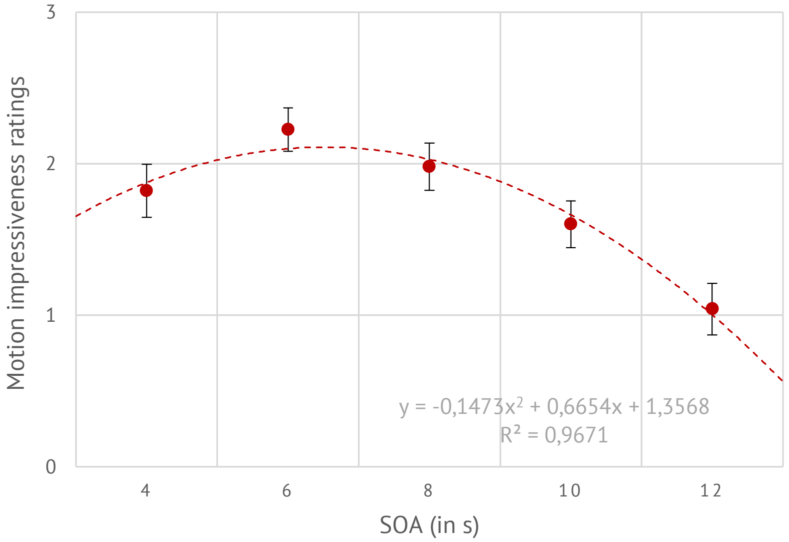


Fig. 6: Mean ratings of motion impressiveness

For speed perception, findings reveal another noticeable trend. As SOAs decrease, there is an observable increase in the perception of speed (see linear trend line in Figure 7). This implies that despite a fixed duration shorter SOAs may induce a feeling of faster motion. We identified a significant effect of SOA speed perception with one-way ANOVA ($F(4, 242) = 9.061$, $p < 0.001$). With our data meeting the assumption of homogeneity of variance ($p > 0.05$), Tukey HSD post hoc test confirms statistical differences between 4s and 12s, 6s and 12s, 8s and 12s, and 10s and 12s ($p < 0.005$).

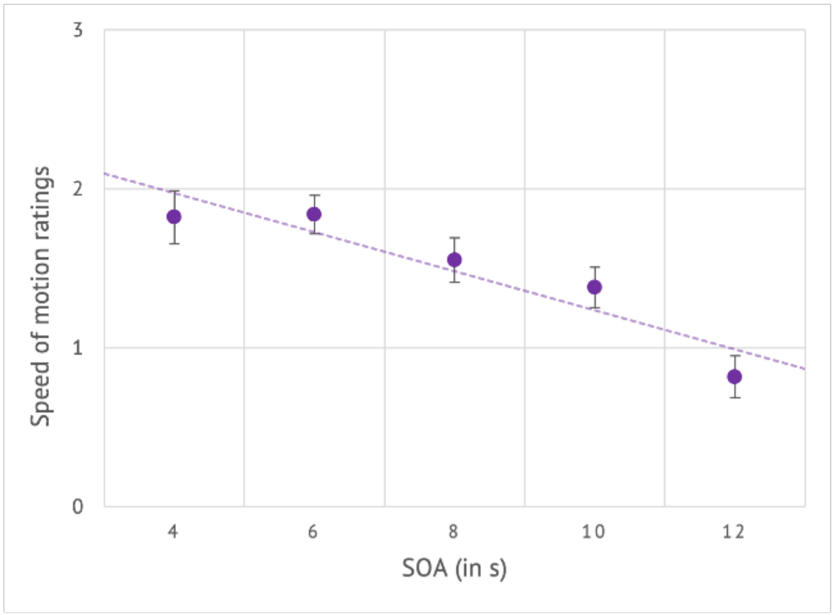


Fig. 7: Mean ratings of speed of motion

3.2 Drawings

In analyzing participants' sketches, we overlaid all drawings and generated a heat map illustrating the occurrence frequency of depicted forearm sections (see Figure 8). Additionally, we represented commonly noted sensations such as distinctions in intensity across different areas. These visual representations align with the ratings of motion impressiveness, revealing that 12s were perceived as less continuous motion compared to SOAs of 6s or 8s. Interestingly, participants indicated that when they perceived motion, it was not in the form of a slender line moving from one point to another. Instead, it manifested as 'spatial expansions' (P10), encompassing broader areas on the forearm and between the two Peltiers. This sensation has been discovered in several illustrations such as in the depicted drawing in Figure 9a. Often the signal at the wrist was perceived as less intense than the one closer to elbow. This was often visualized by a smaller area covered at the wrist (see in Figure 9b). Different perceptions of intensity on the forearm aligns with research on thermal sensation that showed a reduced sensitivity along the arm from proximal to distal [25].

4 Discussion and Conclusion

In this study, we investigated if apparent thermal motion is perceptible on the forearm and what is the optimal SOA timing to perceive clear and continuous motion. Moreover, we examined if SOA would affect the perception of speed and how people perceived motion through drawings.

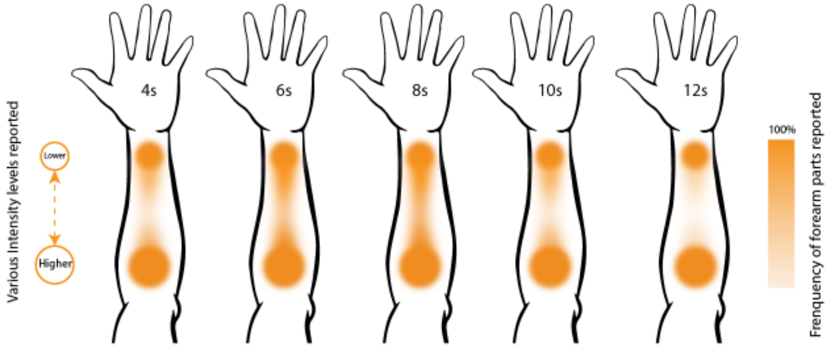
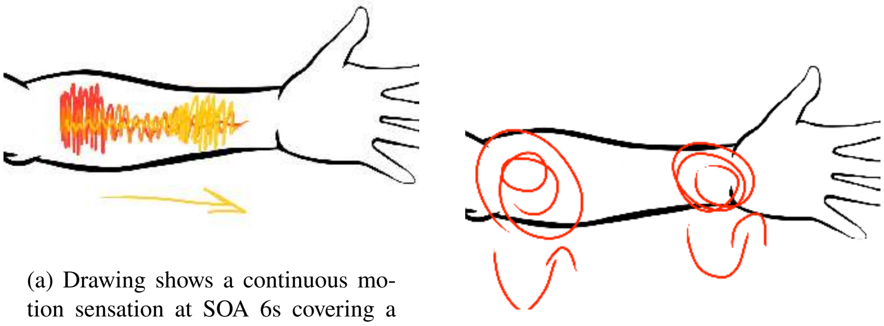


Fig. 8: Patterns of participants' sensations on the forearm produced by different SOAs



(a) Drawing shows a continuous motion sensation at SOA 6s covering a larger area of the forearm. The colors here represent the order of sensations starting from red via orange to yellow (P7).

(b) Drawing shows the sensation of two discrete signals at SOA: 12s (P10). Arrows indicate that thermal signals flare up and disappear again.

Fig. 9: Two participant drawings of thermal motion perception

To our knowledge, this is the first study to examine apparent thermal motion across the forearm. Despite spatial summation and a moderate spatial acuity of thermal stimuli in human perception [27] participants were able to perceive a spatio-temporal change in the thermal signals and reported most continuous sensation of motion on the forearm with SOAs ranging around 6s at a DOS of 8s. This discovery is in approximate alignment with the assertion by Gongora et al. [6], suggesting that a 40% overlap in time results in more continuous motion sensations. In our study, with an ideal SOA timing of 6s the degree of overlap is at 25% of the DOS (8s), while SOAs of 4s or 8s of SOA did not show significantly less motion continuity. Furthermore, we report a significant change in speed perception showing that lower SOAs lead to the perception of faster motion. This may allow the control of speed perception through SOA selection. However, there is a trade-off effect as in very small SOAs ($< 4s$) according to our hypothesis may produce a less continuous motion sensation at the same time. The speed perception task was of subjective nature due to time constraints in the overall experiment time but may be realized as discrimination task in future studies such as in [15].

The varied distribution of thermal receptors across the body [18], and differences even within various regions of the arm [25] may affect the perception of thermal signals and motion. Participants reported that the wrist region often felt less intense than the sensations produced closer to the elbow. When designing thermal motion across body regions different receptor densities and sensitivity levels need to be taken into consideration. Moreover, participants noted an increasing difficulty of discerning and assessing thermal signals over time. We recommend to further mitigate this obstacle by allowing sufficient time for the skin's thermal recovery.

Moving forward, we aim to investigate the impact of varying temperatures (both cold and warm), signal durations, distances and directions (distal to proximal) on the perception of apparent thermal motion on the arm. We also like to investigate the outer, more hairy side of the forearm that is less sensitive to thermal stimuli. We like to highlight that incorporating the drawing task into the experimental procedure proved beneficial, facilitating participants to express and discuss their thermal sensations with the experimenter. This qualitative approach helped us to interpret and understand participants perceptions. Hence, a mixed method approach of quantitative and qualitative data collection tools will support researchers to understand thermal perceptions and the design of future thermal experiences [19]. However, we want to stress that, similar to thermal perception and thermal comfort [14], drawings and verbal communication can be greatly shaped by a participant's cultural background.

The observable apparent thermal motion illusion in our study has the potential to be used for interactive thermal experiences that guide, for instance, the user's awareness with motion feedback to certain body regions or to render dynamic VR experiences such as hot steam traveling across the body. Furthermore, utilizing perceptual illusions can reduce the number of energy-intensive Peltier elements in a wearable device and, hence, contributes to a more sustainable advancement in thermal interfaces.

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