Sensory Interactions in Cutaneous Displays

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***Abstract*— An overview of tactile-thermal interactions is given from the perspective of cutaneous displays that are designed to enhance either object recognition or information transmission. For such multisensory feedback to be effectively implemented it is important to understand how these two sensory systems with fundamentally different spatial and temporal properties interact. Some of these interactions are inherent to the nature of the interface between the skin and a display, namely the contribution of contact area and compliance of the skin. Such factors need to be explicitly considered as part of the design process since they impact the size and overall dimensions of a display. The differences in the temporal properties of the tactile and thermal systems mean that concurrent inputs will be processed on different time scales and so must be accommodated when such displays are used for communication. At present, it is unclear how much changes in the mechanical properties of skin associated with different sites on the body and different inputs need to be taken into account in designing distributed cutaneous communication systems.**

I. Introduction

Over the past 20 years there has been a resurgence of interest in human thermal sensing, and in particular understanding its contribution to object recognition, affective responses to touch, and thermal comfort [1-3]. In parallel with these activities has been the development of a range of thermal displays designed to simulate the changes in skin temperature associated with making contact with an object. The initial work in this area was directed towards presenting thermal cues on the hand that could assist in recognizing an object in situations in which visual information may be limited or absent, or to create a more realistic experience of the contact between the hand and an object in a virtual environment [4-6]. Results from this research demonstrated that model-based thermal displays are able to present temperature cues on the skin that are of sufficient resolution for users to identify and discriminate between objects made from different simulated materials, with a level of accuracy that is comparable to that achieved with real materials [1, 6-8].

Thermal displays have also been evaluated in the context of enhancing user interactions with objects presented on digital media, for example by changing skin temperature to convey emotional content [2, 9], or to present scalar information that is mapped onto temperature [10, 11]. These displays have been used to produce thermal icons [12], by analogy to tactile icons or tactons in the tactile domain [13, 14]. Thermal icons can be created by varying the direction (warming or cooling), amplitude, spatial extent and duration of thermal stimulation. The contexts in which thermal icons have been evaluated include enhancing affective responses in human computer interactions [15], assisting in navigation by giving proximity signals [11], and providing cues regarding the source and importance of incoming text messages on mobile devices [16].

More recently, there has been interest in combining tactile and thermal feedback in haptic devices so that users perceive a more natural experience during object manipulation in virtual environments or teleoperated robotic systems [17-19]. For example, the addition of thermal cues to a display presenting vibrotactile feedback may assist in identifying both the surface texture and material composition of an object [20]. Thermal sensing capabilities have also been incorporated into robotic and prosthetic fingers with the idea of enhancing the autonomous recognition of objects by robotic hands or reproducing the sensory experiences of the intact hand in the prosthetic device [21, 22].

The coupling of tactile and thermal feedback in haptic devices can be challenging from a user perspective and few studies have systematically explored the benefits and costs associated with combining thermal and tactile feedback in a single display. The thermal cues may be perceptually redundant but as part of a multi-sensory display may facilitate performance. The appeal of using thermal stimulation in human-machine interfaces is that it is a rich, salient and emotive sensory modality. The challenge is that the tactile and thermal senses are independent modalities with very different temporal and spatial properties [23].

In contrast to the visual and auditory systems, the sense of touch is distributed across the body which provides a vast landscape for communication. Different regions of the body vary in their sensitivity and areas that are most sensitive to one type of signal, such as the fingertips for tactile inputs, are not necessarily the most sensitive for another modality, for example, changes in temperature [24]. An additional consideration in developing multisensory displays is that the thermal and tactile cues presented to users are almost always well above threshold and so threshold level behavior about which much is known is not necessarily pertinent to understanding how multisensory inputs are processed. Finally, there are many situations in which the hands must be free to perform a variety of tasks. It is therefore important to determine if tactile/thermal signals can be distributed across the body, perhaps at different locations, and still be perceived as integral.

In this paper we provide an overview of tactile-thermal interactions from the perspective of cutaneous displays that are designed to enhance either object recognition or information transmission. The findings presented are from research studies conducted over a number of years in which

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we have attempted to characterize tactile and thermal perception as it relates to the design of haptic devices. For multisensory feedback to be effectively implemented it is important to understand how these two sensory systems interact. A framework that details how different tactile and thermal inputs can be combined or used in isolation in displays should increase a designer's ability to choose among modalities and assign functions and types of information to the channel that is best suited for their presentation. For example, it is known that spatial information maps well on to the human body, particularly the torso and forearm, thus making the sense of touch the preferred medium for displays conveying information related to orientation and navigation [25, 26]. The pervasiveness of vibrotactile alerts in mobile devices attests to their effectiveness in attracting our attention in a subtle yet reliable way. In some situations, tactile and thermal cues may be preferred over auditory signals which tend to be very intrusive and most appropriate for critical alarms that warrant interruption of ongoing activities. The inclusion of tactile and thermal cues in the multisensory interfaces of the future may result from the need for: (1) **synergy**, that is, the merging of information that is presented via several sensory modalities all of which refer to various aspects of the same event; (2) **redundancy** where a number of modalities may be used for processing the same information in an effort to improve detection rates and accuracy, and finally (3) **privacy** which is important when information is confidential or privileged.

II. Contact Conditions

When the hand makes contact with an object the thermal properties of the object, such as its conductivity and heat capacity, and the initial temperatures of the skin and object determine the heat flux conducted out of the skin or object on contact [27-29]. As the resting temperature of skin is usually higher than the ambient temperature of objects encountered in the environment, the skin cools on contact and it is this sense of coldness that assists in material identification [27]. However, it is not only the material composition of the object that determines the change in skin temperature but also the contact force or pressure between the hand and object, as illustrated in the thermal images shown in Fig.1

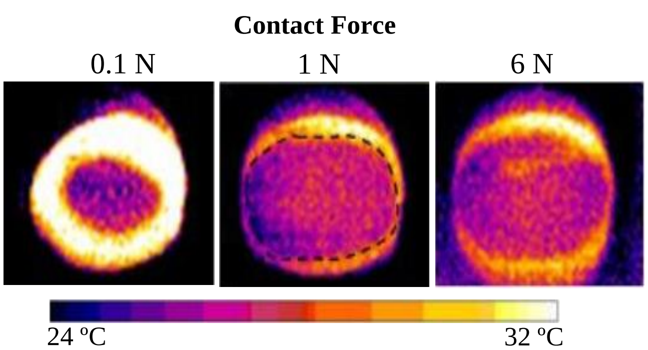

Figure 1. Thermal images of the finger pad as a function of contact force, adapted and modified from [30].

When contact force increases, so too does the contact area between the finger and the object, which allows for a higher heat flux between them [31, 32]. In addition, as contact pressure increases, blood flow in the capillary network beneath the skin's surface is restricted which probably contributes to the decrease in temperature of the finger pad [33]. Over the range of forces typically used to manually explore an object (0.1 N to 6 N) [34], the contact area on the finger pad increases with force and most of this increase occurs by the time the force has reached 1 N. The relation between contact force, contact area and the change in skin temperature is shown graphically in Fig. 2. The overall decrease in temperature is greatest at forces less than 0.5 N and between 4-6 N. These changes are substantial averaging 3.2 ºC and are clearly perceptible.

Such results indicate that fluctuations in contact area and skin temperature with very small variations in finger forces may be used to assist in perceiving the properties of objects in contact with the hand. For example, the change in skin temperature associated with contact pressure may be sufficient for people to use these cues to assist in identifying material properties such as compliance. In this situation, the thermal cues may provide information that is redundant to the information conveyed by cutaneous mechanoreceptors, but possibly confirmatory.

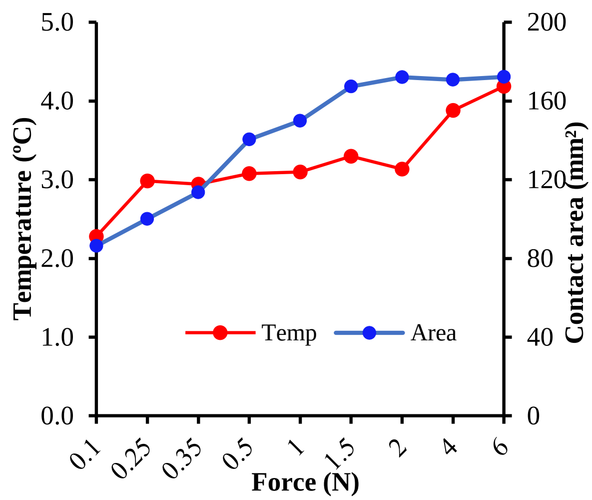

Figure 2. Change in skin temperature (dashed line) and contact area (solid line) as a function of force. Data averaged across 10 participants.

The viscoelastic properties of skin permit it to readily conform to objects in contact with the hand. For surfaces that are textured with features on the macro-geometric scale, the skin can deform on the surface resulting in variations in contact area as a function of the spatial period or groove width of the texture. The changes in skin temperature on contact with materials that have a high contact coefficient $(k\rho c)^{1/2}$, such as copper, may vary with surface roughness. This has been determined experimentally using a set of four copper blocks whose surfaces were machined with a pattern of truncated pyramids spaced at periods of 1000 µm, 1500 µm, 2500 µm and 3000 µm [35]. The average change in skin temperature on the fingerpad over 10 s is shown in Fig. 3.

It is evident that there is a small but consistent decrease in skin temperature as a function of surface roughness, defined in terms of the spatial period of the surface. The rate with which skin temperature changed varied from 0.16

°C/sec to 0.23 °C/sec for the 1000 µm and 3000 µm spatial periods, respectively. Although the overall changes in skin temperature are relatively small, averaging around 2 °C, they are perceptible. When participants were required to choose the cooler of two copper surfaces that varied in spatial period, they could reliably discriminate (defined as 72% correct) between copper stimuli when the difference in spatial periods was 1500 µm or greater. As the stimulus became rougher, the surface was perceived to be cooler. Although the contact area on the top of each stimulus did not change as the contact force was maintained at 1 N, it appears that with the rougher surfaces the finger was able to deform more around the textured surface resulting in a larger contact area (see Fig. 4). This provided a larger surface for heat to flow out of the finger to the copper surface.

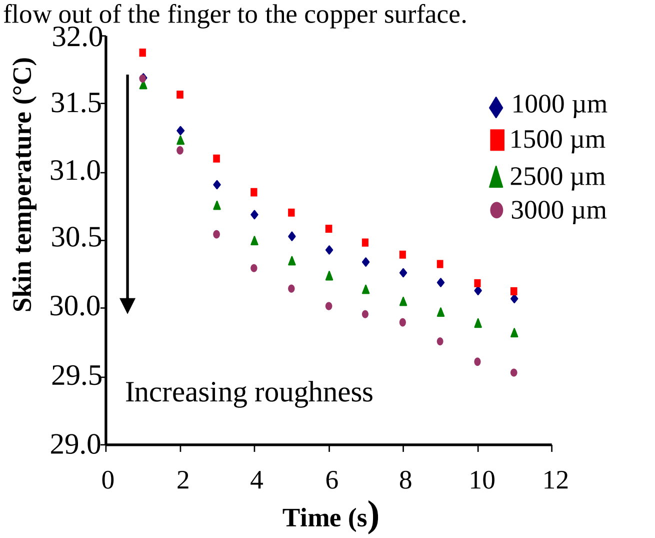

Figure 3. Decrease in skin temperature as a function of time averaged across 10 participants for copper stimuli with varying roughness as defined by the spatial period.

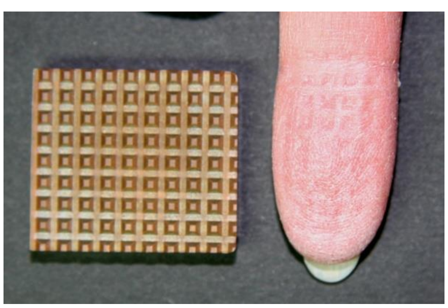

Figure 4. Textured cooper with spatial period of 3000 µm (left) indentations in skin after contact (right).

In these experiments subtle changes in skin temperature associated with increasing contact area are perceptible. This may be interpreted as a synergistic effect in that both skin temperature and perceived roughness are changing concurrently. This temperature-roughness interaction will be dependent on the material in contact with the hand and would not occur over the same time scale for materials with much lower contact coefficients such as ABS or granite. Such tactile-thermal interactions reveal some fundamental properties of somatosensory processing. They indicate that changes in skin temperature can provide ancillary cues that people could use to perceive variations in texture or the contact pressure when grasping an object. The availability of such information has been proposed to account for the ability of a person with a large fiber sensory neuropathy to distinguish between different grasp forces [36].

III. Body Site

The somatosensory system is a distributed system and so the ability to perceive a particular stimulus will vary across the skin surface and the same stimulus will not be perceived identically at different locations. For the cutaneous sensory modalities, namely, touch, temperature, itch and pain, the areas of greatest sensitivity are not necessarily the same. Whereas the fingertips are one of the most tactually sensitive regions of the body capable of resolving displacements in the order of a few micrometers and forces around 10 mN [34], their thermal sensing capabilities are inferior to those measured at the base of the thumb (thenar eminence) and the forearm [24]. This is important to the design of multisensory displays in that it suggests that distributing sensory cues across the skin may be more effective than co-locating them if individual dimensions (e.g. cold, pressure, displacement) are to be perceived. The above differences between touch and thermal sensing reflect threshold level responses whereas most of the cues presented in cutaneous displays are well above threshold. The accuracy with which suprathreshold stimuli are identified and discriminated is not necessarily related to the capacity to detect stimuli at threshold levels. For vibrotactile stimuli it has been shown that tactons are in fact more accurately identified both in terms of percent correct and information transfer (IT) on the forearm as compared to the finger [14, 37], despite the higher density of mechanoreceptors in the fingertips and their associated superior tactile acuity.

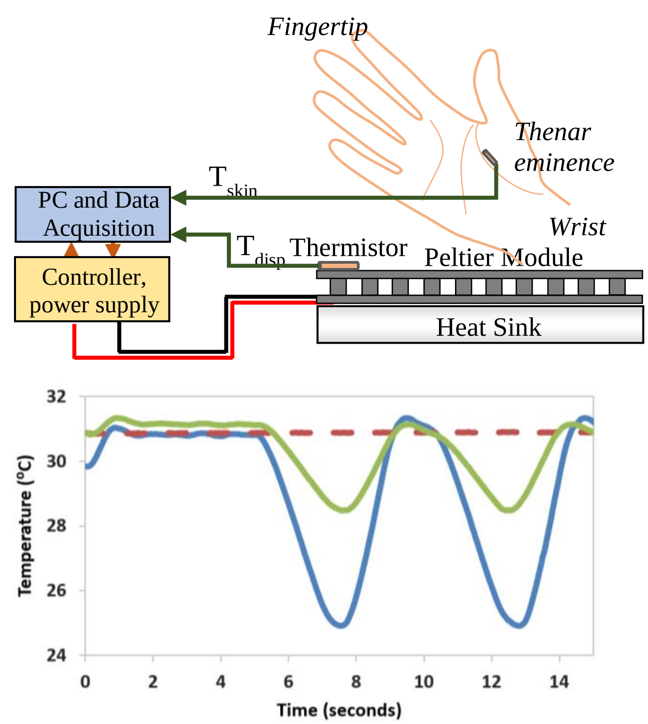

Figure 5. Upper: Schematic illustration of the thermal display with the Peltier module mounted on a heat sink, and the thermistors measuring the temperatures of the module and the skin. Lower: Representative thermal icon presented on the fingertip, thenar eminence and wrist with the temperatures

of the thermal display (Peltier device in blue), skin on the display (green) and skin adjacent to the display (red).

In order to understand whether the location on the skin affects the accuracy with which thermal patterns can be identified a series of experiments was conducted using the same display and similar sets of thermal patterns [12, 38]. The interest here was to determine if performance differences were sufficiently large that a specific site would be regarded as most effective for presenting thermal cues and so lead to certain design considerations. It is quite feasible, for example, for thermal cues to be displayed on the palm of the hand in a mouse-type device, while tactile cues are presented on the fingertips. The locations tested in this work were the fingertips, thenar eminence and the wrist. The six thermal patterns were well above threshold in terms of the amplitude and the rate of change in temperature. In these experiments participants were required to identify the patterns based on a visual template. Performance was best on the thenar eminence and wrist when compared to the fingertips as illustrated in Fig 6, where both percent correct scores and information transfer are shown. This suggests that (1) site-specific threshold differences in thermal sensitivity are also reflected in the ability to identify supra-threshold stimuli and (2) distributing tactile and thermal feedback across the hand in a multisensory display may result in more consistent identification, if the display is used for communication. One further result from these experiments that is noteworthy is that there was no effect of temperature on thermal pattern identification, that is, warm and cold stimuli were identified with similar accuracy. This contrasts with threshold level responses where it is noted that warm thresholds are about twice the size of cold thresholds measured at the same site [24].

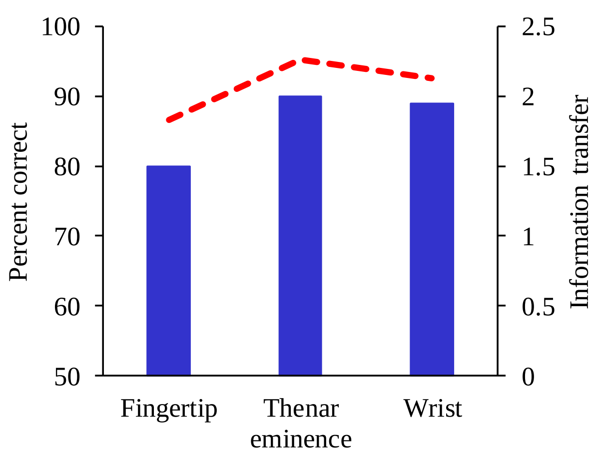

Figure 6. Group mean percent correct responses (blue bars) and information transfer (dashed red line) when identifying six thermal patterns presented at three sites on the arm. Data averaged over 10 participants.

IV. Temporal Properties

Although the channel capacity of the thermal sensory system is comparable to that of the other cutaneous senses as illustrated by the IT values shown in Fig. 6, it is unlikely that a high throughput rate will ever be feasible for thermal icons. One very profound difference between the tactile and thermal senses is the time taken to process sensory information. Tactile reaction times are estimated to be around 140-270 ms, tactile temporal acuity is 10 ms and information transfer rates on the fingertip are estimated to be 10^2 bits/s [34]. The time taken to process thermal information is much slower than that measured for other aspects of cutaneous stimulation, both physiologically and perceptually. This is reflected first in the periphery where the conduction velocities of cold (10-20 m/s) and warm (0.5-2 m/s) afferent fibers are much slower than those of afferent fibers from mechanoreceptors whose conduction velocities are around 80 m/s [23, 39].

As would be expected from these differences in conduction velocities, the reaction time for cold sensations is significantly shorter than that for warmth. Using periodic warming and cooling profiles, Ho et al. [40] found that the delay between the physical and perceived onset of changes in temperature was 318 ms for cold and 460 ms for warm, consistent with the faster neural response to cooling. For other perceptual tasks such as identifying whether a material like copper that has a high heat extraction rate is present in an array of two items, the average response time is 900 ms. This is almost twice the time required (400-500 ms) to encode material properties such as hardness or roughness [41].

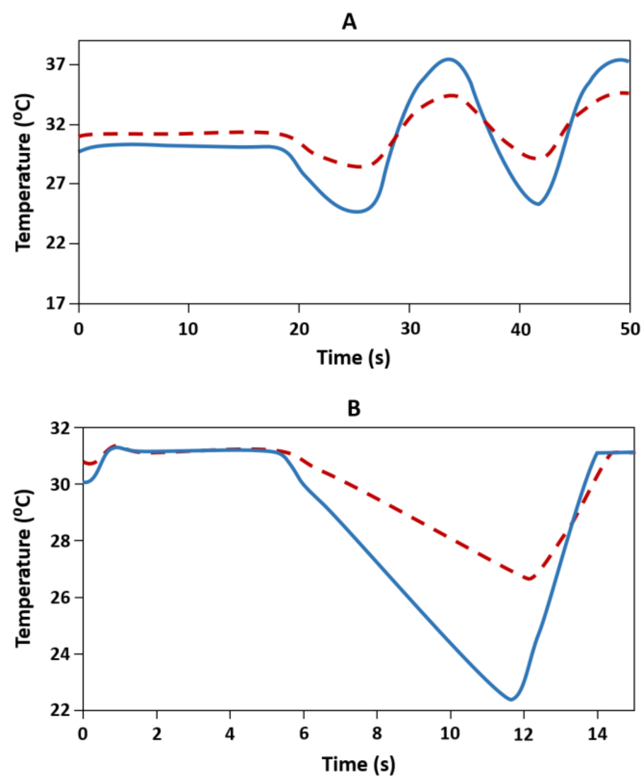

Figure 7. A. Change in skin temperature on the thenar eminence (red) in response to a warming double-pulse thermal input delivered by the thermal display (blue). B. Change in skin temperature on the wrist (red) as the thermal display presents a ramp decrease in temperature (blue).

Due to these temporal aspects of thermal sensing, it is critical when designing thermal stimuli for use in multisensory displays to measure the actual change in skin temperature as a function of the thermal input. An assumption is often made that the skin's response mirrors that of the thermal stimulus. Such measurements become critical if temporal properties such as the rate of warming or cooling are used to create different patterns. As Fig. 7 clearly demonstrates there is a delay in the response of the skin when a thermal display changes temperature, and for time-varying inputs the gain of the skin's response does not track that of the display.

These differences in the temporal properties of the tactile and thermal systems mean that concurrent inputs will be processed on different time scales. When thermal cues are presented simultaneously with vibrotactile cues in a multisensory display, it has been found that the dynamic tactile cues often mask the perception of the more subtle thermal signals. This becomes particularly evident as the intensity of the vibration signal increases and when the peak change in temperature and vibration amplitude are simultaneous. [42]. By introducing a brief delay between the onsets of thermal and tactile signals and ensuring that the temporal profiles of stimulation are distinct, it is possible to minimize this problem. In the above work the thermal and tactile stimuli were delivered at the same site on the hand which may have contributed to the masking effects. With distributed inputs, such as presenting vibration on the fingers and thermal cues on the thenar area such effects may be less pronounced.

Much of the work on integrating thermal and tactile inputs in a single display has focused on combining thermal and vibration signals to give a more realistic experience in VR or AR environments [17, 18, 20]. There have been few studies in which pressure and thermal cues have been presented in a single display. Such inputs may be more promising for displays focused on information transmission in that the relative saliency of the signals can be more readily controlled due to the less dynamic nature of the inputs.

V. CONCLUSIONS

This overview of tactile-thermal interactions has highlighted some of the factors that need to be considered when thermal and tactile feedback are presented concurrently in a multisensory display. Some of these effects are inherent to the nature of the interface between the skin and a display, namely the contribution of contact area and the compliance of the skin, and so should be explicitly considered as part of the design process. Displays with larger contact areas facilitate the processing of thermal information due to the effects of thermal spatial summation; when larger areas of skin are warmed or cooled the stimuli are perceived as more intense. Such displays require more power and efficient cooling systems which is a major consideration if the display is ultimately to be portable or worn as part of a multisensory system. However, if thermal inputs are limited to heating and not cooling the skin, then there are options other than thermoelectric coolers (Peltier devices). Technologies such as Kapton (polyimide-film) heaters are thin and flexible and can readily be used to warm the skin. Such a wearable system could be combined with a vibrotactile sleeve fabricated from electro-active polymers to create a flexible multisensory display.

The focus at present on combinng vibration and temperature cues in displays reflects the importance of these to object identification and to creating realistic sensations of contact in virtual or teleoperated environments. When a person strokes the fur of an animal or touches someone's arm, they are immediately aware of both the texture of the fur and skin and the warmth of the living body it covers. Creating such impressions in virtual environments adds a degree of realism that enhances a sense of presence and may facilitate end effector control in teleoperated environments. In these contexts, vibrotactile and thermal stimuli must be synergistic so that the perceptual experience is convincing.

Due to their excessive reliance on visual feedback, there has been recent interest in multisensory cutaneous displays in order to expand the communication options available in mobile devices and wearable technologies [43, 44]. This has involved combining vibration, pressure and skin stretch cues in a single display and determining whether such inputs can be individually resolved when delivered to the user's arm [44]. These three tactile cues were found to be perceptually distinct elements which suggests that they could be combined in a single display capable of providing a richer palate for communication. For the visual and auditory systems, it has been shown that increased dimensionality of a display enhances the amount of information that can be received by a user [45]. Much less is known about multi-dimensional tactile and thermal displays, and what has been studied has typically focused on static displays and information transfer rather than dynamic displays and the rate of information transfer [46]. Given the very different temporal processing properties of the tactile and thermal sensory systems (see Section IV), future research will have to determine the optimal temporal profiles for presenting tactile and thermal cues so that the signals are not masked. The evidence to date indicates that tactile inputs can readily obscure thermal cues [42].

One final area of research that needs to be explored in this context of combining different inputs is whether such concurrent stimulation affects the mechanical properties of the skin itself. When the skin is warmed, for example, it becomes more compliant which may affect the transmission of vibrotactile signals across the skin surface and hence the number of receptors that respond to the vibration. Warming the skin has been shown to facilitate encoding variations in vibration amplitude, an important element in texture perception [47]. This effect may result from changes in the mechanical properties of skin or possibly in the output from cutaneous mechanoreceptors.

In summary, multisensory displays offer promise in a number of domains from enhancing user experience in VR and AR environments to increasing the dimensionality of signals available to transmit information. In this paper we have highlighted the many types of interactions that occur between thermal and tactile signals. The temporal and spatial properties of the two sensory modalities must be taken into account in designing effective displays, particularly if they are distributed across the skin so that communication is optimized.

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