Perceptual Interactions in Thermo-tactile Displays*

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Abstract— **Thermo-tactile displays have been developed to enhance the degree of realism in virtual environments and assist in the identification of virtual objects. It is unknown whether the simultaneous presentation of thermal and tactile cues enhances user performance and if the two types of sensory signals can be processed independently or interact. The present experiment measured thermal pattern identification in the presence of concurrent vibrotactile feedback on the thenar eminence on the hand. The thermal patterns varied with respect to the direction, rate, and duration of the change in skin temperature and for the vibration inputs the number of pulses was varied. The results indicated that with concurrent tactile stimulation warm stimuli (89%) were easier to identify than cool stimuli (76%) and that the number of pulses in the vibration signal affected thermal identification. The mean Information Transfer (IT) associated with these thermo-tactile patterns was 1.94 bits. These thermal-tactile interactions indicate that in multi-sensory displays the ability to perceive independent channels of communication can be influenced by the concurrent presentation of other sensory cues.**

I. Introduction

Several thermo-tactile displays have been fabricated over the years usually with the objective of presenting a more realistic sensory experience of objects in virtual or remote environments [1-5]. In these multisensory displays, thermal feedback provides information about the material composition of virtual objects and vibrotactile feedback conveys surface texture cues. There do not appear to have been any studies using these displays in which tactile and thermal cues have been presented simultaneously so that the benefits of having additional sources of information on object recognition could be determined. It is also unclear how simultaneous presentation of tactile and thermal cues affects the perceptibility of each type of signal.

Information regarding changes in skin temperature is relayed to the cerebral cortex in pathways that are separate from those that convey information about mechanical stimulation of the skin. Nevertheless, interactions occur between thermal and haptic signals that affect how sensory information is processed. For example, the perceived magnitude of a cold stimulus presented on the fingertip is attenuated if the finger is voluntarily moved across the surface of the thermal display as compared to the condition in which the display is moved externally [6]. These interactions are important in the context of haptic object perception where both thermal and tactile cues can be used to identify and discriminate between objects. The changes in skin temperature when an object is grasped provide information about its material composition, such as whether it is made from copper or plastic [7, 8]. When combined with haptic cues regarding surface texture, shape and weight an object can be rapidly identified [9].

Thermal cues are used not only to identify and discriminate between objects but can also have a profound effect on haptic perception [10, 11]. Weber [12] was one of the first to describe the temperature-weight illusion in which the colder of two weights of equal mass is perceived to be heavier than a weight maintained at skin temperature. He hypothesized that cold intensified the sensations of pressure, a conjecture subsequently confirmed in neurophysiological studies of cutaneous mechanoreceptor activity [13]. The change in perceived weight when an object is cooled is considerable, with estimates increasing by up to 250% under optimal conditions. Warming an object also makes it feel heavier than an object at skin temperature, although this effect is much smaller and more variable [11, 14].

Tactile sensory acuity and the perceived intensity of tactile stimuli can be influenced by the temperature of the device contacting the skin and by the temperature of the skin itself. Two-point and gap detection thresholds decrease (i.e. enhanced sensitivity) when the tips or edges of the devices in contact with the skin are either cooled or warmed [15, 16]. These effects have been termed thermal sharpening and are attributed to highly localized thermal gradients on the skin which facilitate the detection of spatially dispersed tactile stimuli [16]. In contrast, when the skin is cooled tactile acuity is impaired as shown by the decline in sensitivity to changes in pressure [17], roughness [18], and vibrotactile stimulation between 150 Hz and 250 Hz [19]. The decrease in tactile acuity when the skin is cooled is attributed to a decline in the sensitivity of cutaneous mechanoreceptors which are known to alter their discharge rates in response to cooling the skin [20, 21]. The effects of warming the skin on tactile acuity are smaller and less robust. Green [19] reported that warming the skin resulted in a slight increase in thresholds for frequencies of vibration above 80 Hz, but Verrillo and Bolanowski [22] observed no changes in vibrotactile sensitivity for frequencies between 15 Hz to 500 Hz when skin temperature was increased from 30 °C to 40 °C. More recently, Zhang et al. [23] noted that with increases in skin temperature up to 43 °C there was a decrease in vibrotactile thresholds at 25 Hz, but at this temperature there was no effect on vibrotactile amplitude discrimination.

The studies described above have all demonstrated the effect of the temperature of an object or the skin on tactile perception. There have been many fewer experiments on the influence of tactile stimuli on thermal perception. One aspect of thermal-tactile interactions that has been analyzed is how

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the ability to localize a thermal stimulus is affected by concurrent tactile stimulation. Tactile cues have been shown to assist in localizing changes in skin temperature and when they are eliminated by using non-contact thermal stimuli, such as radiant heat, localization deteriorates [24, 25]. However, these interactions between thermal and tactile stimulation can lead to errors in thermal localization. Green [26] described an illusion in which the thermal sensation experienced on the middle finger of the hand changed as a function of the stimuli presented on the two adjacent fingers. When the index and ring fingers were placed on warm (or cold) thermal stimulators and the middle finger was placed on a thermally neutral stimulator, warm (or cold) was felt on all three fingers. The perceived magnitude of the thermal sensations was the same as that experienced in the control condition in which the temperature of only the thermal stimulator under the middle finger was varied and the other two stimulators remained thermally neutral. This referral of thermal sensations required equivalent tactile experiences on the three fingers in that it did not occur when the middle finger was held above the stimulator nor when it was touched by another finger [26]. Further studies of the sensations resulting from thermal referral revealed that the apparent intensity of the resulting sensation was always lower than the intensity of the physical stimuli applied to the adjacent digits [27]. This was interpreted as indicating that the illusory thermal sensation experienced on the middle finger was not simply a copy of the thermal changes on the two adjacent fingers but resulted from perceptual summation and redistribution of the applied thermal changes to all three digits. From a functional point of view, thermal referral may reflect a mechanism that resolves spatial discrepancies between spatial and thermal inputs to produce a unified percept [27].

Other aspects of thermal-tactile interactions have not been systematically studied, and these have become increasingly important as the field of multisensory cutaneous displays emerges. For example, it is unclear how to combine tactile and thermal inputs in a multisensory display so that the individual signals are perceived and one stimulus does not mask another. In virtual and augmented reality (VR/AR) applications, thermal feedback may be used in conjunction with tactile inputs to convey more realistic percepts of objects [2-4]. In other applications, thermal feedback can be a dedicated channel of communication [28-30]. Several studies have evaluated thermal pattern identification on the arm and hand and determined which features of thermal stimuli can be reliably perceived [28, 31, 32]. The objective of the present experiment is to determine whether thermal pattern identification is affected by concurrent presentation of vibrotactile stimuli and whether the temporal profiles of the thermal and vibrotactile inputs influence identification.

II. Experimental Design

The experiment used an absolute identification paradigm in which participants had to identify which of six thermal stimuli was presented on the hand. The thermal stimuli varied with respect to the rate and direction of change in temperature. Vibrotactile stimulation was delivered at the same site concurrently with the thermal stimuli. For the tactile stimuli the duration and number of pulses varied.

A. Participants

Ten normal healthy individuals, ranging in age from 24 to 28 years old (mean: 25 years) participated. They were all right-handed. They had no known abnormalities of the skin or peripheral sensory or vascular systems. They all signed an informed consent form that was approved by the MIT Committee on the Use of Humans as Experimental Subjects.

B. Apparatus

A multisensory display was built to provide thermal and vibratory cues to the skin. The display consisted of a thermoelectric cooler (TEC) (Model CH-38-1.0-0.8, TE Technology, Inc.) mounted on a heat sink. The thermoelectric module was an annular Peltier device, with an outer diameter of 24 mm, a 9.8 mm hole at the center, and a thickness of 3.1 mm, giving a contact area with the skin of 377 mm^2. A coin vibration motor (Model C0720B001F, Jinlong Machinery & Electronics Co. Ltd.) 7 mm in diameter and 2.1 mm thick was placed at the center of the Peltier device and used to provide vibration (see Fig. 1).

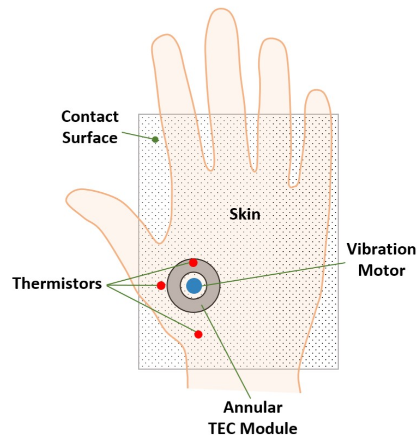

Figure 1. Schematic illustration of the multisensory display with an annular Peltier module and coin vibration motor at its center. The three thermistors monitor the temperature of the module and skin. The base of the thumb is in contact with the Peltier module and hand rests on a surface.

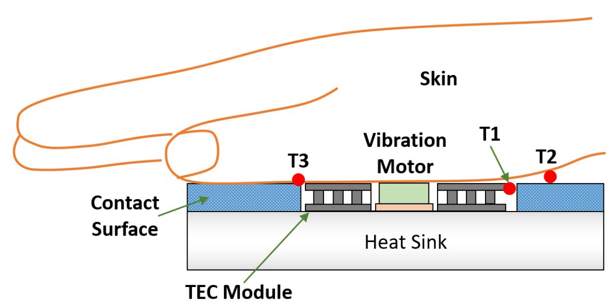

Figure 2. Schematic illustration of the thermal display with a Peltier module mounted on heat sink, and the location of three thermistors measuring the temperature of the module and at two locations on the skin.

Three thermistors, 457 μm in diameter and 3.18 mm in length (Model 56A1002-C8, Alpha Technics) were used in the experiment. The thermistor was chosen on the basis of its small dimensions and low thermal mass. The locations of the thermistors are shown in Fig. 2. Thermistor 1 was mounted on the surface of the thermal display for feedback control of the device's temperature (T_1). Two other thermistors measured the temperature at two locations on the skin. The thermistor at location 3 measured the skin temperature (T_3) at the edge of the contact area of the skin with the Peltier module. This measurement indicated the change in skin temperature due to the thermal stimulus presented on the thermal display. A baseline temperature measurement (T_2) on the wrist was given by thermistor 2. This baseline skin temperature was different for each participant and was unaffected by the thermal stimuli due to its location. A schematic of the thermal display with thermistors and the control setup is shown in Fig. 3.

A fixture was fabricated using laser-cut acrylic sheets to hold the Peltier module and the heat sink. A fan was mounted in the fixture to provide forced convection cooling. The surface of the Peltier module was flush with the acrylic surface so that the location of the Peltier device was not perceptible based on tactile cues. The contact surface material ensured that neither hot nor cold cues were provided to other locations on the palm and wrist.

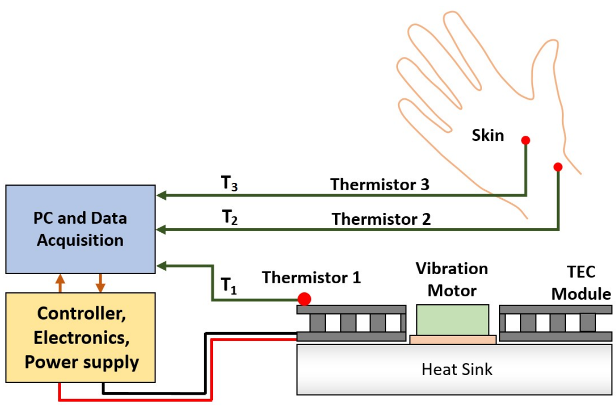

Figure 3. Schematic illustration of the multisensory display with a Peltier module mounted on a heat sink, a vibration motor and thermistors measuring the temperature of the module and at two locations on the skin.

Data acquisition and feedback control of the Peltier device was done using National Instruments Data Acquisition modules (Model NI cDAQ-9174, NI9263, NI9474, NI9205). A LabVIEW-based (NI) graphical user interface (GUI) was used to send commands to control the Peltier module and to record the skin temperatures continuously at 1 kHz. The baseline skin temperature was given as the input to the controller at the start of each trial, and was used as the reference temperature when the thermal stimulus was presented so that the same relative stimulus was delivered to all participants. A second computer was used to run a GUI on which the participants' responses were recorded.

C. Thermal and Vibrotactile Stimuli

The display was developed to present stimuli made up of a combination of thermal and vibratory patterns. The thermal patterns were designed by varying two stimulus dimensions, the amplitude and rate of change in temperature. These patterns were made using three basic profiles (square wave, step and ramp), which provided different rates of temperature change and also varied with respect to the direction of change (warming or cooling) to give a total of six thermal patterns as illustrated in Fig. 4. Preliminary experiments were conducted to evaluate how skin temperature changed in response to the short duration thermal profiles. These pilot studies were used to observe the time course of changes in skin temperature in response to various thermal inputs, and to determine the rate of temperature change, intensity and duration of the stimuli.

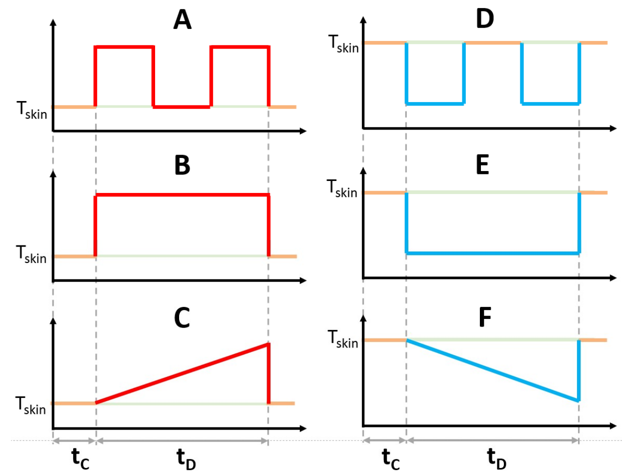

Figure 4. Schematic illustration of the six thermal patterns categorized as warming (left) and cooling (right).

The intensity (ΔT) was kept fixed at 7 °C for both warming and cooling, which was relative to the baseline skin temperature (T_{skin}). The total duration (t_D) of each of the six patterns was 10 s preceded by a 5-s calibration period (t_C) during which the display's surface temperature was maintained at the baseline skin temperature. Patterns A and D were based on a square wave input, B and E were based on a step input, and C and F were linearly decreasing and increasing ramps. The average rate of change of temperature was 3 °C/s for A and D, 1.5 °C/s for B and E, and 0.7 °C/s for C and F. The maximum rate of change of the temperature was limited by the dynamics of the thermal display system. The difference in the direction of temperature change in the above pairs made them distinguishable.

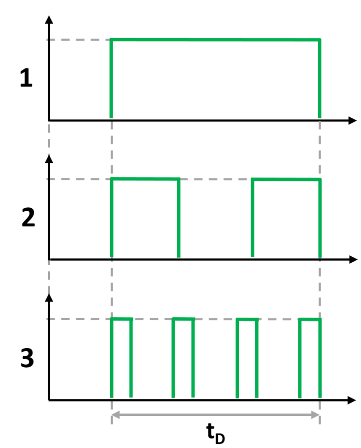

Figure 5. Schematic illustration of the three vibratory patterns which have the same overall duration (t) and intensity but varying number of pulses.

The vibratory patterns were designed with a square wave profile using the dynamics of the vibration motor. The frequency was 100 Hz and the peak amplitude was 1.48 m/s^2 as measured with a low-mass accelerometer mounted on the motor. Three distinct patterns (1, 2 and 3) were created with the same duration (t_D) as the thermal patterns (see Fig. 5).

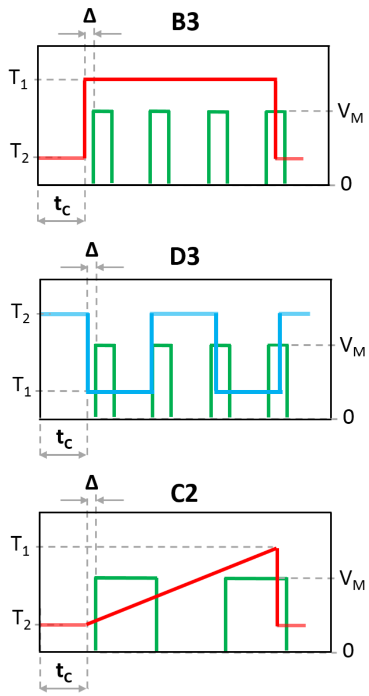

Figure 6. Schematic representation of three patterns (B3, D3 and C2) out of a total of 18 patterns. The temporal profile of the warm (red) and cool (blue) stimuli are shown with the vibration magnitude (Vm) in green. T_1 and T_2 refer to the temperatures measured on the display and skin respectively.

Preliminary experiments were conducted with a combination of these three vibratory patterns and six thermal patterns to optimize parameters such as vibration pulse intensity, duration and number of pulses in the combined stimuli. It was observed in these pilot studies that the vibratory stimulus often masked the perception of the thermal stimulus when they were presented simultaneously. This masking was more profound when the intensity of the vibration pulse was high and the peaks of the thermal stimulus coincided with falling or rising edge of a vibration pulse. To minimize these effects, the vibration motor was operated at 50% of its maximum amplitude and a delay (Δ) was introduced at the onset of the vibratory stimulus relative to that of thermal stimulus. Eighteen patterns (A1, A2, A3, B1, B2, B3, … F1, F2, F3) were created by combining the six thermal patterns with the three vibratory stimuli. Fig. 6 shows three representative patterns.

D. Procedure

Prior to starting the experiment, the procedure was explained to participants. They read the instructions on the computer screen and placed their wrist and the glabrous surface of the hand on the supporting fixture and brought their thenar eminence in contact with the thermoelectric module's surface as shown in Fig. 7. Participants were familiarized with all the thermal and vibrotactile patterns. In the familiarization period participants selected each pattern in turn using a computer mouse and it was presented on the display while they looked at the visual display. This was followed by a series of 10-11 practice trials in which participants indicated the pattern that was presented and received feedback after each response. The experiment commenced after the practice session which typically lasted 5 minutes. The initial skin temperatures of the participants ranged from 29 °C to 32 °C with a mean of 31 °C. The ambient temperature was maintained at 25 °C, as measured with a thermocouple in free air. The thermoelectric module was maintained at the baseline skin temperature between trials before each stimulus was presented.

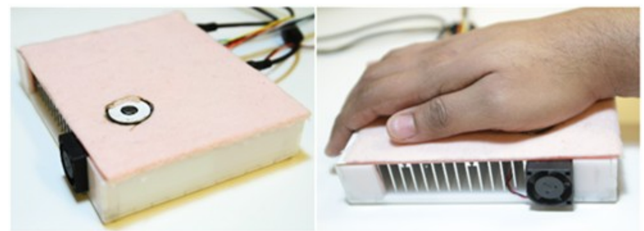

Figure 7. Display with thermoelectric module mounted on a heat sink and fan (left) and with the thenar eminence over the thermoelectric module during stimulus presentation (right).

Each trial lasted 15 s which included a calibration period of 5 s prior to stimulus presentation which lasted 10 s. During the calibration period, the temperature of the thermoelectric module was maintained at the baseline skin temperature as measured by thermistor 2. Each stimulus was presented three times in a randomized order to give a total of 54 trials. Two different auditory cues were provided to signal the start and finish of each stimulus presentation. After the second auditory cue, participants indicated their responses by selecting the checkbox beside the letter (A-F) associated with the visual pattern on the GUI on the screen. Responses had to be made within 10 s and on most trials participants made their responses within a couple of seconds. After every two trials, participants switched the hand that was on the display to avoid any adaptation effects. A rest break was provided when requested. No feedback regarding the correctness of the responses was provided during the main experiment.

III. Results

The temperatures measured on the skin and Peltier module during presentation of the six thermal stimuli are shown in Fig. 8. The measurements clearly indicate that the change in temperature during stimulus presentation was well localized to the site of stimulation and did not affect the adjacent area on the hand. The delay in the skin's response to the stimuli and in the gain of the response is also evident, consistent with other studies using similar stimuli [28].

The percentage of correct responses for each thermo-tactile stimulus averaged across all stimuli and participants ranged from 61% to 100%, with an overall mean of 82% correct. The mean percentage of correct responses for each stimulus as a function of vibration is shown in Fig. 9. For warm stimuli (patterns A, B and C) the group mean percentage of correct responses was 89% and for cool stimuli (D, E and F) it was 76%. For the individual patterns, performance was best for patterns A (100%) and D (96%) which had a square-wave profile with two double pulses. The hardest pattern to identify was Pattern F (61%) which was a linear decrease and then increase in temperature. There was no difference between the hands in performance.

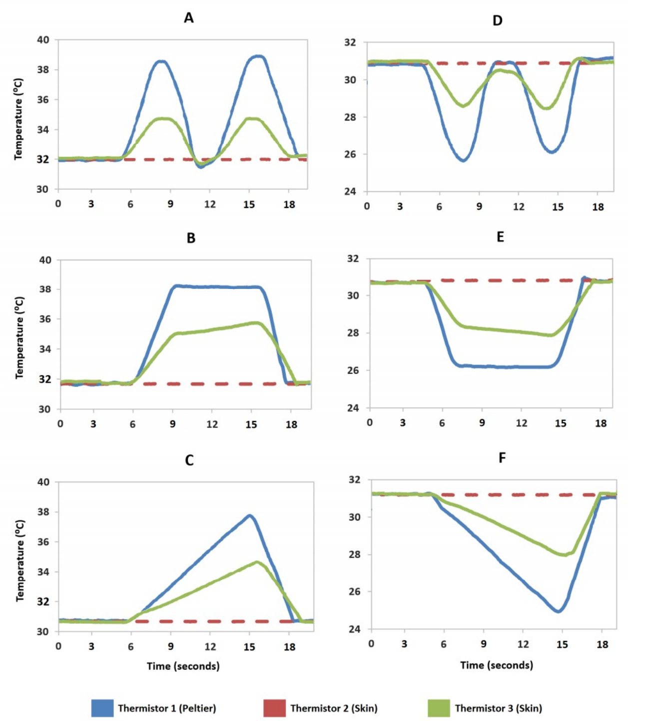

Figure 8. Temperatures measured on the Peltier module (thermistor 1) and at two locations on the skin, one of which (thermistor 2) was not in contact with the thermal display.

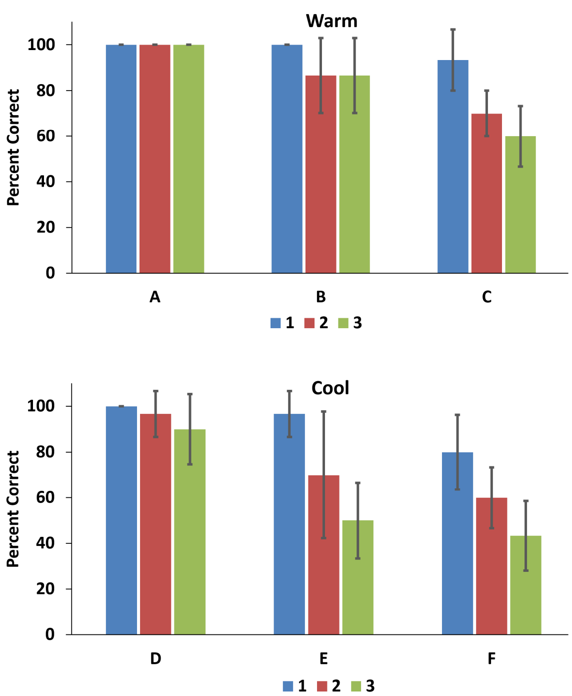

Figure 9. Group mean percent of correct responses for warming (upper) and cooling (lower) thermal patterns as a function of concurrent vibration (one pulse [blue], two pulses [red] and three pulses [green]). The standard deviations (SD) are shown.

An ANOVA was conducted on the participants' responses and indicated that there was a significant main effect of temperature ($F(1,9)=23.28$, $p=0.001$) with warm stimuli being identified more accurately than cool stimuli, a main effect of vibration ($F(2,18)=40.17$, $p<0.0001$) and a significant interaction between temperature and vibration ($F(2,18)=5.56$, $p=0.014$). As the number of pulses in the concurrent vibration increased from one to three, thermal patterns became more difficult to identify and this was particularly true for cool stimuli.

The confusion matrix of the participants' responses is shown in Table 1. The mean Information Transfer (IT) calculated from the confusion matrix is 1.94 bits, indicating that for these six patterns approximately four can be reliably identified. The errors made by participants provide insight into the dimensions of stimuli that may have been difficult to encode. Patterns C and F (ramp inputs) were often misidentified as patterns B and E (step inputs) respectively, and pattern E (step) as D (double step) and pattern F as E. There are clearly asymmetries in these errors in that the ramp inputs were often misidentified as step inputs, but the opposite error was very infrequent.

Table 1. Confusion matrix of the group responses with scores out of a total of 90 trials presented for each stimulus. The highlighted diagonal represents the correct responses.

	Responses					
Stimuli	A	B	C	D	E	F
A	**90**	0	0	0	0	0
B	5	**82**	3	0	0	0
C	5	18	**67**	0	0	0
D	0	3	0	**86**	1	0
E	0	0	0	25	**65**	0
F	0	0	0	0	35	**55**

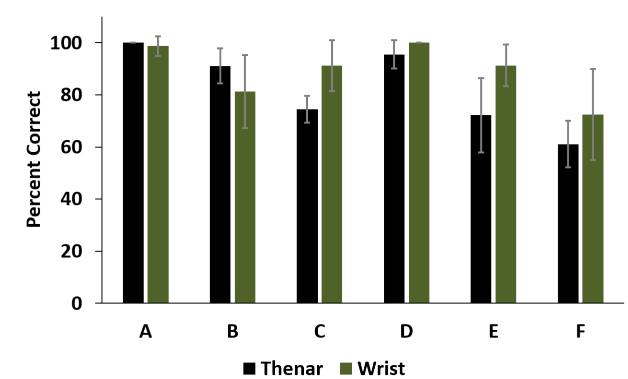

Figure 10. Group mean percent correct responses (with SD) for thermal patterns presented on the thenar eminence during concurrent vibrotactile stimulation (black bars) and on the wrist (green bars) without tactile stimulation [33].

The results on the thenar eminence were compared to those from earlier experiment in which the same stimuli were presented on the wrist, but without any concurrent vibrotactile stimulation [33]. These data are shown in Fig. 10 where it can be seen that vibrotactile stimulation on the hand did affect the perception of thermal stimuli. In the earlier study participants correctly identified 89% of the stimuli, as compared to 82% correct in the present experiment. An ANOVA conducted on these data indicated a main effect of pattern ($F(5,18)=31.21$, $p<0.001$), site tested ($F(1,18)=10.47$, $p=0.005$) and a significant interaction between pattern and site tested ($F5,18)=6.76$, $p=0.001$).

IV. Discussion

The results from this experiment indicate that concurrent vibrotactile stimulation can influence the ability to identify thermal patterns. The effect of tactile stimulation is more pronounced for thermal stimuli that are harder to identify and varies as a function of the properties of the vibration. More dynamic tactile stimuli (those comprising three pulses) had a greater effect on thermal pattern identification than a continuous signal. Previous work has shown that both the temperature of the skin and of an object in contact with the skin affect tactile perception [14-19]. The present study has demonstrated that tactile cues can affect the perception of thermal stimuli, a finding previously demonstrated only in the context of localizing the site of thermal stimulation [25, 26]. The present results also show that vibrotactile stimulation has a greater effect on the perception of cold than warmth, an intriguing finding that warrants further investigation. This suggests that the effect of concurrent tactile stimulation was not simply a masking phenomenon, in which all thermal stimuli were perceptually attenuated.

A comparison of the present findings with the results from an earlier experiment in which the same thermal stimuli were presented on the wrist without any tactile input [33] indicated that there was a slight decline in performance with concurrent tactile stimulation. The thermal sensitivity of the wrist and thenar eminence are comparable [34] and so this difference is likely due to the additional source of cutaneous stimulation.

In the context of multisensory displays, the present findings indicate the importance of understanding how different sensory signals interact, even when users are focusing on a single source of information. Changes in skin temperature in the innocuous range are important to the perception of material properties and when displayed in conjunction with relevant textural cues about virtual or remote objects should enhance object identification.

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