Vibrotactile Pattern Identification in a Multisensory Display

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Abstract. In multisensory cutaneous displays in which both tactile and thermal signals are presented, it is important to understand the perceptual interactions that can occur between the two modalities. Phenomena such as masking, facilitation and inhibition may occur that influence how multisensory inputs are processed. In the present experiment participants were required to identify vibrotactile patterns that varied in intensity and pulse duration while the skin was warmed, cooled or remained at a neutral temperature. The results indicate that the temperature of the skin influences the ability to identify vibrotactile patterns that are well above threshold. This thermal-tactile interaction occurred when the skin was warmed and assisted in the identification of vibrotactile stimuli that varied in intensity. In contrast, warming the skin appeared to impede identification of patterns whose pulse duration varied. These results suggest that the enhanced activity of cutaneous thermoreceptors during warming may facilitate the processing of amplitude-related properties of incoming signals from cutaneous mechanoreceptors.

1 Introduction

In multisensory cutaneous displays, tactile, haptic and thermal feedback may be presented to a user so that objects encountered in virtual or remote environments are perceptually more realistic [1] [2]. For example, the addition of thermal cues in a display presenting vibrotactile feedback may assist in identifying both the surface texture of an object and its material composition [3] [4]. There have been few studies that have systematically explored the benefits of combining such thermal and tactile feedback in a single display. In particular, it is unclear whether one signal masks the perception of another, facilitates its identification, or even if tactile and thermal cues can be perceived as independent sources of information when presented concurrently. With respect to the latter, signals from thermoreceptors in the skin are relayed to the cerebral cortex in pathways that are separate from those that originate in cutaneous mechanoreceptors, so they may well be perceived independently [5]. But it is also clear that interactions between thermal and tactile signals occur at a relatively early

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stage of the somatosensory projection pathways. When noxious thermal stimulation is applied within the same dermatome as vibrotactile stimulation, thresholds for detecting vibration increase regardless of frequency [6].

It has been known for many years that the temperature of an object in contact with the skin can have a profound effect on its perceived weight. Weber was one of the first to describe this 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 [7]. The change in perceived weight when an object is cooled is substantial, with estimates being up to 250% greater than those made under ambient temperature conditions. Warming an object also makes it feel heavier than an object at skin temperature, but the effect is smaller and less consistent across people [8] [9]. The overestimation of the weight of a cold object in contact with the skin is thought to result from changes in the responses of cutaneous mechanoreceptors, not from thermoreceptor activity [10].

The effect of temperature on haptic perception has been studied by varying either the temperature of objects in contact with the skin or of the skin itself. With respect to the former, it has been shown that measures of tactile spatial acuity such as gap detection and two-point thresholds decrease (i.e. increased sensitivity) when the edges or tips of the device in contact with the skin are either cooled or warmed [11] [12]. This effect is referred to as *thermal sharpening* and is attributed to the highly localized thermal gradients that occur on contact that facilitate the detection of the spatially discrete tactile stimuli [12]. Cooling the skin results in impaired tactile perception, as reflected in the reduced sensitivity to changes in roughness at supra-threshold levels [13], and the decrease in sensitivity (i.e. increased thresholds) to changes in pressure [14] and vibration [15]. For vibrotactile stimulation, cooling affects thresholds between 150-250 Hz and has little effect on the perception of lower frequencies (30 Hz), suggesting that decreasing skin temperature primarily affects the sensitivity of Pacinian corpuscles [16].

The effects of warming the skin on vibrotactile thresholds are generally noted to be smaller and less predictable than those associated with cooling. Whereas Green [14] observed that warming the skin to 42 °C resulted in a slight increase in thresholds for frequencies higher than 80 Hz, Verrillo and Bolanowski [17] reported that there were no changes in vibrotactile thresholds between 15 Hz and 500 Hz when the skin temperature was increased from 30 °C to 40 °C. These findings on vibrotactile thresholds clearly indicate the importance of evaluating how both cold and warm stimuli affect perception, particularly at supra-threshold levels.

In the context of multisensory cutaneous displays in which both tactile and thermal signals are presented, it is essential to understand the perceptual interactions that can occur between the two modalities. The stimuli presented are typically at supra-threshold levels and so threshold level behavior, as reviewed above, is not necessarily pertinent to understanding how multisensory inputs are processed. The objective of the present experiment was to evaluate whether skin temperature affected the perception of vibrotactile patterns, if this was temperature specific and if it varied as a function of the particular properties of the vibration, namely the pulse duration and its intensity.

2 Experimental Design

In this experiment, a thermo-vibrotactile display was used to evaluate the effects of changes in temperature on the ability to identify vibration patterns. An absolute identification paradigm was used in which participants had to identify which of six vibration stimuli was presented on the thenar eminence at the base of the thumb. The vibration stimuli varied with respect to the number, duration, and intensity of pulses. Thermal stimulation was delivered at the same site concurrent with the vibration stimuli.

2.1. Participants

Ten normal, healthy, male individuals, ranging in age from 23 to 28 years old (mean: 26 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.

2.2. Apparatus

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

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 Peltier device for feedback control of its temperature. Two other thermistors measured the temperature at two locations on the skin. A baseline skin temperature measurement was recorded by thermistor 2 on the wrist. This baseline temperature was different for each participant and was unaffected by the thermal stimuli presented due to its location. The thermistor at location 3 measured the skin temperature 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 display.

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 as shown in Fig. 3. 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.

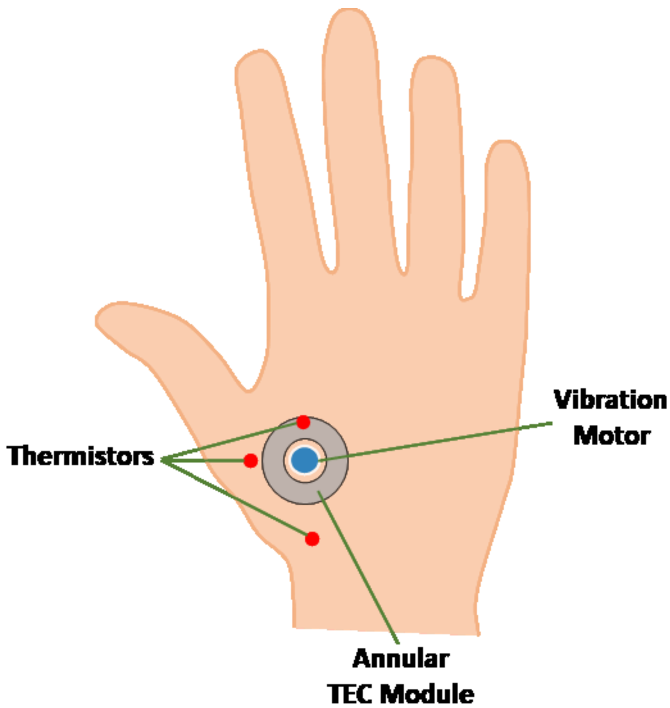

Fig. 1. Schematic illustration of the multisensory display incorporating a vibration motor mounted in the center of an annular thermoelectric cooler [TEC] (Peltier device). Three thermistors monitor the temperature of the Peltier device and the skin.

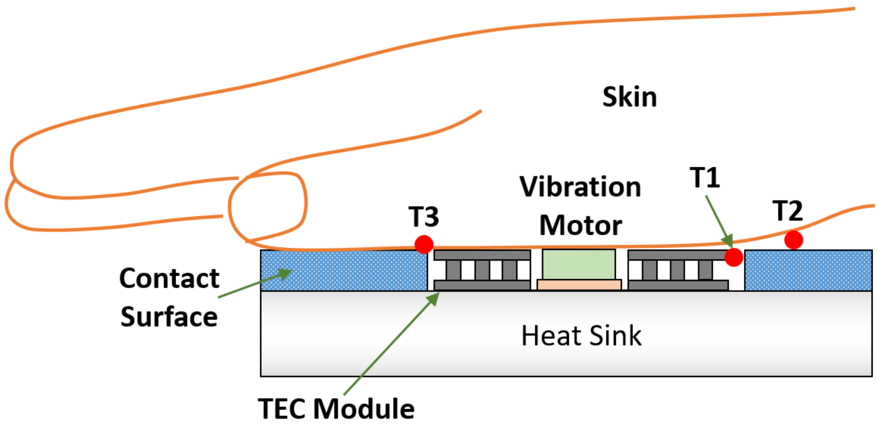

Fig. 2. Position of the hand with respect to the vibration motor (LRA) and Peltier module mounted on the heat sink during stimulus presentation. The locations of the three thermistors (T1, T2 and T3) are shown**.**

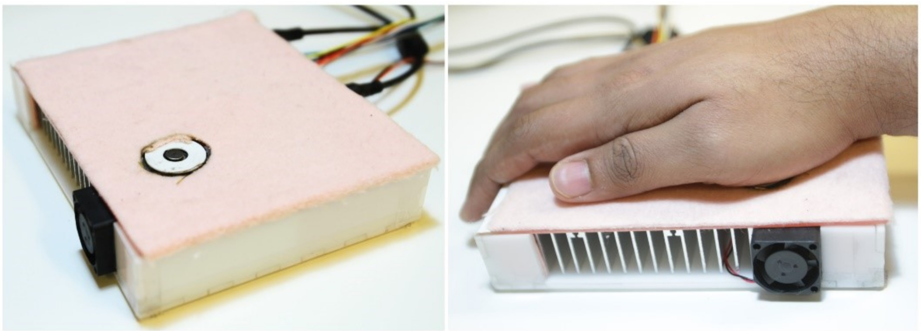

Fig. 3. Left: Display with the Peltier module mounted on a heat sink and fan. The vibration motor is in the center of the module. The thermistor on the Peltier is covered so that its response primarily reflects that of the Peltier device and not the hand. Right: The position of the hand during stimulus presentation.

2.3. Thermal and Vibrotactile Stimuli

The display could provide any combination of vibratory and thermal stimuli on the hand within the capabilities of the motor and Peltier device. The vibratory patterns were designed with a square wave profile using the dynamics of the vibration motor. The frequency was set at 100 Hz and the peak amplitude was 1.48 m/s^2 as measured with a low-mass accelerometer mounted on the motor. The square wave profile varied in intensity, number of pulses, and pulse duration. The vibration patterns were created so that one set of three patterns varied with respect to its temporal profile (pulse duration) and the other set of three patterns varied in intensity. These two dimensions are fundamental to vibrotactile perception [18].

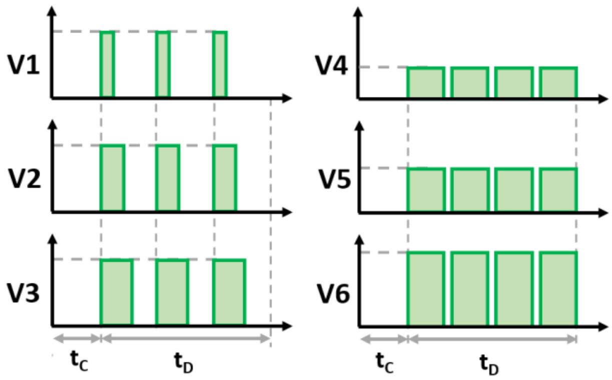

Fig. 4. Schematic illustration of the six vibration patterns with the calibration period (t_C) preceding each stimulus duration (t_D). V1-V3 varied with respect to pulse duration, V4-V6 varied in intensity.

In the first group with patterns V1, V2 and V3, there were three pulses of equal intensity but varying in pulse duration (see Fig. 4). The total duration of each pulse was 2 seconds, and the on duration was 0.5 s, 1.0 s and 1.5 s for V1, V2 and V3, respectively. Patterns V4, V5 and V6 in the second group had four pulses separated by an equal off time but varying in intensity. The maximum intensity of the vibration motor was kept at 80% of its maximum capacity. In total there were six distinct vibration patterns as illustrated in Fig. 4.

The selection of these particular vibration patterns was based on pilot experiments in which the perceptibility of the various patterns was evaluated. These pilot studies were used to observe the response to different parameters of the vibration pulses, and to determine the intensity levels, duration and number of pulses, and overall duration of the stimuli.

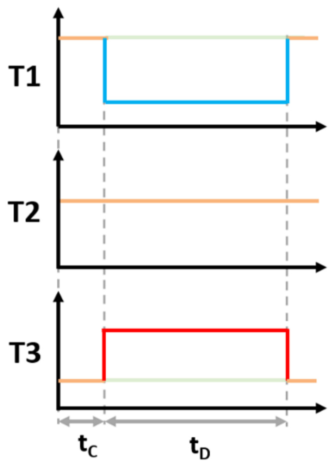

Fig. 5. Schematic illustration of the three thermal patterns which have the same overall duration (t_D) and calibration time (t_C) but varying temperature intensity. T1 is a cool stimulus presented on the thermal display, for T2 the display is maintained at the baseline skin temperature and T3 is a warm stimulus.

Three thermal stimuli (T1, T2, and T3) were created that were defined relative to the baseline skin temperature as illustrated in Fig. 5. T1 was a step decrease in temperature of the Peltier display by 7 °C, T2 maintained the surface of the display at the measured skin temperature, and for T3 the display temperature was increased by 5 °C. The smaller increase in temperature, that is +5 °C as compared to -7 °C, was chosen to avoid any discomfort associated with heating the skin to higher temperatures. The total duration (t_D) of each of these patterns was 7 s preceded by a calibration period (t_C) during which the display's surface temperature was maintained at the baseline skin temperature. The maximum rate of change of the temperature was limited by the dynamics of the thermal display system. As the dynamics of the Peltier device are slower than those of the vibration motor, a delay (Δ) was introduced at the onset of the vibratory stimulus relative to that of thermal stimulus. With three thermal stimuli and six vibration stimuli a total of eighteen patterns (V1-T1, V1-T2, V1-T3, V2-T1 … V6-T1, V6-T2, V6-T3) can be created. Each of these patterns was presented three times to give a total of 54 trials presented in a randomized order. Fig. 6 shows three representative patterns.

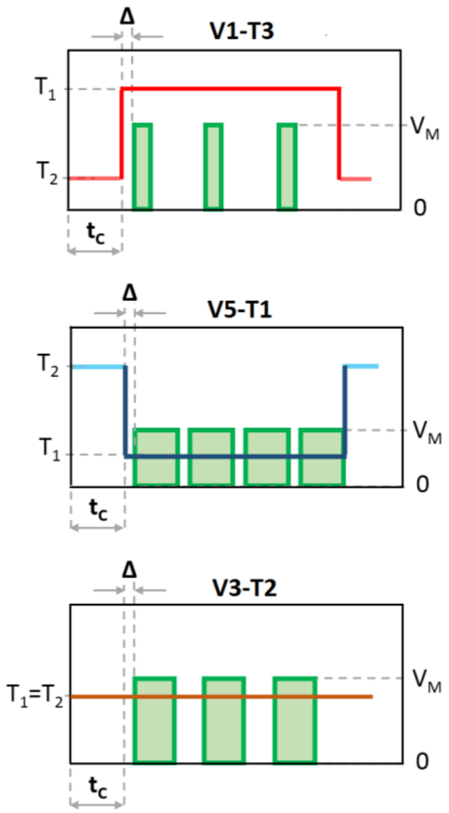

Fig. 6. Schematic representation of three patterns (V1-T3, V5-T1, and V3-T2) out of a total of 18 patterns. The temporal profile of the warm (red), cool (blue) and neutral skin (orange) temperatures are shown with the vibration pulses of magnitude (V_M) in green. T_1 and T_2 refer to the temperatures measured on the display and skin respectively.

2.4 Procedure

Prior to starting the experiment, the procedure was explained to participants. They were told that they would be required to identify which of six vibration stimuli was presented on the hand and that the temperature of their skin could also change during stimulus presentation. A GUI similar to Fig 4 was displayed on a computer screen in front of participants. They placed their wrist and the glabrous surface of the hand on the fixture housing the vibro-thermal display and brought their thenar eminence in contact with the thermoelectric module's surface (see Fig. 3). Using the computer mouse, participants selected each of the vibration patterns displayed on the screen which activated the motor in contact with the hand. They were then presented with the three thermal signals, first on their own and then in conjunction with a vibration signal. This was followed by a series of 10 practice trials in which the experimenter selected the stimulus and participants indicated the pattern that was presented. Feedback was provided after each response. The experiment commenced after the practice session.

The initial skin temperatures of the participants ranged from 28 °C to 32 °C with a mean of 30 °C. The ambient temperature was maintained at 25.5 °C, as measured with a thermocouple in free air. The thermoelectric module was maintained at the baseline skin temperature of each participant (as measured by thermistor 2) between trials and during the calibration period. Each trial lasted 12 s which included a calibration period of 5 s prior to stimulus presentation which lasted 7 s. Two different auditory cues were provided to signal the start and finish of each stimulus presentation. After the second auditory cue, participants indicated their response by selecting the checkbox beside the visual pattern depicting the stimulus (V1, V2 … V6) on the screen in front of them. 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.

3 Results

The percentage of correct responses for each stimulus averaged across all participants ranged from 60% to 100%, with an overall mean of 82% correct. The confusion matrix of the participants' responses is provided in Table 1. These data clearly indicate that grouping patterns in terms of variation in stimulus duration and intensity was perceptually highly salient in that errors only occurred within each group. The overall performance of participants is shown in Fig. 7. As evident in the figure, when the skin was maintained at the neutral baseline temperature, which may be considered the control condition, there was variability in the identification of different vibrotactile patterns with patterns V1 and V4 being the easiest to identify at 100% correct. Pattern V4 with four low amplitude pulses was identified most consistently across all skin temperature conditions.

			Responses			
Stimuli	**V1**	**V2**	**V3**	**V4**	**V5**	**V6**
V1	72	15	3	0	0	0
V2	6	64	20	0	0	0
V3	0	17	71	0	0	0
V4	0	0	0	87	2	1
V5	0	0	0	18	72	0
V6	0	0	0	0	21	69

Table 1. Confusion matrix of the participants' responses across all conditions

By having a range of performance levels in identifying these patterns under neural skin temperature conditions, it was possible to determine whether cooling or warming the skin enhanced or was detrimental to vibrotactile pattern identification. A uniformly high level of performance may obscure any faciliatory effects. The results can be considered in terms of (1) examining which pattern was the easiest to identify by collapsing the data across temperature, (2) evaluating whether the grouping of stimuli in terms of variations in pulse duration versus intensity affected identification, (3) looking at the overall effect of skin temperature on performance and (4) determining the nature of any interactions between vibration pattern identification and skin temperature.

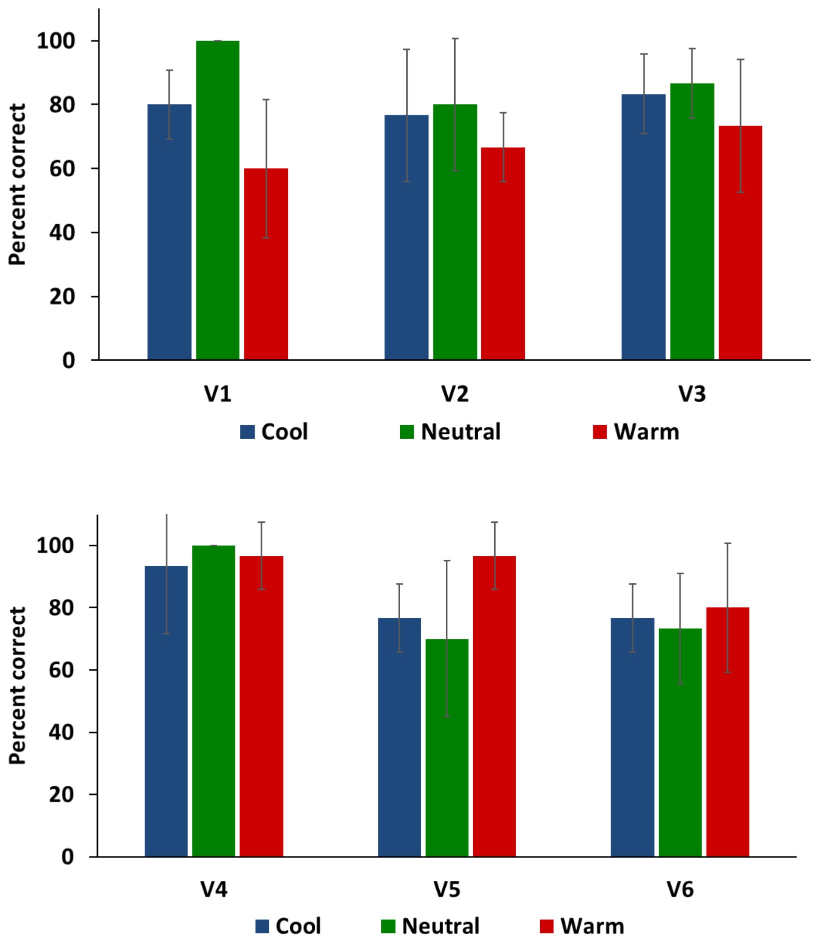

Fig. 7. Group mean percent of correct responses for vibration patterns varying in pulse duration (V1-V3) (upper) and intensity (V4-V6) (lower) as a function of temperature (cool [blue], neutral [green] and warm [red]). The standard deviations (SD) are shown.

When considered independently of changes in skin temperature, pattern V4 was the most consistently identified pattern at 97% correct, with the other patterns averaging between 74% and 81% correct. Pattern V4 had the lowest vibration intensity, with four distinct pulses. When the patterns are grouped based on variations in temporal features as compared to intensity, the overall response rate was 78% for the former and 85% for the latter. If the data are now collapsed across patterns and we look only at the effect of skin temperature on performance, at the neutral baseline temperature 85% of patterns were identified on average, whereas when the skin was cooled it was 81% and 79% correct when warmed. Finally, as Fig. 7 shows there appear to be interactions between vibrotactile pattern identification and skin temperature.

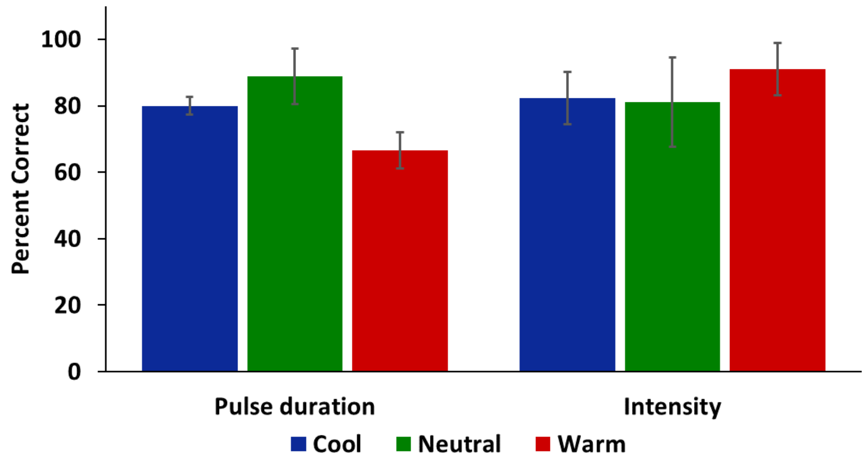

Fig. 8. Group mean percent of correct responses for vibration patterns varying in pulse duration and intensity as a function of skin temperature. The standard deviations are shown.

A repeated-measures ANOVA was conducted on these data with vibration and temperature as factors. In these analyses, vibration patterns based on temporal features and those varying in intensity were grouped. There was a significant main effect of vibration ($F(1,9)=9.26$, $p=0.01$), a significant interaction between vibration and temperature ($F(2,18)=11.69$, $p=0.002$), but no main effect of temperature. Post hoc analyses revealed that warming the skin had a significant effect on identifying vibration patterns that varied in intensity, as compared to pulse duration. The overall means for these two sets of stimuli when the skin is warmed are 62% correct for patterns that vary in pulse duration, as compared to 91% correct for patterns whose intensity is varying. These effects are depicted graphically in Fig. 8. Cooling the skin or maintaining it at the baseline temperature did not significantly influence the ability to identify either set of vibration patterns.

4 Discussion

The results from this experiment indicate that the temperature of the skin influences the ability to identify vibrotactile patterns that are well above threshold. This thermal-tactile interaction occurred when the skin was warmed and assisted in the identification of vibrotactile stimuli that varied in intensity. In contrast, warming the skin appeared to impede identification of patterns whose pulse duration varied. This intriguing finding suggests that the enhanced discharges from cutaneous thermoreceptors during warming facilitates the processing of amplitude-related properties of incoming signals from cutaneous mechanoreceptors [5]. Although most classes of mechanoreceptor would be active during stimulus presentation in the present experiment, the Pacinian corpuscles would be the dominant source of information at frequencies around 100 Hz [18]. Pacinian corpuscles are sensitive to changes in skin-surface temperature, particularly cooling of the skin, but do not appear to be affected by warming the skin up to 40 °C. This is based on the absence of any effect of such temperature increases on vibrotactile thresholds between 0.5 Hz and 500 Hz [19]. It therefore seems likely that the response to warming in the present experiment is in part mediated by warm thermoreceptors.

This experiment demonstrated that concurrent thermal stimulation can affect the perception of vibrotactile patterns. In a related study, Singhal and Jones [20] demonstrated that concurrent vibration can influence the perception of thermal patterns. Warm stimuli were identified more consistently when vibrotactile cues were delivered as compared to cool stimuli, although for both types of thermal patterns there was a slight decrease in performance, as compared to the condition in which there was no concurrent tactile stimulation. These findings [20] also attest to the importance of considering how different sensory signals interact, even when users are focusing on a single source of information. It is not known whether prolonged cooling or warming of the skin would influence vibrotactile pattern identification, since the skin may habituate under these conditions. It is also important to replicate the present findings with a larger number of participants.

In the context of multi-sensory cutaneous displays, the present results suggest there may be optimal combinations of sensory cues that facilitate the identification and discrimination of tactile inputs. The specificity of the present results in terms of a difference between the encoding and subsequent identification of the amplitude and temporal features of a vibrotactile signal indicates that such combinations of sensory cues need to be selected judiciously. Performance can be enhanced or impaired by the addition of an ancillary sensory cue.

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