Space-time Dependencies and Thermal Perception

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Abstract. This experiment was focused on determining whether the spatial representation of thermal stimuli is influenced by the temporal parameters of stimulation as has been demonstrated for tactile stimuli. Four warm thermal pulses within the innocuous range of temperatures were presented on the forearm in varying spatial and temporal sequences. Participants indicated the perceived location of the first two pulses in the four-pulse sequence after each trial. The results indicate that the perceived position of the second pulse changed substantially in the direction of the third pulse when the interval between the pulses was brief (0.2 s). At longer intervals there was no change in perceived location. These results indicate that despite the limitations in the spatial and temporal processing of thermal stimuli, somatotopic information appears to be integrated similarly for tactile and thermal stimuli.

1 Introduction

Perceptual illusions have often been studied to reveal the mechanisms involved in perceiving the external environment and to understand the conditions under which discrepancies emerge between a physical stimulus and its corresponding percept. Much of the research on perceptual illusions has focused on vision, although tactile and haptic illusions have been of interest to those involved in the design of haptic displays [1] [2]. For these devices it has been shown that by selecting particular spatial and temporal sequences of motor activation it is possible to create a display with a higher perceived spatial resolution than is implied by the number of actuators actually present [3] [4]. Haptic illusions have also been used to evaluate the degree of realism in virtual environments by measuring the strength of an illusion in the real and simulated environment [5].

A number of tactile illusions involve distortions in the spatial representation of tactile stimuli applied to the skin, such as the perceived location of the stimulus or the perceived distance between points of stimulation. Such illusions typically result from interactions between the temporal and spatial properties of the stimuli and show how the spatial representation of stimuli on the skin critically depends on the temporal properties of stimulation. One of the classic demonstrations of these effects involves presenting three equally spaced tactile stimuli successively on the skin of the forearm and asking subjects to judge whether the distance between the first and second stimulus is

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equal to, or shorter or longer than the distance between the second and third stimulus. Subjects overwhelmingly judge the distance to be shorter when the temporal interval between the first and second stimulus is brief (250 ms) and longer with greater temporal intervals (500 ms). This illusion which demonstrates the dependence of space on time in estimations of tactile space is known as the tau effect and has also been shown to occur in vision and audition [6]. It is often not observed at very short time intervals, but it can occur tactually when there are long delays (1500 ms) between the two pairs of comparison stimuli. It has been suggested that the ratio between the two temporal intervals should not be greater than 3 to 4 to 1 for the illusion to occur [7].

In contrast to the considerable research on tactile spatial illusions, there have been relatively few reports of spatio-temporal illusions involving the thermal sensory system. A serendipitous observation was reported by Rózsa and Kenshalo [8] during their experiments on spatial summation of cooling pulses delivered to each forearm. They noted that when there was a delay of about 250 ms between the onsets of the temperature change in the two arms, subjects reported that a cool sensation appeared to move from one forearm to the other. This apparent movement persisted until the onset interval between the two stimuli was less than 100 ms. In an earlier study by Békésy [9] on heat sensations on the skin he noted that when two stimuli with no time delay between them were applied to two fingers spaced apart, a sensation of heat could occur outside the skin as if it was "floating in the air" between the fingers. He also observed that the sensation of heat arising from two stimuli spaced 140 mm apart could move from one stimulus to the other as a function of the delay between the stimuli. These studies suggest that the spatio-temporal interactions reported for other sensory modalities also apply to thermal sensory processing. However, the boundary conditions that define when these illusions occur thermally have not been specified. In contrast to the sense of touch, the ability to localize precisely thermal stimulation is limited and as compared to other sensory systems the thermal senses are relatively sluggish [10].

In a recent study Singhal and Jones [11] demonstrated that when four cooling pulses were presented on the forearm in varying spatial and temporal sequences, the perceived position of the second pulse changed as a function of temporal interval and distance between the pulses. When the onset interval between the second and third pulse was brief (0.2 s) and the distance between them greater, the perceived position of the second pulse moved by up to 43-59 mm in the direction of the third pulse which was delivered 150 mm from the second pulse. At longer intervals and shorter distances there was no change in its perceived location.

The present experiment was designed to evaluate whether the perceived location of a warm stimulus also changes as a function of the temporal parameters of stimulation. It was hypothesized that spatio-temporal interactions for warm stimuli may be less robust and more variable than those found for cold because of the decreased sensitivity of all body regions for warmth as compared to cold [12] [13]. In addition, the time to detect warm sensations is longer than that for cold which is presumably a consequence of the slower conduction velocity of warm afferent fibers (1-2 m/s) as compared to cold fibers (10-20 m/s) [14] [15].

2 Experimental Design

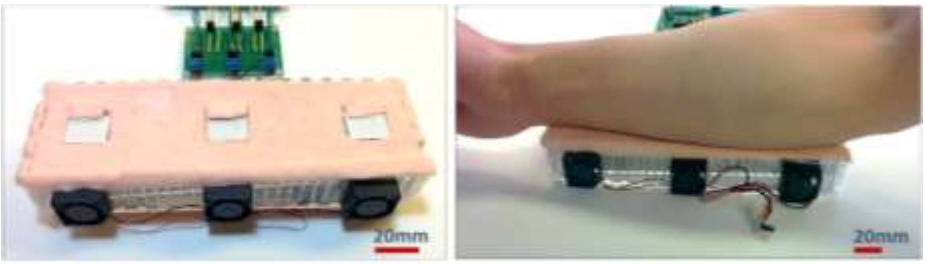
Thermal stimuli in the form of short pulses were delivered to the forearm using a thermal display. These stimuli varied with respect to the location at which they were presented on the arm and the delays between pulses.

2.1 Participants

Ten normal healthy males ranging in age from 24 to 36 years old (mean: 28 years) participated in the experiments. They had no known abnormalities of the skin or peripheral sensory or vascular systems. None of the participants had any significant experience in thermal perception studies. 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 thermal display based on Peltier devices provided the thermal inputs to the skin. The display consisted of three thermoelectric modules (Model TE-83-1.0-1.5, TE Technology, Inc.) 22 mm x 19 mm x 3.8 mm, with a center-to-center distance between the modules of 75 mm. The contact area on the skin for each module was 418 mm^2. Laser-cut acrylic sheets enclosed the display and on the top surface the acrylic sheet was flush with the Peltier devices so that the locations of the Peltier modules were tactually imperceptible. Fans were mounted in the display to provide convection cooling. Fig. 1 shows the assembled thermal display with the Peltier modules, heat sink and fans.

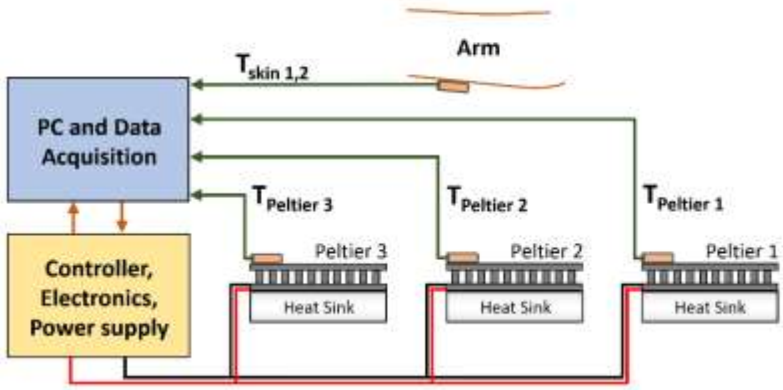


(a) (b)

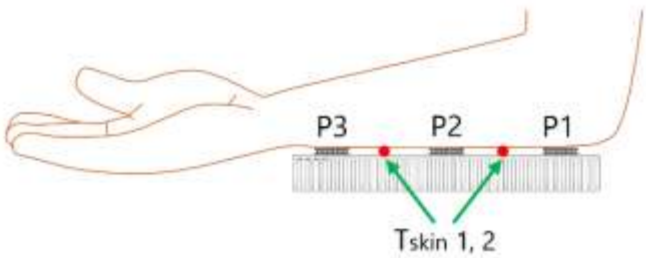
Fig. 1. (a) Thermal display assembly with three Peltier modules, heat sink and fans. (b) The position of the forearm on the thermal display.

Five thermistors (Model 56A1002-C8, Alpha Technics; 457 μm in diameter and 3.18 mm in length) recorded the temperature of the Peltier modules and the skin during the experiment. The display temperature was controlled using a feedback loop with temperature input from the thermistors placed on each Peltier surface. Two other thermistors measured the temperature of the skin in regions not in contact with the Peltier devices. Fig. 2 provides a schematic illustration of the position of the Peltier devices and thermistors on the arm.

National Instruments modules (Model NI cDAQ-9174, NI 9263, NI 9474, NI9205) were used for data acquisition and independent feedback control of each of the Peltier devices. A graphical user interface (GUI) based on LabVIEW (National Instruments) was used to control the temperature of the Peltier modules and continuously record the skin temperature at 1 kHz. At the start of each trial skin temperature was used as the calibration temperature and the display was set to this temperature. This meant that the same relative stimulus was delivered to all participants. When each trial was completed the temperature of the display returned to the calibration temperature. Participants recorded their responses using a GUI running on a separate computer.



(a)



(b)

Fig. 2. (a) Schematic illustration of the thermal display with the Peltier modules mounted on heat sink. Thermistors measured the temperature of the modules and skin on the forearm. (b) The numbering of the Peltier modules in contact with the forearm, and the position of thermistors measuring skin temperature.

2.3 Thermal Patterns

The thermal stimuli were composed of four short temperature pulses (A, B, C and D), all of which had the same amplitude (ΔT) of 6 °C and pulse duration (t_P) of 2 s. There was a fixed interval of 4 s which is twice the pulse duration ($2t_p$), between the onset of Pulse A and B, and between Pulse C and D. A schematic illustration of the different parameters of the patterns is shown in Fig. 3. Prior to the start of Pulse A, the temperature of all three Peltier modules (P1, P2 and P3 as numbered from the elbow) was set at the mean skin temperature (T_{skin}) for 5 s (t_C) as measured simultaneously at two locations on the arm not in contact with the Peltier modules. The first location was midway between Peltier 1 and 2 (P1 and P2), and the second was between P2 and P3.

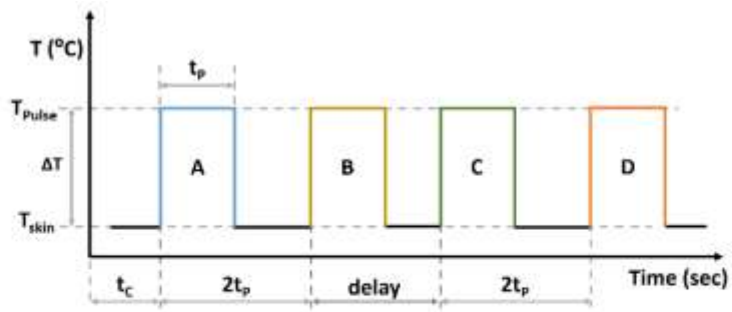


Fig. 3. Different parameters of the four temperature pulses used to create the patterns.

Eight different thermal patterns were created by varying the delay between pulse B and C, the direction of activation of the Peltier devices and the specific Peltier modules warmed as shown in Table 1. In the first sequence (AB-C-D), all the Peltier modules (P1, P2, P3) were activated with at least one pulse whereas in the second sequence (AB-CD) the second Peltier (P2) was maintained at the mean skin temperature and two pulses were delivered to P1 (or P3) and then to P3 (or P1). With a delay of 4 s between Pulse B and C, the pulses were evenly distributed in time. A shorter onset delay of 0.2 s was chosen to determine whether the perceived position of the second pulse changed as a function of the delay between the pulses. Depending on the direction of activation, Pulses A, B, and D were always presented at either the first (P1) or third Peltier (P3) module. Similarly, the direction of activation also determined the location of Pulse C. Each pattern was presented 5 times, giving a total of 40 trials for each participant. The order of presentation of the trials was randomized.

Pattern	Sequence	Delay	Direction	P1	P2	P3
1	AB-C-D	4	P1 P2 P3	AB	C	D
2	AB-C-D	0.2	P1 P2 P3	AB	C	D
3	AB-C-D	4	P3 P2 P1	D	C	AB
4	AB-C-D	0.2	P3 P2 P1	D	C	AB
5	AB-CD	4	P1 - P3	AB	-	CD
6	AB-CD	0.2	P1 - P3	AB	-	CD
7	AB-CD	4	P3 - P1	CD	-	AB
8	AB-CD	0.2	P3 - P1	CD	-	AB

Table 1. Thermal patterns created based on varying the Peltier modules (P) activated, the direction of activation and the delay (in s) between Pulse B and C.

2.4 Procedure

The procedure was initially explained to participants and they were familiarized with the temperature pulses that would be delivered. They were told that four warm pulses each with the same duration and intensity would be presented. The pulses could be presented on any of the Peltier devices in the display and start from any position. At the end of each trial they had to indicate the positions of the first two pulses, A and B.

The initial skin temperatures of the participants ranged from 30 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. At the start of the experiment participants placed their right forearm on the contact surface of the display using markers on the display that indicated the correct placement. One of the eight patterns was then presented (see Table 1) and at the end of each trial an auditory cue signaled that participants should indicate the locations of the first two temperature pulses. A visual depiction of the forearm and the thermal display surface was presented in a GUI on a computer screen in front of the participants (see Fig. 4). They moved a cursor to indicate the locations of each pulse. Responses had to be made within 10 s and on most trials participants indicated the location within a couple of seconds. After every two trials, participants switched the forearm that was on the display in order to avoid any adaptation effects. A rest break was provided when requested.

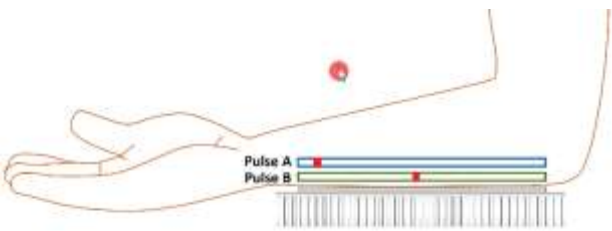


Fig. 4. Screen shot of the GUI presented on the computer screen in front of participants used to record their responses.

3 Results

Temperatures were measured during each trial on the Peltier modules and at two locations on the skin not in contact with the Peltier modules. The temperatures measured during presentation of Patterns 1 and 2 are illustrated in Fig. 5. The skin temperature at the two locations not in contact with the Peltier modules remained constant, indicating that the temperature change was localized to the contact region.

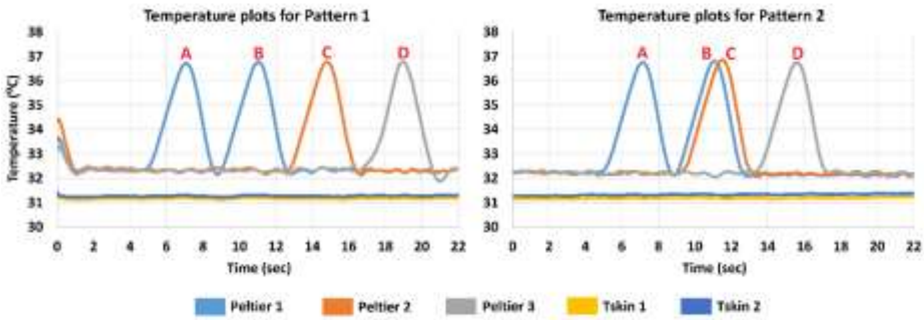


Fig. 5. Group mean temperature recordings throughout two trials from the three Peltier devices and from the skin on the forearm not in contact with the Peltier devices.

The participants indicated the perceived locations of Pulses A and B using the GUI shown in Fig. 4; these data were then digitized using the Image Processing Toolbox in MATLAB (Mathworks, Inc.). The position of each pulse was measured from the wrist. A format devised by Goldreich [16] to conceptualize tactile length illusions has been used to illustrate the perceived location of pulses A and B. The schematic illustration shown in Fig. 6 depicts graphically the temporal and spatial properties of the physical stimuli and the perceived position of pulses A and B on the forearm for each of the eight patterns. Each adjacent pair of patterns (1 and 5, 2 and 6 etc) differs only with respect to where the third stimulus (pulse C) in the sequence was delivered. This representation illustrates quite vividly how the position of pulse B was perceived to move in the direction of pulse C when the delay between the onset of pulses B and C was 0.2 s. When the delay between pulses B and C was longer (4 s) as in patterns 1, 3, 5 and 7, participants perceived the first and second pulses as being close together. Figure 6 also illustrates that at the longer delay participants were more accurate at localizing pulses A and B when they were presented near the elbow as compared to the wrist (1 and 5 as compared to 3 and 7). The elbow may have served as an anatomical landmark to facilitate localization, which has been reported for vibrotactile stimuli [17].

Fig. 7 shows the perceived location of pulses A and B for the eight patterns, averaged across the 10 participants. When the sequence began at the elbow and moved distally the mean perceived location of the first pulse varied across patterns by 15 mm. For sequences that started at the wrist the position varied by 19.8 mm. Pulse B was always delivered at the same location as pulse A, but as is evident in Fig. 7, its perceived position changed substantially when there was a short delay between it and pulse C. On average the position of pulse B changed by 40 mm when the delay was 0.2 s and by only 7.5 mm when the delay was 4 s. The spatial sequence of stimulation (AB-C-D or AB-CD) did not have a marked effect on the perceived position of pulse B.

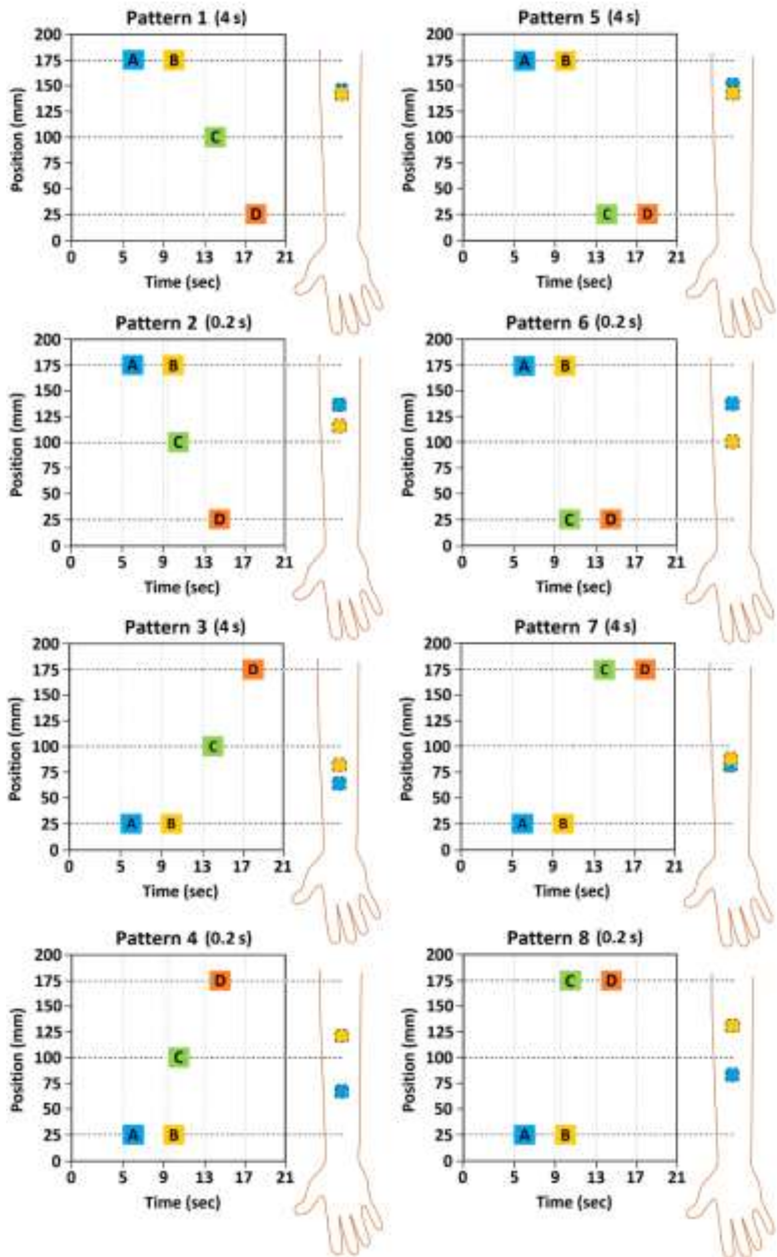


Fig. 6. Schematic illustration of the physical stimuli depicted graphically and the group mean perceived position of those stimuli on the forearm. The horizontal dashed lines indicate the positions of the Peltier modules.

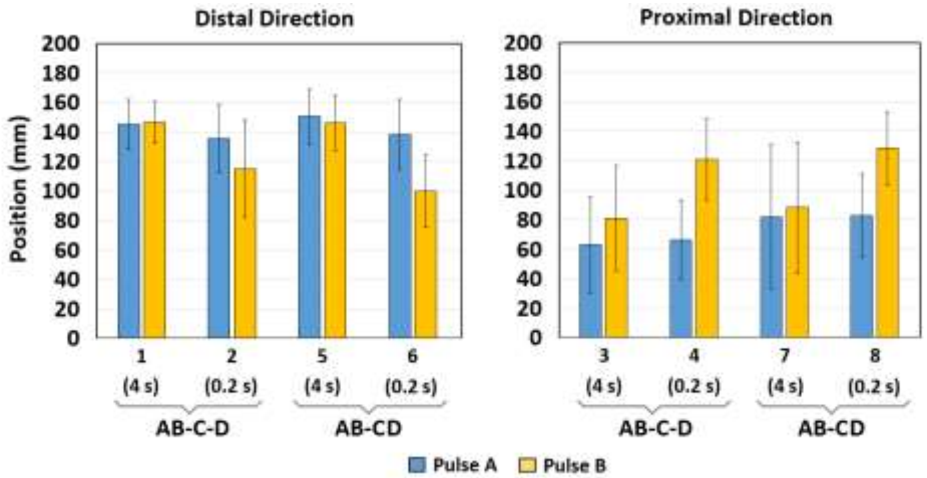


Fig. 7. The group mean perceived position of pulse A and B for each pattern when the direction of the thermal display's activation was either distal (from the elbow) or proximal (from the wrist). Standard deviations are shown.

The effect of the various parameters used to create the warm stimuli on perceived position was evaluated by analyzing the absolute difference in perceived location for pulses A and B. A three-way repeated-measures analysis of variance (ANOVA) was performed on these data with spatial sequence (AB-C-D and AB-CD), delay (0.2 and 4 s) and direction (proximal or distal) as factors. The results indicated a main effect of delay ($F(1,9)=21.56$, $p=0.001$) and of direction ($F(1,9)=8.19$, $p=0.019$), but no effect of sequence. None of the interactions was significant. These findings reveal that the perceived distance between pulses A and B was significantly greater for stimuli with the shorter delay of 0.2 s and was greater for sequences that began at the wrist as compared to the elbow.

The results from the present experiment were compared to those from an earlier study using the same stimulus parameters except that cooling rather than warming stimuli were delivered to the skin [11]. A comparison of the results from these two experiments which involved different participants is presented in Fig. 8. The absolute difference in the perceived locations of pulses A and B for cold and warm stimuli is shown as a function of delay and direction. It is evident that the perceived location of both cold and warm thermal stimuli can change as a function of the temporal parameters of stimulation. Fig 8 also illustrates that for both parameters cold stimuli resulted in a larger change in the perceived position of pulse B than warm stimuli. For cold and warm stimuli, sequences that started near the elbow and sequences with a shorter delay between pulses B and C resulted in a greater change in the perceived position of pulse B. The difference as a function of direction of stimulation was 34 mm for cold stimuli and 15 mm for warm stimuli. However, the change in perceived position with delay was more pronounced for warm stimuli, with a difference of 32 mm as compared to 24 mm for cold stimuli.

A repeated-measures analysis of variance (ANOVA) was performed on the combined dataset from both experiments, with thermal stimuli as a between-subjects factor and sequence, delay and direction as within-subjects factors. The results indicated a main effect of thermal stimuli ($F(1,18)=141.80$, $p<0.001$), of sequence ($F(1,18)=10.99$, $p=0.004$), of delay ($F(1,18)=34.57$, $p<0.001$), and of direction ($F(1,18)=18.48$, $p<0.001$). The interactions between sequence and thermal stimuli ($F(1,18)=6.07$, $p=0.02$) and between sequence, delay and thermal stimuli ($F(1,18)=10.27$, $p=0.005$) were also significant. The interaction between sequence and thermal stimuli reflects the effect of the spatial sequence (AB-C-D and AB-CD) on the perceived location of pulse B for the cold stimuli which did not occur with warm stimuli. The three-way interaction is consistent with the greater change in perceived location for cold stimuli at shorter delays in the AB-CD sequence.

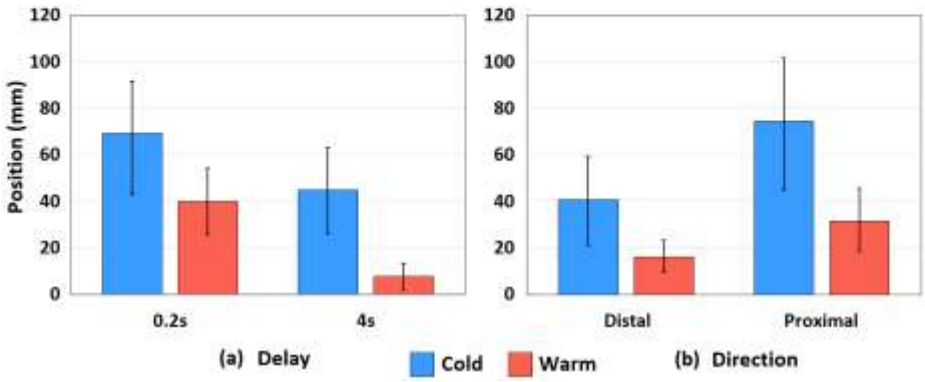


Fig. 8. Group mean absolute difference (with standard deviations) in the perceived location of the first and second pulse for cold and warm stimuli at (a) a delay of 0.2 or 4 s and (b) when the direction of the thermal display's activation was from the elbow (distal) or the wrist (proximal).

4 Discussion

The results from this experiment indicate that the spatio-temporal illusions that have been reported for tactile stimuli also occur for warm stimuli within the innocuous range of temperatures. In this experiment the second pulse was always delivered at the same location as the first pulse, but its perceived position changed as a function of the delay between it and the third pulse. When the delay was short (0.2 s) its position was perceived to move by 40 mm on average towards the location of the third pulse. This occurred independently of whether the third pulse was close to (75 mm, Patterns 2 and 4) or further away (150 mm, patterns 6 and 8) from the second pulse. At longer delays (4 s) the position of the second pulse was perceived accurately, that is, at the same location as the first pulse. These findings provide strong evidence that for the thermal modality, similar to touch, the temporal interval between warm stimuli delivered to the skin can influence their perceived location. The optimal interval for such effects to occur is probably around 200 ms, although this needs to be further studied. For tactile stimuli, intervals between 200 and 250 ms are optimal [18].

A comparison of the results from the present experiment with those from an earlier experiment with cold stimuli [11] reveals some interesting differences between the thermal senses. First, the magnitude of the change in perceived position was greater for cold than warm stimuli (see Fig. 8); second, at short delays the change in the perceived position of a cold, but not warm, stimulus was affected by the distance between the stimuli (i.e. pulses B and C). Consistent with previous studies that have shown that there is better localization for cooling than for warming stimuli on the forearm [19], in the present research there was more accurate localization when the first stimulus was cold. In summary, these results indicate that despite the limitations in the spatial and temporal processing of thermal stimuli, somatotopic information appears to be integrated similarly for tactile and thermal stimuli.

These interactions between the temporal and spatial properties of thermal stimuli offer an opportunity to enhance the representation of information in thermal displays. They show that in addition to the quality (warm or cold), amplitude and rate of change of thermal stimuli it is possible to vary the perceived location of stimulation by changing the inter-stimulus interval. In the context of social touch such thermal cues may provide information related proximity or separation.

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