Space-time Interactions and the Perceived Location of Cold Stimuli*

Anshul Singhal and Lynette A. Jones

Abstract—**The objective of this experiment was to determine whether illusions of space and time that have been demonstrated for mechanical stimulation on the skin also occur for thermal stimuli within the innocuous range of temperatures. Four cooling pulses 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 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) and the distance between the second and third pulse was larger. At longer intervals and shorter distances there was no change in perceived location. These findings demonstrate that the tau effect does occur with thermal stimuli, and that the temporal interval between thermal stimuli applied to the skin can influence their perceived location.**

KEYWORDS: sensory saltation, tau effect, thermal display, touch,

INDEX TERMS: H1.2 [Model and Principles]: User/Machine System; H5.2 [Information Interfaces and Presentation]: User Interfaces – Theory and methods; User-centered design

I. INTRODUCTION

Studies of perceptual illusions have provided insight into the cognitive mechanisms people use to perceive the world and internally represent the stimuli they experience. For the haptic modality, these illusions have been used to enhance the display of information by compensating for missing components of a perceptual experience and as a metric for evaluating the degree of realism in virtual environments [1-3]. A number of haptic and tactile illusions have been described and these can be classified in terms of those that relate to objects and their properties, such as the size-weight and thermal grill illusions, and others that pertain to the haptic perception of space, both with respect to the body and the external environment [4].

One of the best known cutaneous spatial illusions is sensory saltation, which refers to the illusory feeling that a mechanical stimulus delivered sequentially at a number of discrete locations is moving progressively across the skin. This illusion was first described by Geldard and Sherrick [5] who delivered a series of short pulses at three different loci on the skin and noted that participants perceived the stimulus moving across the skin "as if a tiny rabbit was hopping" in a smooth progression from the first mechanical stimulator to the third (p. 178). They demonstrated that the optimal number of mechanical stimuli for the illusion is between three and six, but it will occur with as few as two and as many as sixteen stimuli. Under the latter condition, the illusion is considerably reduced in strength. In addition to the number of mechanical pulses delivered to the skin the time between stimuli influences the strength of the illusion, with intervals between 20 and 250 ms being optimal. With shorter intervals the stimuli are perceived as being closer together spatially, until at 20 ms there is no perceptible spatial separation at all [6]. At intervals around 300 ms and higher, the mechanical stimuli are accurately localized [7].

For tactile stimuli, it is possible to create cutaneous illusory movement in two or more directions by optimizing the temporal and spatial activation of the mechanical stimuli. The original demonstration of sensory saltation involved three stimulators spaced along the forearm, but many subsequent experiments involved what is referred to as a 'reduced rabbit' paradigm in which three stimuli were presented at two sites [7-9]. In these studies subjects were asked to report whether a tactile stimulus was felt at the mid-point between the two sites of stimulation. Subjects' performance under this condition was then compared to their performance when a stimulus was actually delivered at the mid-point, which provides an index of the strength of the saltatory illusion [10]. Across different studies the illusion has been reported to be robust, that is it occurs on 80-90% of trials, and under optimal conditions subjects are unable to distinguish between real and illusory stimuli [10].

The area over which the tactile stimuli are delivered also determines whether sensory saltation occurs. On the glabrous surface of the index finger the area is small, around 2.28 cm^2, whereas on the forearm it is 145.7 cm^2. The size of the saltatory area therefore appears to be negatively correlated with the density of sensory innervation, which is in turn directly related to the size of the cortical receptive field [11]. A number of experiments have been conducted to evaluate how the anatomical organization of the somatosensory system constrains sensory saltation. The illusion does not occur across the body's midline unless mechanical stimuli are actually delivered to the midline [7], but the mechanical stimulus can appear to "hop out of the body" onto an external object such as a stick laid across the tips of the index fingers [12].

In contrast to the wealth of information regarding tactile spatial and temporal illusions, there has been substantially less research on illusions involving the thermal sensory system. One of the few illusions that has been studied is the thermal grill illusion which refers to the burning pain sensation that can result from touching interlaced warm (36-42 ºC) and cool (18-24 ºC) stimuli [13-15]. When touched

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individually such stimuli are perceived to be innocuous. If participants are asked to match the thermal sensation associated with making contact with the interlaced warm and cool stimuli to that of a uniform thermal surface, the matching temperatures are around 46 ºC [15]. It has been proposed that the burning sensation results from the activation of polymodal C-nociceptors that are normally inhibited by activity in afferent fibers from cold thermoreceptors.

Reports of spatio-temporal illusions involving the thermal system are sparse. A number of factors may contribute to this, in particular the pervasive nature of spatial summation which limits the capacity of individuals to localize precisely the site of thermal stimulation [16]. In one of the few studies of these illusions, Békésy reported that when there was a delay of 140 ms between two warm stimuli delivered to the skin the sensation of heat was completely localized to the first stimulus presented. Moreover the perceived intensity of this stimulus was larger than that of a single stimulus delivered at the same site, a phenomenon that he referred to as "funneling" [17]. In another study on thermal spatial summation there is an anecdotal report of apparent movement of a cool sensation from one forearm to the other when the interval between the onset of the two thermal stimuli was about 250 ms [18], which is similar to "phi" phenomenon reported for vibration [19]. Thermal stimuli within the nociceptive range have been used in conjunction with mechanical inputs in tactile sensory saltation studies to determine if such stimuli can be used to "tag" mechanical pulses. Geldard [7] reported that a cold stimulus was more effective than a hot stimulus in producing sensory saltation. One illusion that involves an error in perceiving varying intensities of thermal stimuli displayed across the skin is known as thermal referral. In this illusion, first described by Green [20], thermal sensations arising from a finger change as a function of the sensations experienced at the two adjacent fingers. When the index and ring fingers are placed on thermal stimulators that either heat or cool the fingers and the middle finger is placed on a thermally neutral stimulator, all three fingers feel warm or cool. On the basis of their experiments on the perceived intensity of the thermal stimuli resulting from thermal referral, Ho et al. [21] proposed that this illusion is mediated by two separate processes, one of which determines the perceived intensity from the physical intensity and the area of thermal stimulation, and the other determines the localization of these sensations based on tactile stimulation.

Thermal sensory saltation has been described in the context of stimuli that are within the range of temperatures that elicit painful sensations. Trojan et al. [22] used a CO_2 laser to deliver three 20 ms infrared laser pulses to the forearm at 15.3 and 25.4 ºC above skin temperature. The first two stimuli were delivered at one location with an inter-stimulus interval of 1000 ms and the third stimulus was presented 105 mm from the first two stimuli after a variable delay ranging from 60-516 ms. With this setup the stimuli are invisible and there is no mechanical stimulation of the skin. The perceived position of the second stimulus was displaced in the direction of the third stimulus by an average of 51 mm, and this mislocalization increased slightly with decreasing delays. The stimuli in this experiment were perceived as being unpleasant and/or painful indicating that both warm and nociceptive fibers would have been activated. These results are consistent with the tau effect rather than saltation, as the illusion is one of a change in perceived position rather than an illusory movement.

The objective of the present experiment was to determine whether the perceived location of a thermal stimulus changes as a function of the temporal parameters of stimulation. Cold stimuli were selected to investigate this phenomenon because all body regions have been shown to be more sensitive to cold than warm stimulation [23-25], and the reaction time for detecting cold sensations is significantly shorter than that for warmth [26]. The forearm was chosen as the site of study as it provides an extensive surface area. Its thermal sensitivity is superior to the fingertips but inferior to the face, the most thermally sensitive region of the body [23].

II. Experimental Design

A thermal display based on thermoelectric modules (Peltier devices) was designed and built to present thermal stimuli on the forearm. The thermal stimuli varied with respect to the location at which they were presented and the delay between pulses.

A. Participants

Ten normal healthy individuals, 9 males and 1 female, ranging in age from 24 to 29 years old (mean: 27 years) participated in the experiments. They were all right-handed and had no known abnormalities of the skin or peripheral sensory or vascular systems. None of the participants had any significant experience in tactile or 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.

B. Apparatus

A thermal display was built to provide short thermal pulses to the skin. The display consisted of three thermoelectric modules (Model TE-83-1.0-1.5, TE Technology, Inc.) mounted on a heat sink. The thermoelectric modules were Peltier devices 22 mm long and 19 mm wide, with a thickness of 3.8 mm, giving a contact area with the skin of 418 mm^2. The center-to-center distance between the Peltier modules was 75 mm and the length of the display was 200 mm.

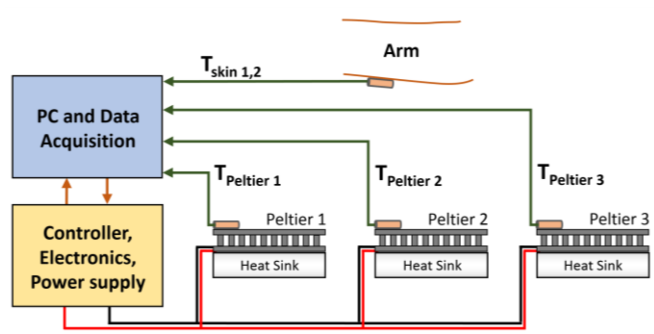

Figure 1. Schematic illustration of the thermal display with three Peltier modules mounted on heat sink, and thermistors measuring the temperature of the modules and of the skin on the forearm

Five 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. A thermistor was placed on each of the Peltier modules to feedback the temperature to the controller. Two other thermistors measured the temperature at two locations on the skin not in contact with the Peltier devices. Data acquisition and independent feedback control of each of the Peltier devices was done using National Instruments data acquisition modules (Model NI cDAQ-9174, NI 9263, NI 9474, NI9205).

A schematic of the thermal display with thermistors and the control setup is shown in Fig. 1. A fixture was fabricated using laser-cut acrylic sheets to hold the Peltier modules and heat sink. Multiple fans were mounted in the fixture to provide forced convection cooling. The surface of the Peltier modules was flush with the acrylic surface so that the locations of the Peltier devices was not perceptible based on tactile cues.

A LabVIEW-based (National Instruments) graphical user interface (GUI) was used to send commands to the controller for independent control of each Peltier module, and to record the skin temperature continuously at 1 kHz. The input to the controller when the thermal stimulus was presented was the temperature of the display rather than skin temperature so that the same relative stimulus was delivered to all participants. Skin temperature was used as the calibration temperature at the start of each trial. A second computer was used to run a GUI on which the participants' responses were recorded.

C. *Thermal Patterns*

Each thermal pattern comprised four short temperature pulses in a fixed sequence of A, B, C and D. The amplitude (ΔT) and duration (t_P) of each pulse were constant across patterns. The temperature decrease was 8 °C, and the pulse duration was 2 seconds. Fig. 2 provides a schematic illustration of the different parameters of the patterns. 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 average skin temperature as measured concurrently at two locations on the forearm for 5 seconds (t_C). The first location was midway between Peltier 1 and 2 (P1 and P2), and second between P2 and P3.

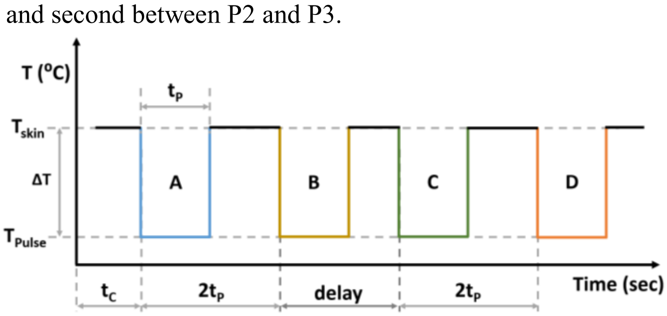

Figure 2. Different parameters of the four temperature pulses used to create the patterns.

The time between the onset of Pulse A and B, and between Pulse C and D was fixed at 4 seconds. The direction of activation of the Peltier modules, the specific Peltier modules cooled, and the delay between the onset of pulse B and C, were the parameters used to create a total of eight patterns, as depicted in Table 1. With a delay of 4 seconds between Pulse B and C all the pulses were evenly distributed in time; a shorter delay of 0.2 seconds was chosen to determine whether an illusory change in position occurred. Pulses A and B, and Pulse D were always presented at either the first (P1) or the third Peltier (P3) module depending on the direction of activation. The location of Pulse C varied between the second (P2), first (P1) or third (P3) Peltier module depending on the direction of activation.

Each pattern lasted 20 seconds and was presented 5 times, giving a total of 40 trials for each participant. The order of presentation of the trials was randomized.

D. *Procedure*

Prior to starting the experiment, the procedure was explained to participants and they were familiarized with the temperature pulses that would be delivered. They were told that four temperature pulses each with the same duration and intensity would be delivered to their forearms and that 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. Markers on the thermal display guided the participants as to the correct placement of their forearm. One of the eight patterns was then presented on the display (see Table 1). At the end of each trial an auditory cue signaled to the participants to indicate the locations at which they perceived the first two 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. 3). They moved a cursor to indicate the location of each of the pulses. The position for each pulse was measured from the wrist. Responses had to be made within 10 seconds and on most trials participants made their responses 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. No feedback regarding the correctness of the responses was provided during the experiment.

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

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

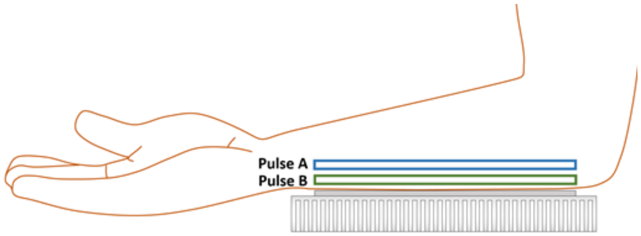

Figure 3. Screen shot of the GUI presented on the computer screen in front of the participants, and used by them to record their responses

III. Results

The temperature measured on the Peltier modules and on the skin is illustrated for two patterns in Fig. 4. It is evident that the temperature of the skin not in contact with the Peltier devices remained constant throughout the trials, indicating that the temperature change during stimulation was well localized to the contact region.

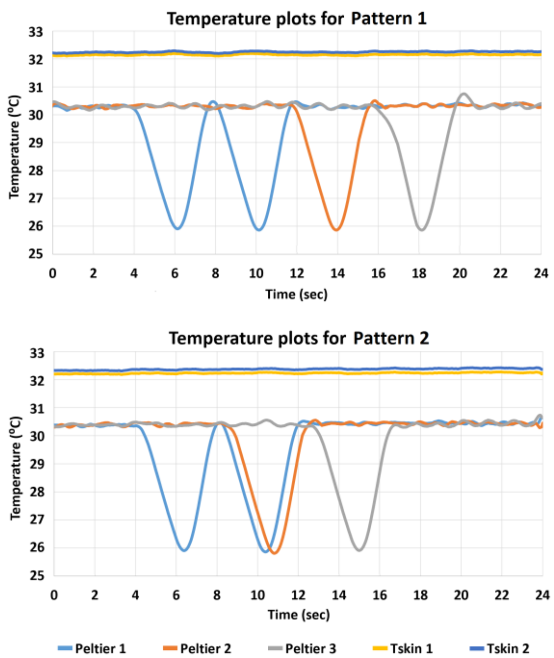

Figure 4. Temperature recordings throughout two trials from the three Peltier devices and from the skin on the forearm not in contact with the Peltier devices

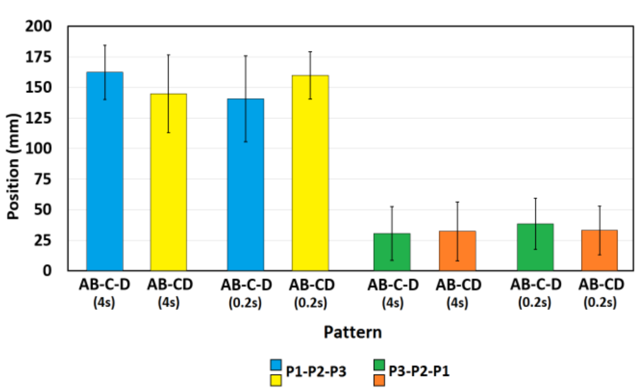

Figure 5. The group mean perceived position of the first pulse in each pattern. Standard deviations are shown.

Participants indicated the perceived location of Pulses A and B by moving the cursor to the location on the GUI (Fig. 3). These data were then digitized using the Image Processing Toolbox in MATLAB (Mathworks, Inc.). Distance was measured from the wrist. Fig. 5 shows the perceived location of the first stimulus (pulse A) for the eight patterns presented. There is variability across participants, particularly when the sequence began at the elbow (P1-P2-P3) as compared to the wrist (P3-P2-P1). The group means vary by 22 mm for the former set of patterns but only by 8 mm for the latter set.

The perceived position of the second stimulus (pulse B) in each pattern is shown in Fig. 6. The experimental condition that resulted in a substantial change in the perceived position of pulse B was the AB-CD sequence with a delay of 0.2 seconds. The perceived position of B has moved by 43 mm and 59 mm towards the location of pulse C. With the 4-second delay the positon of B is not perceived to change as a function of the spatial sequence presented (AB-C-D vs AB-CD).

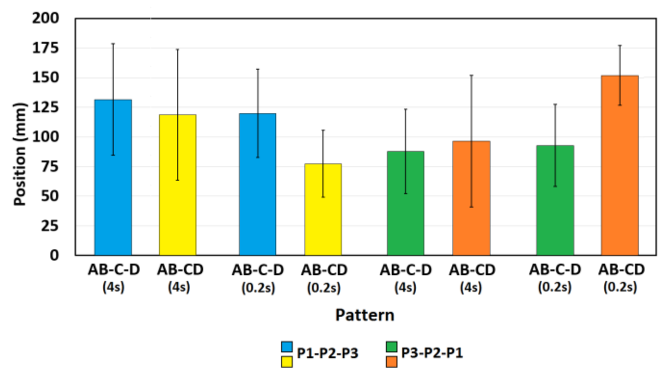

Figure 6. The group mean perceived position of the second pulse in each pattern. Standard deviations are shown.

The perceived location of pulse B in the various experimental conditions can best be visualized using a format devised by Goldreich [27] to conceptualize tactile length illusions. The schematic illustration shown in Fig. 7 depicts graphically the temporal and spatial properties of the physical stimuli and the perceived position of pulse B on the forearm for each of the eight patterns. Each adjacent pair of patterns differ only with respect to where the third stimulus (pulse C) 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 pulses B and C was short and pulse C was delivered at some distance from pulse B. When the distance between pulses B and C was shorter (around 75 mm), there was no change in the perceived position of pulse B. Figure 7 also illustrates that participants were more accurate at localizing both the first and second pulse for the longer delay sequences when they occurred near the elbow as compared to the wrist. This may reflect the use of the elbow as an anatomical landmark to facilitate localization, as has been reported for tactile stimuli [28].

The effect of the various parameters used to create the thermal 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 (first pulse on P1 and P3) as factors. The results indicated a main effect of sequence ($F(1,9)=10.59$, $p=0.01$), a main effect of delay ($F(1,9)=15.79$, $p=0.003$) and a main effect of direction ($F(1,9)=10.37$, $p=0.01$). These findings indicate that the perceived distance between pulse A and B was significantly greater for the AB-CD sequence, for the shorter 0.2-second delay and for sequences that began at the wrist as compared to the elbow. The only interaction that was significant was the interaction between delay and sequence ($F(1,9)=10.78$, $p=0.009$), reflecting the greater distances or change in perceived location associated with the shorter delay and AB-CD sequence.

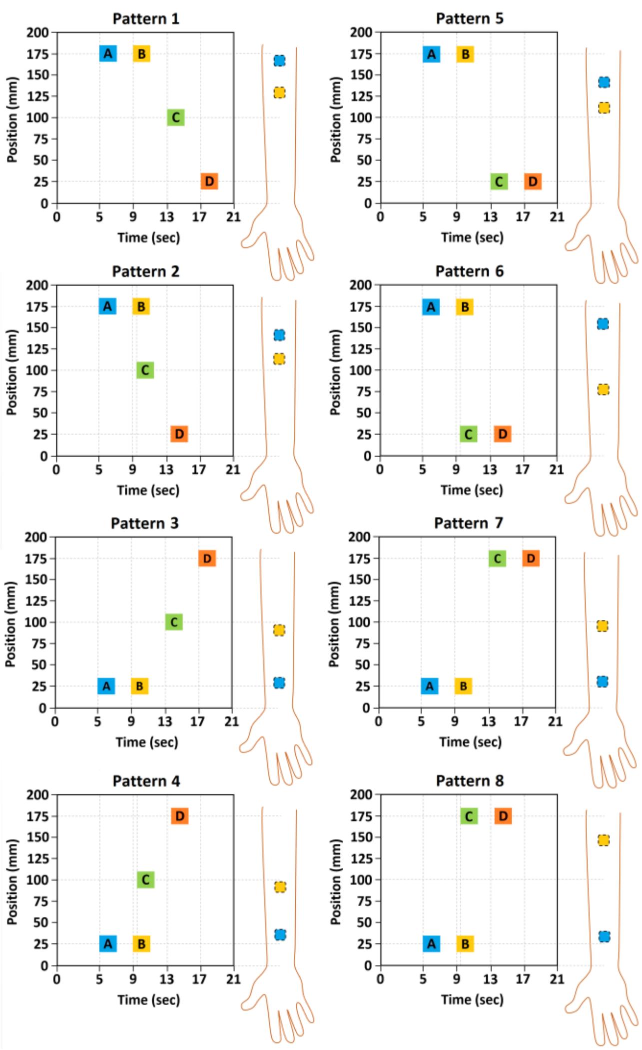

Figure 7. Schematic illustration of the group mean data for the physical stimuli depicted graphically and the perceived position of those stimuli on the forearm.

IV. Discussion

The objective of this experiment was to determine whether illusions of space and time that have been demonstrated for mechanical stimulation on the skin also occur for thermal stimuli within the innocuous range of temperatures. This was studied using four cooling pulses that were presented on the forearm in varying spatial and temporal sequences. Participants were asked to indicate the perceived location of the first two pulses in the four-pulse sequence. The results indicate that the position of the second pulse changed substantially (on average between 43 and 59 mm) in the direction of the third pulse when the interval between these pulses was brief (0.2 seconds) and the distance between the second and third pulse was greater. At longer intervals (4 seconds) and shorter distances there was no change in perceived location. These findings indicate that the tau effect does occur for thermal stimuli and that stimuli that occur closer together in time are perceived to be spatially closer. The absence of any change in perceived location for pulse B when pulse C was close spatially may reflect the limited spatial acuity of the thermal perceptual system. The perceived location of pulse B in all conditions was in the direction of pulse C and so these two stimuli may have been difficult for participants to resolve spatially.

The paradigm used in this experiment was one that has frequently been employed in studies of tactile sensory saltation [9], [29]. It has the advantage that an objective measure of the position of a stimulus is provided and changes in perceived positon can be related to factors such as inter-stimulus delays and the distance between stimuli. The mislocalization of pulse B in the present experiment in the direction of pulse C is consistent with the findings on sensory saltation reported for tactile stimuli [9], [29]. However, for the sense of touch it is clear that saltatory stimuli cause both a change in the perceived position of a stimulus and a perception of its movement across the skin. The thermal stimuli used in the present experiment were not perceived to move across the skin and the onset and offset of each stimulus was much less distinct than would occur with a mechanical input, no doubt reflecting the slow changes in skin temperature.

The results from this experiment provide several interesting insights into the perceptual mechanisms involved in processing the spatial properties of thermal stimuli. First, despite the number of studies that have documented the very poor spatial resolution for thermal stimuli [16], [30], [31], it was surprising to find that participants could identify reliably the location of the first thermal stimulus, particularly when it was presented in the area around the elbow (see Fig. 5). Stimuli were never mislocalized in terms of being perceived at the endpoint of stimulation, for example, the region around the elbow for sequences that started at the wrist. Measurements of temperature on the skin not in contact with the Peltier devices confirmed that the decreases in skin temperature were well localized (Fig. 4). This is consistent with other studies that have shown that the changes in skin temperature during contact with different objects are localized to the contact area [32]. Although participants were informed that the pulses could be presented at any location, for all sequences they perceived the second pulse to be localized in the direction of the third pulse and not at the same location as the first pulse.

A second finding of interest relates to the time delay required for the illusion. A delay of 0.2 s between the second and third pulse was probably optimal for the change in perceived location to occur, although additional experiments would need to be performed with delays between 0.2 and 4 s to confirm this. For tactile stimuli it has been shown that the tau effect is optimal when the ratio of the two time intervals is no greater than 4 to 1 [33], [34]. In the present experiment the ratio is 20 to 1.

In conclusion, this experiment has demonstrated an interesting illusion in a sensory modality that is known for its limited spatial and temporal processing capacity. These findings demonstrate that the space-time interactions reported for other sensory modalities can also occur with thermal stimuli and so presumably represent a fundamental aspect of perceptual processes. These illusory phenomena not only offer insight into how the external environment is sensed but also provide tools that may be used to optimize the presentation of information in haptic and thermal displays. In particular, these findings demonstrate that by varying the onset of different thermal stimuli it is possible to create stimuli whose spatial location is perceived to vary. This provides an extra dimension to use to present information in a thermal display and potentially could result in a display that functionally has a higher spatial resolution than the number of thermal elements would indicate.

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