VISUAL CUES EFFECTS ON TEMPERATURE PERCEPTION

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VISUAL CUES EFFECTS ON TEMPERATURE PERCEPTION

By

Carrie Anne Balcer

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Title of Thesis:

This thesis by Carrie Anne Balcer is recommended for approval by the student’s Thesis Committee and Department Head in the Department of Psychology and by the Assistant Provost of Graduate Education and Research.

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ABSTRACT

VISUAL CUES EFFECTS ON TEMPERATURE PERCEPTION

By

Carrie Anne Balcer

The purpose of this study was to measure reaction times (RTs) when a conflict arises between the visual feedback and the temperature of an object. This study focused on the quantifiable RTs along with the qualitative feedback of the participants. It was hypothesized that when the information of the visual and temperature stimuli are incongruent (blue-warm or red-cold), the RTs will be slower than when they are congruent (blue-cold or red-warm). We suggest that vision could convey temperature perception in an independent but complimentary manner. We utilized the Oculus Rift to create a virtual environment that allowed us to control the visual cues of an objects’ temperature and a Peltier thermo-device to provide the tactile temperature stimuli. The results confirmed our initial expectation that participants RTs are longer for incongruent stimuli than congruent stimuli. The results also showed that participants rated cold temperature sensations warmer when presented simultaneously with a visual red color cue and warm temperature sensations cooler when presented simultaneously with a visual blue color cue.
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INTRODUCTION

Temperature awareness in humans can be conveyed through multiple modalities. Each modality such as visual, tactile or auditory sends separate but complimentary information to form a unified perception of temperature. Auditory and visual modalities have the ability to enrich or reduce tactile perception. For instance, the color red is often associated with hot temperatures while the color blue is associated with cold ones. These color cues allow for proper behavioral responses that are related to temperature. Although several senses convey thermal cues, a real experience of temperature occurs mainly through touch. For instance, when boiling water, hearing the shrill whistle of the teapot reaching the boiling point of 100°C and seeing the steam billow from the spout give us indications about the temperature. However, we truly experience temperature when we grasp the handle of the teapot. Although all visual, tactile and auditory inputs are interconnected and contribute to our perceptual knowledge, the temperature of a hot sensation is felt only when the tactile modality comes into contact with the handle. That said, the other modalities clearly contribute to the way we interact with the world and modify the sensorimotor loop. Not seeing the steam or hearing the whistle can potentially lead to burning accidents. Therefore, confirmation about the temperature of a surface or object can be facilitated through vision or audition.

Associating a crackling fires warmth is clearly associated to previous knowledge of high temperature. Same holds true for looking out the window at the sun shining in the summer or the snow blowing in the winter, visualizing the weather (snow - cold or sun - warm) before entering the environment is our temperature cue of how to proceed before
actually sensing the outside temperature. This cohesive cross-modal interaction allows for the organism to have appropriate behavioral responses in association with temperature.

For the scope of this thesis, we studied the relationship of visual color priming with tactile temperature cues. The results matched our expectation that participants had significantly shorter reaction times to the congruent color-thermal stimuli presented (e.g. red/warm) compared to the incongruent stimuli (e.g. red/cold).

Chapter 1 summarizes previous findings related to temperature research and the ability of researchers to build upon past scientific findings. It also includes an overview of touch receptors, from afferent and efferent neurons to thermoreceptors and nociceptors. Finally, chapter 1 discusses recent findings in crossmodal interaction between color cues and thermal stimuli as background for the scope of this thesis.

Chapter 2 discusses the experimental process of incorporating a virtual reality (VR) environment to test thermal cues. The VR setting allowed controlling of visual cues along with hand tracking that fully immersed participants while interacting with thermal objects. This task presented a unique opportunity to study not only quantitative reaction times to congruent and incongruent stimuli but also participant’s qualitative responses to perceived temperature. This experiment provides an ample base for future thermal studies using VR. We used the Oculus Rift, one of the most developed head mounted displays (HMD) on the market and a Creative-Intel hand tracking camera to track hand movement. We encountered several technical and logistical issues during this phase. The first problem originated in perceiving the temperature of the cup through visual cues. Originally we planned to use visual thermal cues such as ice for cold and steam for hot. However, adding these visual cues in the VR environment would have delayed the project. The second issue
was related to calibration, as sometimes the virtual environment tended to shift with participant’s movement. Although the cup was always positioned in the same spot for the right hand grasp, if the environment shifted the virtual cup would appear to either the left or right of the actual cup. Fortunately, this small technical issue did not interfere with experimental reaction times, as the participants were aware of this issue and adapted their head movement according to the shifted virtual environment. Their grasping position did not change, as they were mindful of the position of the real cup. Finally the last issue occurred with the software used to record reaction times. This unfortunate technical difficulty was persistent throughout testing which would sporadically not record any of the experimental trials for a participant. This issue forced us to test many more participants then was originally expected. Despite these issues, that we are hoping will be resolved in the future, we were able to present this work at the Haptic symposium 2014 in Houston. This system could be used in the future for new and developing experimental procedures in thermal perception research.
CHAPTER ONE: THERMOSENSATION

1. INTRODUCTION

When exploring an object, several physical features are encoded and integrated for the final recognition. When we touch a surface of an object we encode information such as texture, temperature and familiarity that helps us make perceptual decisions about that object for purpose of memory recall or action (Ho & Jones, 2007). Most attributes of touch come from the stimulation of cutaneous mechanoreceptive afferent neurons in both the epidermis and dermis layers. These mechanoreceptors (Merkel cells, Meissner corpuscles, Pacinian Corpuscles, and Ruffini corpuscles) respond to a unique type of mechanical stimuli (Johnson, 2001). Similarly, temperature is perceived through the tactile channel. It has been shown that participants can successfully identify materials based on thermal cues (Jones & Berris 2003; Jones & Ho, 2006).

After a brief history related to temperature research, this chapter details the several sensory receptors before exploring the conveyance of temperature perception through several sensory modalities.

2. HISTORY OF TEMPERATURE RESEARCH

The tactile modality combines separate senses such as cutaneous, kinesthetic, proprioceptive, temperature, and pain; all of them mediated by the somatosensory and motor cortices. Indeed, not only do we perceive a variety of sensations such as rough, fluffy, pressure, edges, curves and smooth textures, but also if objects are warm, cold or neutral. Interestingly, conversely to texture perception, temperature perception is always in a warm-cold paradigm and is often associated to pain perception thresholds (Darian-
Smith & Johnson, 1977). We either feel non-noxious (warm, neutral, and cool) stimuli or noxious painful stimuli (hot and cold), but there is rarely sensory variations in-between.

E. H. Weber (1795-1878) differentiated the ability of the skin to sense differences in pressure and temperature along with the ability to locate sensations on the body (Stevens & Green, 1996). These three attributes, were not three separate senses, but the functional ability of the skin to discriminate between distinct sensations. Using an analogy to color visualization, where humans have the ability to distinguish between brightness, contrast and saturation, they also have the ability to distinguish between touch sensations. To validate this concept, he used the Thaler illusion (a cold coin feels heavier than a warm coin) to demonstrate that temperature and pressure are unified within the tactile modality. This aspect of unified sensations of the tactile modality would come under scrutiny later, as we have to wait until early forties for first investigations (Boring, 1942; Stevens and Hooper, 1982).

Weber elaborated that temperature was an estimation rather than a perception, “since we perceive the effect of an increase or decrease in heat (Weber, 1834)” instead of an absolute temperature, through our tactile modality. He posited that both the material of the object and the summation of the skin in contact with it increase the error rate of temperature estimation. Indeed, in a temperature discrimination task, Weber immersed participants’ one hand (including himself) into a wooden flask of water at 29.5 degrees using the Reaumurian scale (approximately 37°C) while the index finger of the other hand was immersed into a wooden flask of water at 33 degrees (approximately 41°C). All participants determined that the hand fully immersed in the colder water was warmer than the finger immersed in the warm water. These findings have since been confirmed by research exploring spatial
summation in the cold and warm modality (Stevens & Marks, 1979) which will be discussed in depth later in this chapter. Due to these results Weber determined that a small degree of heat over a larger surface of the skin produced the same sensation as a large sensation of heat on a smaller portion of skin surface. Importantly, Weber also stated that temperature estimation is more accurately perceived when it is not accompanied by pain. Finally, the estimation of thermal stimulation is more accurate when a larger portion of the skin comes into contact with the object (Weber, 1834). This being determined, temperature is reliant on the spatial summation of the thermal cues that are presented to the skin.

In 1879, Ewald Hering theorized that the temperature sense was interrelated, although warmth and cold are dependent on different physiological processes (Boring, 1942). This theory seemed to coincide with Muller’s theory of specific nerve energies, which states that perceptual awareness is not transmitted only by the external stimulus, but also through the nervous structures that these stimuli excite (Muller, 1838). With the discovery of sensory spots by three separate laboratories; Blix (1882) in Sweden, Goldschneider (1884) in Germany, and Donaldson (1885) in America, four distinct sensations were revealed; pain, pressure warmth and cold (Boring, 1942; Stevens & Green, 1996; Pearce, 2005). Unlike Weber who treated these sensations as interrelated characteristics of touch, Maximilian von Frey (1952-1932) viewed these sensory qualities of tactile sensations as independent modalities. The identification of four separate modalities within the sense of touch led to relate each of these separate sensory qualities to specific nerve types (Stevens and Green, 1996) such as pain-nociceptors (nociceptive organs of the skin as classified by Sherrington in 1906 are naked nerve endings that can be stimulated by multiple modes of excitatory energy) and temperature–thermoreceptors.
Blix continued the research on sensory spots in relation to temperature by using a hollow conical metal point through which warm or cold water could be passed to stimulate the skin. He was able to map cold and warm spots, where he showed that cold spots outnumber warm spots. This discovery allowed him to separate the temperature sense into two separate categories of cold and warm senses. Goldscheider replicated the mapping of sensory spots for warmth, cold and pressure and determined that they were separate qualities or specific energies within the tactile modality (Boring, 1942; Pearce, 2005). Additionally to the three specific nerve energies of warmth, cold and pressure, von Frey demonstrated the existence of separate pain spots, analgesic to that of other stimuli. He also noted in 1895, what he called *paradoxical cold spots*, which respond with a cold sensation to a warm stimulus between 45° and 50°C. The combination of these separate discoveries strengthen the cutaneous specific energies approach and reinforced the separation of warmth and cold into two distinct modalities. With this evidence von Frey surmised that each modality had a specific receptor, though he wrongly determined that Krause bulbs were cold receptors and Ruffini endings were receptors for warm stimuli (Boring, 1942).

As discussed above sensory spots were determined to elicit separate sensations within the touch modality. Darwin first emphasized this aspect by suggesting in 1796 that there may be more than five senses, such as temperature. The “heat sense”, in particular could be considered as a separate sense that is generated either externally through the skin or internally through exertion (Darwin, 1796). With von Frey’s paradoxical cold spots, Altruz (1889) deduced that quality of hot is very different from the quality of warm and could be experienced with or without pain. He proposed that the quality of hot was dependent upon
both the excitation of warm and the activation of close proximity paradoxical cold spots by warm stimuli. This introspective proposal of paradoxical cold pain was later qualified by Thunberg in 1896 with the thermal grill illusion that consisted of non-noxious warm and cool stimuli applied to the skin concurrently, which produced a burning sensation that is generally associated with cold pain (Craig & Bushnell, 1994). Though much of historical research into temperature perception is based on personal introspection or qualitative data, it has provided a strong base for further research, as it has been demonstrated through the linear progression of paradoxical cold through von Frey (1895), Altruz (1889), Thunberg (1896) and continually in recent studies Craig and Bushnell (1994), Craig et al., (1996), Bouhassira et al., (2004) and others.

Finally Boring (1942) separated tactile sensations into four different categories: physiological, functional, qualitative, and perceptual. For the specific case of temperature these four categories can be described as: 1) physiological: different thermal stimulation spots on the skin for cold and warm, 2) functional: the organism’s awareness of heat compared to other states such as hunger, 3) qualitative: thermal sensations are introspectively different, warm from cold or hot from warmth, and finally 4) perceptual: adaption to an environment may alter thermal cues (Boring, 1942). These four characteristics of thermal receptors (physiological), pain (functional), sensation (qualitative), and regulation (qualitative) are still in use today in temperature research.

2.1. TOUCH RECEPTORS

2.1.1. AFFERENT AND EFFERENT NEURONS

The peripheral nervous system administers the sense of touch by communicating sensory information to the central nervous system, such as environmental cues of
temperature or physical cues of pain. The neurons that provide this diverse sensory information are located in the dorsal root ganglia (DRG) and in the trigeminal ganglion (TG). These DRG neurons are clusters of afferent or sensory neurons that are located in the vertebral column. Afferent neurons receive information from the external environment and are sent to CNS. Efferent or motor neurons are responsible for body reactions such as muscles contraction after receiving the information from CNS. These afferent nerve fibers facilitate the sensation of non-noxious thermal stimuli and transport thermal information from a range of temperatures. Finally, it is important to point that afferent neurons can refer to mechanoreceptors, proprioceptors, thermoreceptors, or nociceptors (Hensel & Boman, 1960).

2.1.2. THERMORECEPTORS

The localization of sensory spots on the skin revealed a distinction between sensations of warmth and cold. Our skin serves as a sensory organ for thermosensation, as it allows for correct detection of stimuli to ensure the most appropriate and accurate behavior. The skin physiology allows to distinguish harmful or noxious stimuli that pose an immediate danger to the body from stimuli that are comparatively non-noxious (Stevens & Marks, 1979). Afferent neurons that are responsible for thermal sensation are called thermoreceptors. Thermoreceptors are sensory neuron located in the epidermal and dermal skin layers which are excited by changes in temperature, predominantly in the non-noxious range and are considered unimodal afferent neurons (Darian-Smith & Johnson, 1977). There are two separate but distinct populations of thermoreceptors that are activated by temperatures in the non-noxious range; warm fibers respond when the temperature of the skin rises and cold fibers respond when skin temperature decrease. Warm fibers respond
to skin temperatures between 29-43°C whereas cold fibers respond to temperatures in the 17-40°C range (Darian-Smith et al., 1973). Their main function is to sense environmental temperature changes and signal the CNS for appropriate behavioral responses. Tactile information from the skin must first travel to the spinal cord via the DRG which includes subclasses of sensory neurons related to temperature and pain that project to the dorsal horn interneurons (laminae I-VI of the spinal cord) (Patapoutian et al., 2003; Tan & Katsanis, 2011). Thermal information then is transported from the thermoreceptors to the cortex into the somatosensory area 1 (S1) by way of the spinothalamic pathway.

The particular molecules that identify and transport thermal stimuli are thought to be specific receptor proteins that are found within the free nerve endings in the dermis and epidermis layers of the skin (Patapoutian et al, 2003). More specifically, transient receptor potential (TRP) ion channels have been identified as sensitive to thermal stimulation (Patapoutian, 2005). Thermo TRP cell bodies are found in the DRG neurons (Moqrich, 2005; Patapoutian, 2005). TRP ion channel expression is essential for the establishment of thermal sensitivity, when it comes to temperature sensing afferents (Pongs, 2009). Temperature transduction involves thermal effects on temperature sensitive ion pump mechanisms (Pearce, 2005). Three particular families are of importance in thermo TRPs: vanilloid TRP channels (TRPV), melastatin TRP (TRPM) and the ankyrin TRP (TRPA) (Schepers & Ringkamp, 2010). Thermosensitivity involves a complex interaction of ion channels, receptors and proteins in addition to TRP channel activation.

2.1.3. NOCIRECEPTORS

Nociceptive afferents are bare nerve endings that are activated by noxious stimuli including thermal, pressure and chemical (Schepers & Ringkamp, 2010). The nociceptors
that are activated by noxious pressure or heat stimulus are thinly (1-5 um) myelinated Aδ fibers that signal sharp or ‘first pain’. Unmyelinated C-fibers (1.02-1.5um) respond to dull pain or ‘second pain’ activated by intense stimuli of various types including pressure, heat, cold and chemical (Hensel & Boman, 1960; Bessou & Perl, 1969). The first discovery of nociceptive neurons in the periphery goes back to research on action potentials of single C-fibers in cats while applying graded stimuli to the skin (Bessou & Perl, 1969). The authors discovered polymodal nociceptors that can be activated by a variety of tactile stimulation. These C-fibers that are considered polymodal thermoreceptive nerves have the ability to respond to hot and cold stimulus along with the ability to be excited by mechanical stimulation (pressure) (Hensel & Boman, 1960) or chemical stimulation (menthol or capsaicin) (Voets et al., 2004; Tominaga & Caterina, 2004; Wasner, Schattschneider, Binder & Baron, 2004).

More specifically, thermal nociceptors are dedicated to detection of noxious heat and cold stimulus, which have to be distinguished from thermoreceptors that are not necessary associated to noxious stimuli. Nociceptors fibers start firing at painful temperatures that is depicted by an increase in firing rate along with the increase in painful sensations. Different ranges of skin temperature excite different thermoreceptors and thermosensitive nociceptors (McCleskey, 1997). Neurophysiological studies have shown that excitement of C-fiber mechano-heat nociceptors (CMH) induces a sensation of burning pain in the brain. These studies have also shown that heat thresholds of CMHs depend upon the absolute temperature rather than temperature increases. Desensitization or sensitization can occur with repeated contact with cold or heat stimulus, dependent upon the particular
nociceptor (LaMotte & Campbell, 1978; Tominaga & Caterina, 2004; Churyukanov, Plaghki, Legrain & Mouraux, 2012).

Capsaicin a compound found in chili peppers that induces the spicy hot sensation was found to also bind to free nerve endings that respond to an increase in temperature (Caterina et al., 1997). This receptor was cloned and the protein was found to be part of the family of transient receptor potentials (TRP) and activates the TRPV1 channel. Normally the TRPV1 job is to detect noxious heat and to inform the organism of potential danger. This TRPV1 channel is activated by temperatures greater than 43°C and uses C-fiber axons and is associated with dull pain also known as ‘second pain’. TRPM8 (also known as CMR1 – cool menthol receptor) another temperature gated ion channel that uses C-fibers associated with dull pain, is activated by cool stimulus (<~25-28°C) and can also be activated by the chemical menthol (Voets et al., 2004; Tominaga & Caterina, 2004; Wasner, Schattschneider, Binder & Baron, 2004). The thermal activated ion channel TRPV2 responds to even higher temperatures greater than 52°C and uses Aδ fibers that send signals to the spinal cord very quickly, sending the message that the organism is in danger. Other channels that are also used in thermal sensation are TRPV3 (>~34-38°C), and TRPV4 (>~27-35°C) that respond to non-noxious warming stimuli, each ion channel is responsible for a diverse set of temperature ranges (Patapoutian et al., 2003; Tominaga & Caterina, 2004; Patapoutian, 2005; Pongs, 2009; Takashima, Ma, & McKemy, 2010).

The identification of these ion channels allowed to establish a molecular basis for thermosensation and thermonociception, although not all TRP’s are thermosensitive (Patapoutian, 2005). In temperature sensing afferents, central integration of information acquired by peripheral nerve endings and TRP ion channel expression is fundamental for
the establishment of thermal sensitivity (Tominaga & Caterina, 2004; Takashima, Ma & McKemy, 2010).

2.2. THERMAL PAIN THRESHOLDS

Thermal pain thresholds have been studied since Weber’s temperature-weight experiment (see section 2). Despite the consistent number of studies, thermal pain thresholds consist of a range of temperature rather than an exact threshold value as summarized in Table 1. Temperature pain thresholds are the thresholds that display the most individual differences. Usually two psychophysical methods are commonly used to determine thermal perception and pain thresholds, as detailed below.

2.2.1. FORCED CHOICE METHOD – SENSORTEK METHOD

This method uses static thermal cues where participants are asked to determine the warmer of the two thermal controlled stimuli, the thermal stimuli are controlled through Peltier devices. Participants are asked to touch alternatively a thermal reference plate of 30°C and a comparison plate with temperatures set above or below the reference by 0-20 °C. Participants’ responses are then plotted using the up-down-transformation rule (UDTR) (Levy, Abraham & Reid, 1989). The UDTR, developed by Levitt for Psychoacoustics based on von Bekesy simple up-down method, is a power psychophysics method that reduces the number of trials in a two-force choice method by increasing the stimulus (here the temperature) by (x) increment subsequent to an incorrect response and decreasing the temperature by following (y) correct answers (Wetherill, Chen, & Vasudeva, 1966).

2.2.2. METHOD OF LIMITS – MARSTOCK METHOD

The method of limits allows for examination of dynamic thermal detection and thermal pain thresholds. A thermode Peltier device that can deliver both sensations of cold and hot
is applied to a skin area and is set at a reference level close to skin temperature (30-32°C). To determine thermal detection thresholds, the temperature is increased until participants feel a sensation of warmth, where they activate a switch to reverse the thermal stimulation. When participants feel the thermal stimulation cooling, they activate the switch to reverse the current and the order of increment of the temperature. The thermal detection threshold is obtained by averaging crossover points for each trial. A similar method is utilized for thermal pain thresholds. Once participants perceive the thermal stimulation as painful, they activate a switch to reverse the thermal current to return to the reference level. Once the reference level has been reached, the next painful thermal stimulation is applied. These trials are then averaged to obtain the thermal pain threshold (Fruhstorfer, Lindblom, & Schmidt, 1976; Levy, Abraham & Reid, 1989).
<table>
<thead>
<tr>
<th>Reference</th>
<th># of Participants</th>
<th>CDT °C</th>
<th>WDT °C</th>
<th>CPT °C</th>
<th>HPT °C</th>
<th>Tested Region</th>
<th>Method used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wolf and Hardy 1941</td>
<td>2 (The authors)</td>
<td></td>
<td></td>
<td>18</td>
<td></td>
<td>Immersed Hand</td>
<td>Water baths</td>
</tr>
<tr>
<td>Fruhstorfer, Lindblom, &amp; Schmidt 1976</td>
<td>26</td>
<td>33.0</td>
<td>35.0</td>
<td>14</td>
<td>45.2</td>
<td>Right Thenar</td>
<td>Method of Limits</td>
</tr>
<tr>
<td>Levy, Abraham &amp; Reid, 1989</td>
<td>78</td>
<td>Baseline for both methods set at 30.0</td>
<td>Baseline for both methods set at 30.0</td>
<td>Baseline 30.0</td>
<td>11.7**</td>
<td>Forced Choice*</td>
<td>Method of Limits**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.35*</td>
<td>0.35*</td>
<td>0.30*</td>
<td>5.0*</td>
<td>SD 2.4**</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD 0.30*</td>
<td>SD 0.30*</td>
<td>SD 1.8**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meh and Denislic, 1994</td>
<td>67 Females 83 Males</td>
<td></td>
<td></td>
<td>F 24.09 SD 4.87</td>
<td>F 37.69 SD 4.21</td>
<td>Thenar</td>
<td>Method of Limits</td>
</tr>
<tr>
<td>Davis and Pope, 2002</td>
<td>18</td>
<td>28.2 ±0.5</td>
<td></td>
<td>14.9 ±1.5</td>
<td></td>
<td>Right Thenar</td>
<td>Method of Limits</td>
</tr>
<tr>
<td>Kuhtz-Bushbeck et al., 2010</td>
<td>141</td>
<td>Baseline set at 32 -1.4 SD 0.7</td>
<td>Baseline set at 32 1.7 SD 0.6</td>
<td>10.2 SD 6.4</td>
<td>45.7 SD 3.6</td>
<td>Right Thenar</td>
<td>Method of Limits</td>
</tr>
<tr>
<td>Music, Finderle, &amp; Cankar 2011</td>
<td>18 Males</td>
<td>Baseline set at 30.0 0.48±0.05</td>
<td></td>
<td>18.64 ±1.3</td>
<td></td>
<td>Left Thenar</td>
<td>Method of Limits</td>
</tr>
</tbody>
</table>

**Table 1. Diversity of thermal testing:**

**Cold detection threshold (CDT), Warm detection threshold (WDT), Cold pain threshold (CPT), and Hot pain threshold (HPT). Standard deviation (SD) is reported when available. Previous methods include a water bath held at a constant temperature while a participant immerses their hand for a set period of time. The Thenar eminence is the group of muscles located on the palm side at the base of the thumb.**
After the establishment of C-fibers and Aδ fibers in nociception and thermosensation (Bessou & Perl, 1969), pain has been accepted as a separate sensory modality. There have been many improvements on the quantitative testing of thermal detection and pain thresholds, from water baths in 1941 to thermocouples that are used currently. In a study involving 300 participants, researchers found that women are more sensitive to thermal detection and pain than men (Kuhtz-Buschbeck et al., 2010). They also determined that the range of cold pain perception is 10.2°C (SD 6.4) and heat pain perception at 45.7°C (SD 3.6).

2.2.3. TEMPERATURE PERCEPTION AND SPATIAL SUMMATION

Thermal diffusivity refers to the way heat spreads though an object or a material (Bergmann Tiest & Kappers, 2009). Materials that feel either ‘warm’ or ‘cool’ to the touch has very little to do with the temperature of the object but rather with the rate at which heat is extracted (Bergmann Tiest & Kappers, 2009). Thermal cues have been researched in the past as a way to discriminate between different types of material (Ho & Jones, 2006; Galie & Jones, 2010). These studies have determined participants can differentiate between materials using thermal prompts when other textural cues are limited, as long as the differences in thermal properties of the materials are pronounced (Ho & Jones, 2006; Jones & Berris, 2002). Judging of absolute temperature is a weakness in humans even with the separate warm and cold sensitive systems. Adaptation is believed to play a role in this mechanism when the skin comes into contact with an explicit temperature.

Adaptation occurs when the skin reaches a specific temperature using either water, air or commonly in research a thermal device such as a Peltier (Bergmann Tiest & Kappers, 2009). Once adapted, cold detection, warm detection, cold pain, and hot pain become
contingent on the adapted skin temperature. To examine thermal adaptation, one hand is immersed in marginally cool water while the other is immersed in marginally warm water. The thermal sensation difference eventually ceases and both hands will feel at the same temperature. Moving both hands to a water bath of a neutral temperature (32°C) will result in perceiving a variation in temperature (Stevens & Green, 1996). This variation is due to an adaptation process as opposed to the idea that a thermal physiological zero can be fixed.

In a 1941 study by Wolf and Hardy, deep thermal pain and skin adaptation were examined. The left hand up to the wrist was immersed in a water bath at temperatures of 18°, 15°, 12°, 10°, 5°, 2°, 0°, and -2°C. As the temperature of the water bath progressively dropped, pain increased with the intensity progressively from the stimulus onset, although adaptation started after 60 seconds. It was also found that immersing the hand in water at 20°C and slow cooling over a 60 minutes period to 0°C induced no painful sensations, although “pins and needles” sensations were felt at approximately 12°C. Two important conclusions were drawn from this experiment: 1) adaptation begins to occur only after the painful stimulus had subsided and 2) cold pain is independent from cold sensation (Wolf & Hardy, 1941).

Although this part of the study measured qualitative response of the participants, it established a foundation for pain threshold and adaptation research.

As mentioned in section 2 spatial summation has been associated with thermal stimulation since the early temperature research (Weber, 1834). The larger the stimulated area, the greater the magnitude of sensory response (Stevens & Green, 1996) – in thermal stimulation a larger area of the skin (whole hand) warmed to 36° will feel warmer/hotter compared to a smaller skin area (single finger) stimulated at the same temperature. The ability of the skin to sublimate thermal cues allows for the organism to have a proper
response to even slight changes in temperature. It has been found that the rules of cold summation differ from those of warm summation, warmth summation decreases systematically as the temperature rises towards the pain threshold, whereas the summation of cold tends to remain constant. These findings give substantial evidence to the separate integration in the central nervous system of the effects of warm and cold stimuli. As warm stimuli increases towards pain thresholds, summation of stimulation is less of a necessity, this allows the skin to signal the organism to take swift thermoregulation action. (Stevens and Marks, 1979).

2.3. HOW VISION AND AUDITORY CONVEY TEMPERATURE PERCEPTION

Other senses such as vision or auditory can convey to some extend temperature perception such as hearing ice cubes clink against the glass of lemonade or the sizzle of frying bacon. Indeed, it has been shown that visual experience influences tactile perception of stimuli and the specific experiences shapes the subsequent behavioral responses. The research on the perception of the size and shape of the items that we haptically interact with has revealed that vision tends to dominate over touch (Spence, Shore & Klein, 2001). Although visual inputs tend to dominate over tactile stimulation, it is not always the case, as demonstrated by a Bayesian model suggested by Ernst and Banks (2002). This model interprets the potential sensory conflicts or interferences that are present in the environment. According to this model the brain integrates sensory signals by constructing a maximum-likelihood estimate (MLE) in three steps: 1) it takes into account the prediction of each modality separately (for instance vision and temperature), 2) weights each prediction in proportion to its variance (or reliability $1/\sigma^2$), and then 3) combines these weighted predictions. This model has been supported by empirical data (Ernst & Bülthoff,
2004; Drewing & Ernst, 2006) and it emphasizes the idea that the CNS appears to combine the incoming bimodal information is similar to the MLE rule: each modality estimation is weighted according to its variance. When temperature of an object is being examined based on visual and tactile inputs, the brain integrates the information based on the weight of each modality that can be estimated by using their respective variance. To our knowledge, only one study explored multisensory interaction between vision and temperature perception (Ho et al., 2014). The studies detailed below explored more specifically color-temperature interaction and how it is affected by the congruency or incongruency of the presented stimuli.

Color interaction with other senses is not new. In 2008, a pilot study investigated the effects of color exposure on somatosensory and auditory perception. This study revealed that red light stimulation had an increasing effect on loudness perception (lowered hearing thresholds) compared to the white light loudness perception baseline, whereas green light had a decreasing effect from baseline loudness. This study also investigated the effect of color exposure to thermal thresholds and thermal detection; the authors demonstrated that red light exposure lowered pain thresholds for cold stimuli and green light increased the detection threshold for warm stimuli and hot pain (Landgrebe et al, 2008).

Two other studies associated color cues with thermal pain (Martini, Perez-Marcos, & Sanchez-Vives, 2013) and with nasal thermal sensations (Michael, Galich, Relland, & Prud’hon 2010). Each study showed that participants’ thermal judgment of stimuli is affected by color cues presented simultaneously. Hot pain thresholds assessed on the right palmar wrist increased when seeing a virtual blue arm when compared to seeing a virtual red arm; while wearing a head-mounted device (HMD) (Martini et al, 2013). In the same
scope, a study investigated the cooling or warming of the nasal cavity in combination with color. The color green was associated with a cooling sensation such as smelling mint, while red was associated with warming sensations (Micheal et al, 2010). These studies provide a substantial foundation for our hypothesis that states that reaction times of thermal stimuli perception will be reduced when visual and tactile cues are congruent.

Very recently, effects of color priming and thermal compatibility were determined using the Implicit Association Test, a test designated for evaluating the relationship between automatic associations and certain concepts (for instance red is usually associated with hot). The authors tested priming effects by pairing a color patch (red/blue) on a computer screen with a thermal word cue (warm/cold) during congruent (red/hot and blue/cold) and incongruent (red/cold and blue/hot) conditions. Participants were instructed to respond as quickly and correctly as possible by pressing one of the two assigned response keys. It was shown that reaction times (RTs) were significantly faster for congruent trials compared to the incongruent ones. In the same study, the authors tested color cues with thermal stimulation that was presented to the index finger via a Peltier device, using 34.2°C for warm stimulus and 17.3°C for cold stimulus. The priming color patches were presented on a computer monitor for a duration of 2s before participants were instructed to place their index finger on the Peltier thermal device. Results showed that RTs were significantly shorter for congruent trials. (Ho et al 2014).

Ho et al. study provided a viable basis for our hypothesis that congruently paired stimulus presented to the participant via color (red) coded cups in a virtual environment and thermal stimulus (warm) presented to the palmer portion of the hand will have significantly shorter reaction times compared to incongruently paired stimuli (red/cold). It
also established the relationship between color cues and thermal temperatures that our study examines.
CHAPTER 2: VISUAL AND TACTILE INTERACTION IN THERMAL SENSATION

1. INTRODUCTION

As discussed in chapter one, participants have shorter reaction times when visual and tactile stimuli are congruent when compared to incongruent. These previous results demonstrate that an interaction is present for visual cues while simultaneously interacting with a thermally controlled object. In our study, participants were instructed to discriminate between cold and warm stimulus when presented with a color coded cup. This task allowed for collecting reaction times (RTs) and participants’ ranking of thermal stimuli. It is hypothesized that RTs will be significantly shorter when color cues and cup temperatures are congruent (red/hot or blue/cold) as opposed to incongruent (red/cold or blue/hot).

2. MATERIALS AND METHODS

2.1. PARTICIPANTS

Fourteen (11 females and 3 males) aged between 18 and 27 (Mean 19.5, SD 2.28) took part in this experiment. They were all PY100 (introduction to psychology) students from Northern Michigan University and received course credit for their participation. Participants were screened through a short non-invasive health questionnaire for any known abnormalities in tactile or thermal sensory systems. They all reported that were not suffering from any temperature altering illness or skin disorder. Participants were all right-handed and gave their informed consent upon participation. This research was approved by the Institutional Review Board of Northern Michigan University.
2.2. **Apparatus and Stimuli**

The stimulus consisted of touching stainless steel cups that were either warm or cold while displaying a virtual hand touching a virtual cup with temperature cues (red for warm and blue for cold). The virtual environment was created using the UNITY game engine connected to the Oculus Rift, a head-mounted display (HMD) that has a 7-inch screen that mimics normal human vision, which created a strong sense of immersion. Mounted to the Oculus Rift, a CREATIVE interactive gesture camera in collaboration with Intel® tracked participants’ hand movements, using the isu middleware, a platform for tracking gestures. Hand movements were synchronized with the movements of the virtual hand in the UNITY environment. The interactive camera was attached to the Oculus using a holder (Figure 1) printed on a 3D printer (MakerBot® Replicator™ 2X).

![Figure 1. Intel® Skeletal hand tracking camera mounted to the Oculus Rift.](image)

Two Winco stainless steel bar shakers (cups) were utilized to present thermal stimuli to the participants’ hand. The thermal properties of stainless steel allow for a larger heat
flux out of skin contact than other materials (Galie and Jones 2010). Thermal stimuli were maintained at a mean of 17°C (SD .24°C) for the cold cup and a mean 36.9°C (SD .8°C) for the warm cup. To ensure that this study measured temperature perception and not pain perception, temperatures were kept in the non-noxious stimulus range, above 16.6°C for painful cold stimuli and below 42.1°C for painful heat stimuli (Kuhtz-Bushbeck et al., 2010 see Table 1). The cups were supported by a custom created rotating device that delivered either cold or warm temperatures. The cold temperature was controlled by a 12V Peltier thermo-electric cooler mounted to a heatsink and 12V fan. The warm temperature was controlled by an electric heating pad 10cm x 5cm, powered by a 5VDC. The temperature of each cup was recorded by a TMP-36 temperature sensor, which provided an accuracy of ± 2°C for temperatures between -40°C and +125°C. The grasp duration was measured by using an Infrared Proximity Sensor (Short Range - Sharp GP2Y0A41SK0F) attached at the exterior bottom of each cup. The Infrared sensor was connected to an Arduino board by an Infrared Sensor Jumper Wire - 3-Pin JST (Figure 2). The temperature and grasp times were recorded through an Arduino into an Excel file each time the participant grasped and released the cup.
The support consisted of a rotating device to conceal all modes of thermo cooling or heating and to present one cup at a time to the participant (Figure 3). Because we are manipulating temperature, this method allowed changing the cups quickly without the participants’ knowledge, as they were wearing the HMD and therefore were only perceiving the virtual world. The experiment was carried out in a quiet room under normal lighting and temperature conditions in the Action and Perception Lab in the Psychology Department of Northern Michigan University.
2.3. Procedure

Participants were asked to wash their hands before entering the testing room. They answered a short non-invasive health questionnaire (see Appendix A) to control for peripheral vascular diseases or illnesses that may interfere with temperature perception. A Veridian Healthcare digital thermometer (Model 08-350) with protective probe covers, were used to measure the oral temperature of each participant. The participant’s initial oral temperatures ranged from 33.3°C to 37.0°C (Mean 35.6, SD 1.1). Palm temperatures were assessed using the Fluke 62 Max+ an infrared thermometer (Figure 4) ranging from 26.4°C to 35.7°C (Mean 33.2, SD 2.46). During the first set of twenty-four trials (training phase) skin temperature ranged between 26.2°C and 36.8°C (Mean 33.8, SD 2.4). During the second set of forty-eight trials (experimental phase) skin temperature ranged between 26.5°C and 36.6°C (Mean 33.9, SD 2.1). Room temperature was maintained at approximately 22.4°C for the entirety of the experiment.
The participants’ were then seated at a table with the rotating device, cups and thermo-components covered from sight. Before starting the experiment, participants were introduced to an identical stainless steel cup and were instructed to practice grasping with their right hand to insure an accurate grasp and reaction time recording. Once participants were confident with grasping instructions they were then introduced to the temperature rating scale. The numerical ratings were on a 1-5 scale, (1-cold, 2-cool, 3-neutral or room temperature, 4-warm and 5-hot). After the participants’ understood the temp scale and were comfortable with the cup grasping task, the participant was introduced to the HMD and it was fitted to their head to fully immerse participants in the virtual environment. This environment consisted of a virtual room containing a chair, a table with a round platform, a red or blue cup that would appear on the platform, and their virtual hand that matched the movements of their real hand (Figure 5).
The whole system creates a visuo-proprioceptive feedback by hand tracking with the HMD in the virtual environment, which allowed for full immersion of the color-temperature paradigm. Participants were then asked to become accustomed to the environment to ensure the synchronization of the virtual hand with their real hand and that the virtual cup matches the location of the real cup. Once participants were comfortable with the virtual hand grasp, the experiment began.

Participants were instructed to place their right-hand on the provided resting box situated to the right of the rotating table (that was hidden from their view), while the left hand was placed below the real table (see Figure 6).
For the training phase participants were informed that a red cup in the virtual environment indicates a warm cup in the real environment and a blue cup in the virtual environment indicates a cold cup in the real environment. Once either a red or blue cup appeared, participants grasped the cup, assessed the temperature by giving a numerical rating of 1-5 (recorded by the experimenter), released the cup and returned their hand to the resting box. This was repeated twenty-four times, counterbalanced across trials and participants, with a 30 second pause between each trial. Reaction times and cup temperature were recorded for each grasp and palm temperature was reassessed. Participants were asked during the training phase and experimental phase after the fourth set of stimulus if the temperature of the cups were painful or uncomfortable, this was again asked half way through each set of trials. All participants stated that the temperature was neither painful nor uncomfortable. After all twenty-four trials were completed during the training phase, the rotating temperature device was hidden from view, and the HMD was removed.

Participants were given a 10 minute break before commencement of the experimental phase. This phase included four stimuli combination in total (congruent red/cold, blue/warm and incongruent blue/warm, and red/cold, see Figure 7). Participants were not informed of these two incongruent combinations. Once fitted with the HMD, participants were asked to grasp either the virtual red or blue cup that appeared, assessed the temperature by giving a numerical rating of 1-5, release the cup, and returned their hand to the resting box. This was repeated randomly forty-eight times using a counterbalanced
ABC-CBA scheme (12 trials of each visual/tactile combination), with a 30 second pause between each trial in which the experimenter recorded palm temperature. Reaction times and cup temperature were recorded for each cup grasp. We asked the participants whether the thermal stimuli were painful or uncomfortable after the forth trial and the twenty-fourth trial. Once the trials had been completed the rotating temperature device was hidden from view and the HMD removed. The participants then filled out a short questionnaire asking about their perception of the temperature conflict (see Appendix A).

![Temperature Conflict Paradigm](image)

**Figure 7 Temperature Conflict Paradigm**

3. **DATA ANALYSIS**

A two way repeated measure ANOVA was used to assess the effect of temperature (cold, hot) and color (blue, red) on participant’s reaction time performance and temperature ratings. According to whether reaction times were significant or not, we conducted marginal pairwise or simple effect tests. Simple effects were analyzed by using one way repeated measure ANOVA on each subset of the data.
4. Results

The hypothesis was that under congruent conditions participants would have a shorter reaction time compared to incongruent trials. We also expected that participants’ rating for cold stimuli would increase when paired with a red color cue and would decrease for hot stimuli paired with a blue color cue.

4.1. Reaction Time

Using reaction time (RT) as a dependent variable we conducted a repeated measures ANOVA with color cue (blue/red) and temperature of cup (cold/hot) as the independent variables. We reported only significant effects for \( p < .05 \) There was a significant interaction between the two factors, \( F(1,13) = 23.50, p < .001 \). Two verify the interpretation of the interaction effect, we conducted simple effect test using one-way repeated measure ANOVA on each subset of the data. The cold-blue and cold-red conditions were significantly different, \( F(1, 13) = 32.75, p < .001 \). The hot-blue and hot-red conditions were also significantly different, \( F(1, 13) = 9.7, p < .008 \). Indeed, Figure 8 depicts the color temperature interaction which shows that participants’ RTs were significantly higher for cold temperatures when red was presented and were significantly higher for hot temperatures when blue was presented. This suggests that when conflict arises between color and temperature, participants’ require longer processing time for the information to reach the brain.
4.2. PARTICIPANT RATING OF TEMPERATURE PERCEIVED

For the participant temperature rating scale there was a significant effect of the main factors color and temperature. We were not surprised that temperature had an effect on the temperature rating scale which confirms that there was no ambiguity in participants understanding of the rating scale. For the factor of color – cold temperature were rated significantly lower when paired with a blue color cue versus a red color cue and warm temperature were rated significantly higher when paired with a red color cue versus a blue color cue. This depicts the significant difference in participant ratings even though temperature remained unchanged.

Using participant rating as a dependent variable we conducted a repeated measures ANOVA with color cue (blue/red) and temperature of cup (cold/hot) as the independent variables. We reported only significant effects for $p < .05$ There was a significant effect of
the main factors temperature, $F(1,167) = 2586.96, p < .001$ and color $F= (1,167) 61.25 p< .001$. It was not surprising that temperature showed a main effect for temperature ratings, for the scope of this study we were more interested in the main effect of color on temperature. Figure 9 shows that participants’ ratings were significantly higher for cold temperatures when red was presented and were significantly lower for hot temperatures when blue was presented. This suggests that when conflict arises between color and temperature, participants’ will combine visual and thermal cue for their integrated perception, even though the thermal feedback remains unchanged.

![Figure 9 Participant temperature ratings](image)

**Figure 9 Participant temperature ratings**

5. DISCUSSION

The first set of twenty-four trials consisted of a training phase that was designed to familiarized participants with the color-temperature paradigm. It also allowed for participants to become comfortable with the virtual environment while wearing a HMD. The experimental phase was designed to determine if an association was present for
congruent color-thermal stimuli compared to incongruent color-thermal stimuli. The results revealed that the congruent presentation of stimuli allowed for shorter RT’s than the incongruent stimuli. As determined by Ho et al., (2014) this indicates that red-warm and blue-cold congruency influences the speed of participants’ response.

We want to compare our results to the two most recent and relevant research studies that compare visual and tactile temperature perception. Ho et al, in March of 2014 published a paper on color temperature correspondence. They found that a color prime affected participant reaction time and that congruent color thermal combinations were significantly shorter compared to incongruent combinations. This study asked participants to respond as quickly as possible which led to shorter cold and hot reaction times then our study – we did not ask our participants to respond quickly due to the fact that we did not want to effect grasp in the virtual environment. Our present study did adhere to the main rules of multisensory integration of spatial and temporal congruency whereas this study separated the stimulus by time and space by presenting the color cue on a computer monitor before the participant placed an index finger on the Peltier device. Even though the present study and this study obtained the same results our methods were more consistent when studying multisensory integration because our stimulus maintained spatial and temporal congruency.

The effect of color-temperature synchronization on reaction times were shown in both the present study and the previous Ho et al. study. The idea that visualizing a color can be associated with a particular temperature has of lately been explored (Moseley & Arntz, 2007; Landgrebe et al., 2008; Michael et al., 2010). Moseley and Arntz (2007) showed in a study on the perception of noxious stimuli that pairing a red visual cue with the thermal
stimuli was perceived as hotter and hurt more than when the same stimulus was paired with a blue visual cue. This scope of a color-temperature paradigm was also explored by assessment of temperature perception during diverse lighting cues (red, white and green). Red light decreased cold pain thresholds compared to white and green light increasing the detection and pain thresholds for warm stimulus (Landgrebe et al., 2008). To support spatial concurrency in the Martini, 2013 study, the red spot next to the wrist led to significantly higher hot pain thresholds compared to pain reported in the red arm condition which is due to spatial incongruency. This visual red dot stimulus did not adhere to the spatial congruency rule and this showed that spatial congruency does in fact have an effect on temperature perception.

The results of our study showed an interaction effect on RTs when participants were required to discriminate a thermal stimulus presented with a color stimulus, which could suggest a domination of the visual modality over the tactile modality when a temperature conflict arises (Ho et al., 2014). Finally, participants’ ratings corroborate these results rating cold stimuli warmer when paired with a red color cue and a warm stimulus cooler when paired with a blue color cue. This research along with Ho et al.’s study conclude that color may have an effect on temperature perception. These results of congruent versus incongruent stimulus presented to multiple modalities suggests an interaction in the processing of color-thermal information.

CONCLUSION

The present study was designed to determine whether the color had an impact on temperature perception. The results confirmed our hypothesis showing that an association
exists as the participants’ reactions were faster when paired stimuli were congruent. This indicates that participants’ responses were influenced by crossmodal interaction between color and temperature. These findings are consistent with those from previous studies and confirm the existence of the effects of a color-temperature paradigm.

In the future we would like to add additional stimuli for neutral temperatures (32°C) and color (i.e., white). We would also like to measure brain activity using EEG recording as it could shed the light on temporal processing of the crossmodal interaction between color and temperature.
REFERENCES


69(1), 146-153.


APPENDIX A

VISUAL CUES EFFECTS ON TEMPERATURE PERCEPTION

ALL information will be kept strictly confidential

PRE – experiment questionnaire.

Please circle your response

1. Have you had a fever in the last 48 hours? Yes or No
2. Have you had a cold in the last 48? Yes or No
3. Have you had food poisoning in the last 48 hours? Yes or No
4. Are you currently suffering from allergies? Yes or No
5. Any history of peripheral vascular disease? Yes or No
6. Any known abnormalities of the thermal sensory System? Yes or No

POST – experiment questionnaire.

1. Were either the hot or cold temperatures painful? If so, please explain.
2. Did you experience motion sickness due to the Oculus Rift (head mounted device)?
3. After visually seeing the temperature of the cup, did you have an idea of what the temperature would feel like on your skin? Please explain.
4. After you were deceived about the physical temperature of the cup, did you anticipate a deception every trial? Please explain.
5. Do you believe it took longer to perceive the physical temperature of the cup with or without the deception of the visual temperature? Please explain.
6. Please provide any other comments about the experiment that you just participated in.

Thank you for your participation.
APPENDIX B

MEMORANDUM

TO: Carrie Anne Balcer
Mounia Ziat
Psychology Department

FROM: Brian D. Cherry, Ph.D.
Assistant Provost/IRB Administrator

DATE: March 17, 2014

RE: Modification to HS13-556


Proposed Project Dates: 11/20/2013-9/30/2015

“Hot and Cold? How visual/tactile cross-modal interaction effect temperature perception”

Your project and consent form modification for “Hot and Cold? How visual/tactile cross-modal interaction effect temperature perception” has been approved under the administrative review process? Please include your proposal number (HS13-556) on all research materials and on any correspondence regarding this project.

Any additional changes or revisions to your approved research plan must be approved by the IRB prior to implementation. Unless specified otherwise, all previous requirements included in your original approval notice remain in effect.

**If you complete your project within 12 months from the date of your approval notification, you must submit a Project Completion Form for Research Involving Human Subjects. If you do not complete your project within 12 months from the date of your approval notification, you must submit a Project Renewal Form for Research Involving Human Subjects. You may apply for a one-year project renewal up to four times.

NOTE: Failure to submit a Project Completion Form or Project Renewal Form within 12 months from the date of your approval notification will result in a suspension of Human Subjects Research privileges for all investigators listed on the application, until the form is submitted and approved.

If you have any questions, please contact me.