https://doi.org/10.2352/CIC.2023.31.1.10

Color-temperature Cross-modal Association: The Relationships of Hue, Saturation, and Brightness with Temperature

***Weiran Cui*[1,2]*,Sunao Iwaki*[1,2]**
[1] ***University of Tsukuba; Tsukuba, Ibaraki, Japan***
[2] ***National Institute of Advanced Industrial Science and Technology (AIST); Tsukuba, Ibaraki, Japan***

Abstract

The cross-modal association is a specific connection experienced between stimuli, attributes, or perceptual dimensions. Most previous studies related to the cross-modal association of color and temperature use subjective report methods, and the underlying mechanisms behind this association are unclear. This study used the Implicit Association Test (IAT) paradigm combined with event-related potentials (ERPs) elicited by color stimuli to explore the cross-modal association between color, in terms of hue, saturation, and brightness, and temperature. Cross-modal associations between hue and temperature, as well as saturation and temperature were found. There was no evidence for the existence of a brightness-temperature cross-modal association. Additionally, significant differences in the average N1 amplitudes were observed in the hue IAT task. Significant differences in the average N2 and N400 amplitudes were observed in both the hue and saturation IAT tasks, indicating that both corresponding cross-modal associations have a semantic basis to some degree.

Introduction

Vision is among the crucial senses of humans and serves as the primary channel through which humans acquire external information. Visual cues play a vital role as communication tools; they capture attention, provide sensory pleasure and stimulation, and convey product or brand attributes[1].

Colors are fundamental and common visual cues that influence various aspects of human cognition. For example, incorporating additional color cues into visual scenes can aid in the effective processing and storage of images. The relationship between color and temperature is frequently observed in industrial and environmental design[2]. Using color as a cue or indicator to display information about temperature is a common practice. In many countries, faucets are labeled “red” and “blue” to indicate hot and cold water, respectively.

Cross-modal associations are unique connections between stimuli, attributes, or intuitive dimensions experienced by individuals[3]. Research on cross-modal associations between color and temperature, usually overlooks the specific relationship between the three dimensions of color and temperature. Based on the well-established and widely applied Munsell color system, colors can be divided into three dimensions: hue, saturation, and brightness[4]. Most current research, such as the well-known “hue-heat hypothesis,” primarily focuses on the relationship between hue and temperature, which suggests that red light in the visual spectrum or colors are perceived as warmer[3]. However, there is a dearth of research on the relationship between saturation and temperature[5]. Early studies of the relationship between saturation and temperature reveal that people tend to associate “warmth” more strongly with high saturation colors compared to “coolness.”[5] In terms of brightness, some studies suggest that an increase in brightness leads to a perception of colder temperatures[5]. Conversely, studies have found that people associate warm connotations with lighter shades of color[6]. Hence, there is currently no consensus regarding the relationship between saturation, brightness, and temperature. Thus, this study aimed to validate the “hue-heat hypothesis.” Additionally, while controlling for hue consistency, this study investigated the relationships between saturation and brightness with temperature.

Although substantial research has explored the cross- modal association between color and temperature, most studies have relied on subjective measures. These include tasks such as comparing different colors, reporting which appears warmer, or rating the warmth level of different colors[3][6]. Currently, research employing objective experimental methods to explore this topic is lacking, which is a major concern[2]. In this study, we employed an objective behavioral measurement approach using the Implicit Association Test (IAT) paradigm to investigate the cross-modal association between color and temperature. The IAT is designed to assess the strength of associations at the response selection level and can effectively capture automatic evaluative associations[7]. The core of these tasks involves creating compatible and incompatible conditions. Empirical research has demonstrated that participants’ response times in compatible conditions, where associated stimuli share a the same response key, are significantly faster compared to incompatible conditions, where unrelated stimuli share the same response key. By employing precise measurements and controlled experimental setups, IAT enables researchers to provide a more accurate understanding of this cross-modal association.

Finally, existing research on the cross-modal association be- tween color and temperature has predominantly focused on the behavioral level, with limited investigation of its underlying mechanisms. Therefore, this study also aimed to investigate cognitive processing involved in a color-temperature IAT task using Event-Related Potentials (ERPs). Quantitative evaluations provide researchers with more objective and precise delineations of corresponding relationships, thus enhancing the understanding of their cognitive underpinnings. The main components of interest in this study were visual N1, N2, and N400.

Visual N1 is a visually evoked component that occurs between 100-200ms after stimulus onset, and is associated with selective attention and discrimination of stimulus features such as location, color, and motion[8]. Discrimination effects of N1 have been observed in both color-based and form-based discrimination tasks. In this study, selective attention and discrimination effects on stimuli could be inferred to play a role in different tasks if N1 differences were observed in the IAT[9].

The N2 component is commonly used to investigate perceptual processing, and is widely believed to be associated with cognitive control and mismatch. It reached its peak between 200-350ms after stimulus onset, and larger N2 amplitudes are elicited when habitual responses conflict with the required responses in a task, necessitating response inhibition[10]. In the go/no-go paradigm, the N2 amplitude for no-go responses was enhanced because of the need for response inhibition. In the IAT, as the required responses to incompatible tasks contradict habitual cognition, larger N2 amplitudes may be induced.

The N400 component is commonly used in language research, particularly for investigating the semantics of sentences or individual words. When a word is compatible with its context (e.g., I take coffee with cream and sugar), the N400 amplitude appears to be smaller. When an encountered word deviates from expectations and deviates from its original context (e.g., I take coffee with cream and dog), larger N400 amplitudes are observed[11]. In the IAT task, N400 amplitudes may be enhanced in incompatible tasks.

Method

Participants

Participants were recruited from the University of Tsukuba. 22 Chinese students participated in this experiment, comprising 11 males and 11 females aged between 20 and 35 (25.82 ± 3.42). All participants had normal or corrected-to-normal vision. The Ishihara test was administered to screen the participants for color vision deficiency prior to the experiment. One male and one female were excluded from the analysis because of a color vision deficiency and inability to complete the experiment, respectively. All participants provided informed consent in compliance with the research protocol approved by the Institutional Review Board of the National Institute of Advanced Industrial Science and Technology (AIST).

IAT materials

The experiment used two types of stimuli: color patches and words. The words included those representing higher temperatures, such as "warm" and "hot," as well as words representing lower temperatures, such as "cool" and "cold."

For the color-patch stimuli, the basic color patches included red, orange, blue, and green, which were used in the hue and temperature IAT paradigms. To ensure that the modified color patches, after manipulating saturation and brightness, still belonged to the same perceptual color category as the original color patches (e.g., a desaturated red after manipulation remaining in the red category) and to prevent them from becoming different color categories (e.g., a blue color becoming light purple after manipulation), the saturation and brightness of the basic color patches were intentionally made to be inconsistent. However, long- and short-wavelength colors could still be clearly distinguished. Therefore, in this study, these basic color patches were considered suitable stimuli for different hues. Darker red, orange, blue, and green patches were obtained by reducing the brightness of the basic color patches by half. The adjusted and original color patches were used in the brightness-temperature IAT experiment. Similarly, low-saturation versions of the red, orange, blue, and green patches were obtained by reducing the saturation of the basic color patches by half. These four color patches, along with the original color patches, also served as color stimuli in the brightness- temperature IAT experiment (Figure 1).

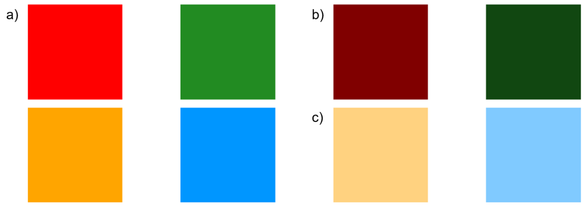

Figure 1. Materials for the IAT task. a) Examples of the hue IAT task. b) Examples of the brightness IAT task. c)Examples of the saturation IAT task.

Experimental Setup

The experimental stimuli were presented on a 24-inch monitor with a display resolution of 1980 × 1080 pixels. The distance between the participants and the monitor was fixed at 50 cm. The experiment lasted for three months, from the end of February to May in 2023. The room temperature was maintained at a normal temperature. The lights were turned off, and the blinds were closed during the experiment to prevent the influence of lighting on color perception.

Procedures

The IAT procedure used in this study was similar to the classic IAT paradigm proposed by Greenwald et al. in 1998. Participants initially performed matching tasks between color and response keys, followed by matching tasks between words and response keys. Each matching task consisted of five blocks with four trials per block, resulting in 20 trials for each task. After completing the matching tasks, participants engaged in practice and test trials for the first association task. During the practice phase, participants completed three blocks with eight trials per block for a total of 24 practice trials. During the testing phase, participants completed 20 blocks of tests with eight trials per block, resulting in 160 trials under the hue condition. As the saturation and brightness conditions consisted of two separate experimental procedures for long- and short-wavelength colors, participants completed 10 blocks of tests during the testing phase, totaling 80 trials. Both procedures combined totaled 160 trials. After completing the first task, participants learned the response keys associated with the reversed color and subsequently proceeded to practice and test trials for the second association task. The IAT hue task lasted 15 minutes, whereas the saturation and brightness tasks lasted 10 minutes. Participants were provided with a 3–5 min break between different task conditions.

In the compatible condition, long-wavelength, bright, and high-saturation colors were associated with the response keys for warm words, while short-wavelength, dark, and low-saturation colors were associated with the response keys for cold words. In the incompatible condition, long- wavelength, bright, and high-saturation colors were associated with the response keys for cold words, while short- wavelength, dark, and low-saturation colors were as- sociated with the response keys for warm words. The order of the compatible and incompatible tasks was counterbalanced across participants. Additionally, the order of the hue, saturation, and brightness experiments was counterbalanced across participants.

ERP assessment

The Brain Products Standard 62Ch actiCAP snap was used to collect EEG data. Scalp electrodes were placed according to the extended 10-20 system montage standard. The data were sampled at a rate of 1kHz, resulting in the acquisition of data from 64 chan- nels, including four channels for the EOG. The default channel (FPz) served as the ground electrode, and the online reference electrode was positioned on the participant's nose. During the data collection process, the impedance of all electrodes was reduced to below 25 kΩ.

Segments severely contaminated by muscle and eye artifacts were manu- ally removed during data preprocessing. Low-pass and high-pass filtering were applied to remove noise below 0.5 Hz and above 30 Hz, respectively, and eliminate certain artifacts. Subsequently, re-referencing was performed using the mastoid electrodes (M1 and M2)[15]. Independent component analysis (ICA) was applied to decompose EEG signals into multiple independent components, removing artifacts caused by eye and body movements[16]. Finally, stimulus-locked epochs were extracted from 200ms before stimulus onset to 1500ms after stimulus onset, and baseline correction was performed from 200ms to 0ms. The components of interest were quantified by averaging the amplitudes within specific time windows following stimulus presentation. Specifically, the N1, N2, and N400 time windows ranged from 110ms to 170ms, 240ms to 370ms, and 400ms to 520ms, respectively [17].

Result

IAT

When the stimuli differed in hue, the participants' accuracy rate in the compatible task was 96.38%, whereas it was 86.13% in the incompatible task. When the stimuli differed in saturation, the accuracy rate for the compatible task was 95.51%, whereas it was 86.60% for the incompatible task. When the stimuli differed in brightness, the accuracy rate for the compatible task was 94.78%, whereas it was 91.03% for the incompatible task.

A repeated-measures analysis of variance (ANOVA) was conducted on the reaction times of the participants with a 2 (compatibility: compatible, incompatible) × 3 (dimension: hue, saturation, brightness) design(Figure 2). The results revealed a significant main effect of task compatibility, $F(1, 19) = 67.91$, $p < 0.001$. Participants displayed significantly faster reaction times in the compatible task ($M = 690.82 \pm 7.70$ms) compared to the incompatible task ($M = 703.91 \pm 10.97$ms).

A significant interaction effect of reaction times (RTs) between compatibility and dimensions, $F(2, 38) = 11.74$, $p<0.001$ was found. Post-hoc tests revealed a significant IAT effect under the hue and saturation conditions. Reaction times in the compatible task ($M = 651.63 \pm 6.83$ms) were significantly shorter than those in the incompatible task ($M = 804.70 \pm 10.13$ms) when stimuli differed in hue. Similarly, reaction times in the compatible task ($M = 695.65 \pm 7.52$ms) were significantly shorter than those in the incompatible task ($M = 818.31 \pm 12.87$ms) when stimuli differed in saturation.

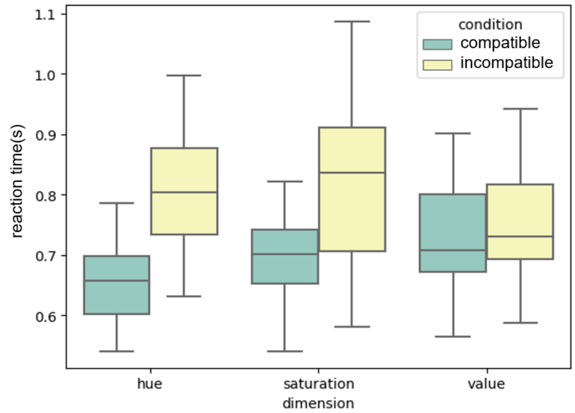

Figure 2. *Reaction times for the compatible and incompatible tasks.*

ERP

Based on the behavioral data, an IAT effect was observed under the hue and saturation conditions, whereas no significant difference in reaction times between the compatible and incompatible tasks was observed under the brightness condition. Therefore, only the differences in the N1, N2, and N400 amplitudes under the hue and saturation conditions were analyzed. The results of the normality test indicated that the data did not meet the criteria for a normal distribution. Therefore, the Wilcoxon rank-sum test was employed to analyze the differences in amplitude across the Fz, FCz, Cz, CPz, Pz, and Oz electrode locations as well as the differences in amplitude between different locations (Figure 3). The average ERP waveforms are shown in Figure 4, depicting the brainwave patterns recorded at the Fz, FCz, and Cz electrodes during the compatible (solid line) and incompatible (dashed line) condition tasks.

N1. Significant differences in N1 amplitudes were observed between the compatible and incompatible tasks under different hue conditions (Wilcoxon statistic = 2357, $p<0.01$). The compatible task elicited larger N1 amplitudes than the incompatible task. Further analysis of compatibility differences across different sites revealed a significant difference at Cz (Wilcoxon statistic = 46, $p<0.05$), indicating larger N1 amplitudes during the compatible task. However, no significant N1 amplitude differences were observed under different saturation conditions due to task compatibility.

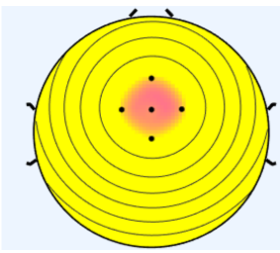

Figure 3. *The middle column, from top to bottom, represents Fz, FCz, Cz.*

N2. Significant differences in amplitude were observed between the compatible and incompatible tasks when the color stimuli varied in hue (Wilcoxon statistic = 2071, p<0.001). The incompatible task elicited larger N2 amplitudes than the compatible task. Analysis of compatibility differences across sites revealed significant amplitude differences at FCz (Wilcoxon statistic = 46, p<0.05) and Cz (Wilcoxon statistic = 46, p<0.05), indicating that compatibility induced significant amplitude differences, with the incompatible task eliciting larger N2 amplitudes than the compatible task.

A significant main effect of task compatibility was observed when the color stimuli varied in saturation (Wilcoxon statistic = 1515, p<0.001). The incompatible task elicited larger N2 amplitudes than the compatible task. Analysis of the amplitude differences across sites revealed significant differences in Fz (Wilcoxon statistic = 36, p<0.05), FCz (Wilcoxon statistic = 34, p<0.05), Cz (Wilcoxon statistic = 36, p<0.05), and CPz (Wilcoxon statistic = 38, p<0.05). The incompatible task elicited larger N2 amplitudes at all sites.

N400. A significant main effect of task compatibility was observed under different hue conditions (Wilcoxon statistic = 2570, p<0.05). The incompatible task elicited higher N400 amplitudes. However, site analysis did not reveal any significant differences in N400 amplitudes induced by task compatibility. A significant main effect of task compatibility was found under different color saturation conditions (Wilcoxon statistic = 1710, p<0.001). The incompatible task elicited larger N400 amplitudes than the compatible task. Significant amplitude differences were observed at the Fz location for compatibility-induced effects (Wilcoxon statistic = 43, p<0.05), with the incompatible task inducing larger N400 amplitudes.

Discussion

This study used the IAT paradigm to investigate the cross-modal associations between hue, saturation, brightness, and temperature, and elucidate the cognitive processes underlying these associations. The results revealed a significant cross-modal association between hue and temperature, and between saturation and temperature. Colors with higher saturation were perceived as warmer, whereas colors with lower saturation were perceived as colder. These findings supplement prior studies on the cross-modal association between saturation and temperature, and address some limitations of the existing literature. No cross-modal association was observed between brightness and temperature, and participants did not show a tendency to associate brighter colors with warmer or colder temperatures.

Hue-temperature cross-modal association

Participants in the hue-temperature IAT experiment demonstrated a tendency to associate longer-wavelength colors with warm words, consistent with prior research. This finding aligns with the "hue-heat hypothesis," which suggests that colors or light wavelengths primarily located towards the red end of the visual spectrum tend to be perceived as warmer, while those primarily located towards the blue end are perceived as colder[12].

Ho et al. conducted a study on the association between hue and temperature using the IAT paradigm and reported that participants showed significantly faster response times for the pairing of "red-warm, blue-cold" compared to "red-cold, blue-warm." This finding indicates that the hue-heat hypothesis holds true at the response selection level, with response times being influenced by the color-temperature correspondence in color or heat stimuli[2]. Albers et al. investigated the practical application of the color-temperature hypothesis by studying the effects of different colors of ambient lighting in a simulated aircraft cabin. The results revealed that individuals perceived the cli- mate as warmer and reported a greater sense of comfort in terms of temperature under yellow lighting. This effect was found to directly or in- directly influence overall satisfaction with the climate through a psychological warming mechanism[13].

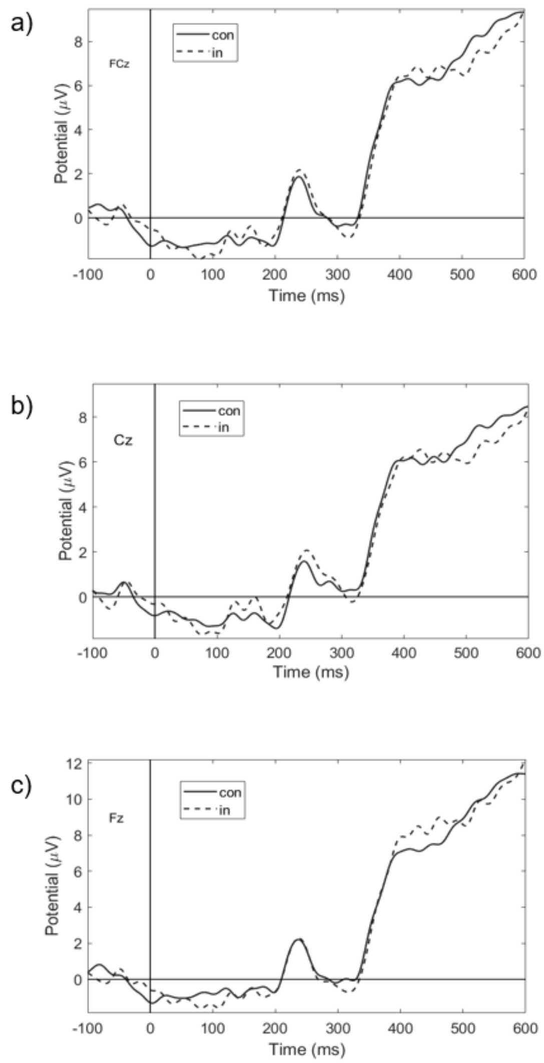

Figure 4. *Waveforms of a) FCz under the hue condition, b) Cz under the hue condition, and c) Fz under the saturation condition. The Compatible task is abbreviated as "con", and the incompatible task is abbreviated as "in".*

The ERP results of the color-temperature IAT experiment revealed that tasks consistent with the color-temperature hypothesis elicited larger N1, smaller N2, and smaller N400 amplitudes. The N1 amplitude represents a mechanism of gaining sensory control. Increasing attentional focus on a specific region of the visual field can enhance N1 amplitude, facilitating the processing of relevant perceptual information within that region[8]. The larger N1 amplitude elicited by compatible tasks suggests that the hue-temperature association consistent with individual cognitive habits automatically captures more attention, and this unconscious allocation of attention simultaneously promotes the response to target stimuli.

The N2 amplitude is crucial for revealing the cognitive processes related to cognitive control, response conflict, and response inhibition[10]. In this study, the larger N2 amplitude elicited by incompatible tasks suggests a perceptual conflict between associations such as "red-cold, blue-warm," and those typically recognized by individuals. During responses, inhibition is required to suppress the habitual association of long-wavelength colors with warmth and short-wavelength colors with cold. This indicates that the association between long-wavelength colors and warmth is dominant in general cognition and exhibits a certain degree of stability.

The N400 amplitude has been widely applied in studies of semantic consistency. In this study, the larger N400 amplitude elicited by incompatible tasks reflects the semantic inconsistency in the association between "red-cold, blue-warm." This suggests that the association between hue and temperature is moderated by semantics to some extent. Individuals may internalize this association through long-term experience and connect it through semantics, permitting bottom-up unconscious processing of the association between "red-warm, blue-cold."

Saturation-temperature cross-modal association

Participants in the IAT experiment of saturation and temperature demonstrated a tendency to associate high saturation with warmth and low saturation with cold. To the best of our knowledge, this is the first study to investigate the association between saturation and temperature using objective measures, and the results are largely consistent with the findings of prior research. Collins used color images with the same hue but different saturation levels as stimuli and asked participants to assign meanings to these "saturated" and "weak" colors. Among them, 83% attributed "warm" to "saturated" colors, while 53% attributed "cold" to "weak" colors[5].

According to the ERP analysis, the incompatible tasks (high saturation-cold, low saturation-warm) elicited larger N2 and N400 amplitudes. The difference in N2 amplitudes suggests that participants perceive the association of "high saturation" with "cold" as inconsistent with their preexisting associations, eliciting a larger N2 amplitude that inhibits their habitual response. This indicates that the association between "high saturation-warm, low saturation-cold" is more consistent with the general cognition of individuals, and is relatively stable. The larger N400 amplitude elicited by the incompatible task can partly indicate a semantic inconsistency between "high saturation-cold, low saturation-warm". This finding suggests that the cross-modal association between saturation and temperature is influenced, at least to some extent, by semantic relatedness.

Brightness-temperature cross-modal association

The IAT experiment on brightness and temperature did not yield any significant results, as participants did not show a tendency to associate "bright color-warm, dark color-cold" or "bright color-cold, dark color-warm." However, the findings of studies investigating the relationship between brightness and temperature have been inconsistent. Ross's research findings indicate no relationship between brightness and warmth in the blue region; however, in the red region, a correlation between low brightness and warmth was observed. Newhall reported that participants perceived darker colors as warmer and lighter colors as colder[5]. Additionally, Motokia et al.'s study revealed that individuals tend to more strongly associate warm words with light colors compared to cold words, demonstrating a stronger connection between warm words and light colors[6].

There may be two reasons for these inconsistent results. On one hand, there could be substantial individual differences in the association between brightness and warmth. However, variations in the experimental materials used may have contributed to these discrepancies. Some studies have solely employed colored words as stimuli. Even when using color stimuli, differences between colors themselves may influence the perceived warmth induced by brightness.

Accounts for hue, saturation-temperature cross-modal association

There are four main explanations for the cross-modal association between color and temperature[3]. First, cross-modal associations may result from the internalization of natural statistics in the environment, possibly based on the coupling of prior beliefs, according to Bayesian decision theory. The second explanation lies in the neural basis, which suggests a common neural encoding of stimulus dimensions. The third explanation involves a linguistic approach, suggesting that the use of similar adjectives to describe different aspects of sensory experiences may serve as the basis for certain cross-modal associations or enhance these associations. The fourth explanation relates to emotional mediation, proposing that people may match stimuli based on shared or elicited emotions, or affective associations.

The cross-modal association between hue and temperature may be explained by the internalization of natural statistics from the environment, where the metaphoric representations of "red-warm" and "blue-cold" are pervasive. For instance, flames are typically red, whereas icebergs are depicted in blue or white. Morgan's research on age differences in color-temperature associations revealed that the conventional association (e.g. hot-red, cold-blue) became random from the 18-year-old groups to 6-year-old groups. Based on these findings, the link between temperature and color may be based on cultural norms gradually acquired during late childhood and adolescence[18]. Additionally, the observed differences in N400 amplitudes in this study support the linguistic approach, suggesting that consistency between long-wavelength colors and the meaning of warmth may reinforce this cross-modal association to some extent.

This study also supports the linguistic approach to the cross-modal association between saturation and temperature. The semantic similarity between high saturation and warm words, as well as between low saturation and cold words, may facilitate the cross-modal association between saturation and temperature. Studies on color and emotion suggest that highly saturated colors are more vivid, evoke greater pleasure, and have higher arousal and valence[14]. Generally, warmth is associated with increased comfort and a positive mood. The shared emotional arousal between these two factors partially explains the widespread and stable association between high saturation and warmth.

Future direction

While this study addresses some of the limitations of prior research on cross-modal associations between color and temperature, particularly regarding the associations of saturation and brightness with temperature and the cognitive processes underlying these cross-modal associations, many unresolved issues need further investigation. The neural underpinnings of cross-modal associations between color and temperature remain unclear. Although emotional mediation can partly account for cross-modal associations between color and temperature, further research is needed to substantiate this claim. Furthermore, the cross-modal associations between saturation and brightness may be modulated by hue, as evidenced by the varying strengths and directions of the cross-modal associations between long- and short-wavelength colors. Future research is expected to investigate the moderating role of hue.

Conclusion

This study examined the cross-modal associations of hue, saturation, and brightness with temperature. Significant cross-modal associations between hue and temperature were found, with long-wavelength colors associated with warmth and short-wavelength colors associated with cold. Robust cross-modal associations between saturation and temperature were also found, with a highly saturated color associated with warmth and a low-saturated color associated with cold. To some extent, both cross-modal associations have a semantic basis. These findings confirm the previous hue-heat hypothesis,and provide new perspectives on saturation-temperature associations in both behavioral and neural level. However, no cross-modal associations between brightness and temperature were observed, as the participants did not tend to associate light colors with warmth or cold.

References

[1] Vermeir, Iris & Roose, Gudrun, Visual design cues impacting food choice: A review and future research agenda, Foods, 9, 10(2020).

[2] Ho, Hsin-Ni, Van Doorn et al., Colour-temperature correspondences: when reactions to thermal stimuli are influenced by colour, PloS one, 9, 3(2014).

[3] Spence, Charles, Temperature-based crossmodal correspondences: Causes and consequences, Multisensory Research, 33, 6(2020).

[4] Kuehni, Rolf G, The early development of the Munsell system, Color Research & Application: Endorsed by Inter-Society Color Council, The Colour Group (Great Britain), Canadian Society for Color, Color Science Association of Japan, Dutch Society for the Study of Color, The Swedish Colour Centre Foundation, Colour Society of Australia, Centre Français de la Couleur, 27, 1(2002).

[5] Wright, Benjamin, The influence of hue, lightness, and saturation on apparent warmth and weight, The American Journal of Psychology, 75, 2(1962).

[6] Motoki, Kosuke, Saito et al., Light colors and comfortable warmth: Crossmodal correspondences between thermal sensations and color lightness influence consumer behavior, Food quality and preference, 72(2019).

[7] Greenwald, Anthony G, McGhee etal., Measuring individual differences in implicit cognition: the implicit association test, Journal of personality and social psychology, 74, 6(1998).

[8] Luck, Steven J, Woodman et al., Event-related potential studies of attention, Trends in cognitive sciences, 4, 11(2000).

[9] Vogel, Edward K, Luck et al., The visual N1 component as an index of a discrimination process, Psychophysiology, 37, 2(2000).

[10] Folstein, Jonathan R, Van Petten et al., Influence of cognitive control and mismatch on the N2 component of the ERP: a review, Psychophysiology, 45, 1(2008).

[11] Kutas, Marta, Hillyard et al., Reading senseless sentences: Brain potentials reflect semantic incongruity, Science, 207, 4427(1980).

[12] Wang, Haiying, Liu et al., Experimental investigation about thermal effect of colour on thermal sensation and comfort, Energy and Buildings, 173, (2018).

[13] Albers, Frank, Maier et al., In search of evidence for the hue-heat hypothesis in the aircraft cabin, Lighting Research & Technology, 47, 4(2015).

[14] Wilms, Lisa, Oberfeld et al., Color and emotion: effects of hue, saturation, and brightness, Psychological research, 82, 5(2018).

[15] Delorme, Arnaud, Makeig et al., EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis, Journal of neuroscience methods, 134, 1(2004)

[16] Chaumon, Maximilien, Bishop et al., A practical guide to the selection of independent components of the electroencephalogram for artifact correction, Journal of neuroscience methods, 250, (2015)

[17] Williams, John K, Themanson et al., Neural correlates of the implicit association test: evidence for semantic and emotional processing, Social Cognitive and Affective Neuroscience, 6, 4(2011)

[18] Morgan, George A, Goodson et al., Age differences in the associations between felt temperatures and color choices, The American Journal of Psychology, (1975)

Weiran Cui is a graduate student pursuing a Master's degree in Design at the University of Tsukuba, Graduate School of Comprehensive Human Sciences (2023). Her research focuses on cross-modal associations and their possible application in design.

Sunao Iwaki received his Ph.D. from the University of Tokyo in 1998. Since 1998, he has been a research scientist at National Institute of Advanced Industrial Science and Technology (AIST), where his work involves the development of multimodal neuroimaging techniques. He is the Deputy Director at the Human Information and Interaction Research Institute, AIST, and is a Professor at the University of Tsukuba. Dr. Iwaki is a member of IEEE BME Society, Society for Neuroscience, and Organization for Human Brain Mapping.