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RESEARCH ARTICLE

Chemical Approach to the Thermal Grill Illusion

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Ethics Committee of the University of Electro-Communications, Japan.

ABSTRACT This study proposes a novel approach to elicit the thermal grill illusion (TGI)–a phenomenon characterized by the concurrent application of hot and cold stimuli to the skin that causes sensations of pain and burning. Contrary to conventional techniques that manipulate heat physically through Peltier elements or water, our method employs chemicals, namely, capsaicin and menthol, to activate transient receptor potential ion channels. This approach perceptually conveys hot and cold sensations and synergistically induces TGI. Notably, the proposed technique offers both energy efficiency and compactness, enhancing its suitability for practical applications. We conducted three experiments to validate the effectiveness of the proposed technique. Experiment 1 aimed to ascertain the feasibility of inducing TGI by contrasting sensations produced individually and collectively by each chemical, targeting to elicit both hot and cold sensations. Experiment 2 focused on exploring the impact of temporal disparities in the application of chemicals inducing hot and cold sensations on TGI induction. Experiment 3 investigated the correlation between the positioning of stimulus sites, delivering warmth and cold sensations, and the intensity of the resultant TGI. The findings demonstrate that adjacent applications of capsaicin and menthol can successfully generate TGI. Moreover, the intensity of TGI can be modulated by varying the time interval between the applications of these two chemicals and altering the locations of the stimuli. Specifically, a more pronounced TGI was achieved by applying capsaicin on the proximal side and menthol on the distal side of the forearm. These results hold promise for practical implementations, particularly in developing itch-suppressing patches.

INDEX TERMS Chemical haptics, thermal grill illusion, virtual reality.

I. INTRODUCTION

Thermal grill illusion (TGI) phenomenon involves the concurrent application of warm and cold stimuli to the skin, eliciting sensations of burning and pain [1], [2], [3]. This phenomenon facilitates the induction of pain sensations through non-damaging temperature stimuli [4], [5] and finds applications in simulating pain within virtual reality environments [6], as well as in suppressing itch [7]. TGI is known to induce a burning pain sensation as well as a sensation similar to cold freezing pain [4], [8].

Traditionally, the generation of TGI has employed Peltier elements [9], [10], heat lamps, and ultrasound [11]. These methods, however, are constrained by their substantial energy demands and bulky equipment. An alternative perceptual method to these physical approaches involves the application of chemicals to the skin [12], [13], [14]. Capsaicin is an extract from chili pepper, which triggers a sensation of heat through the activation of the TRPV-1 channel [15], whereas menthol, obtained from mint, produces a sensation of coolness via the TRPM-8 channel [16] This chemical methodology facilitates the conveyance of temperature sensations through topical application.

The objective of this research is to induce TGI without actual heat, using chemicals for a more energy-efficient and compact approach to pain induction. This study focuses on the subjective evaluation of pain and thermal sensations elicited by capsaicin and menthol to explore the chemical

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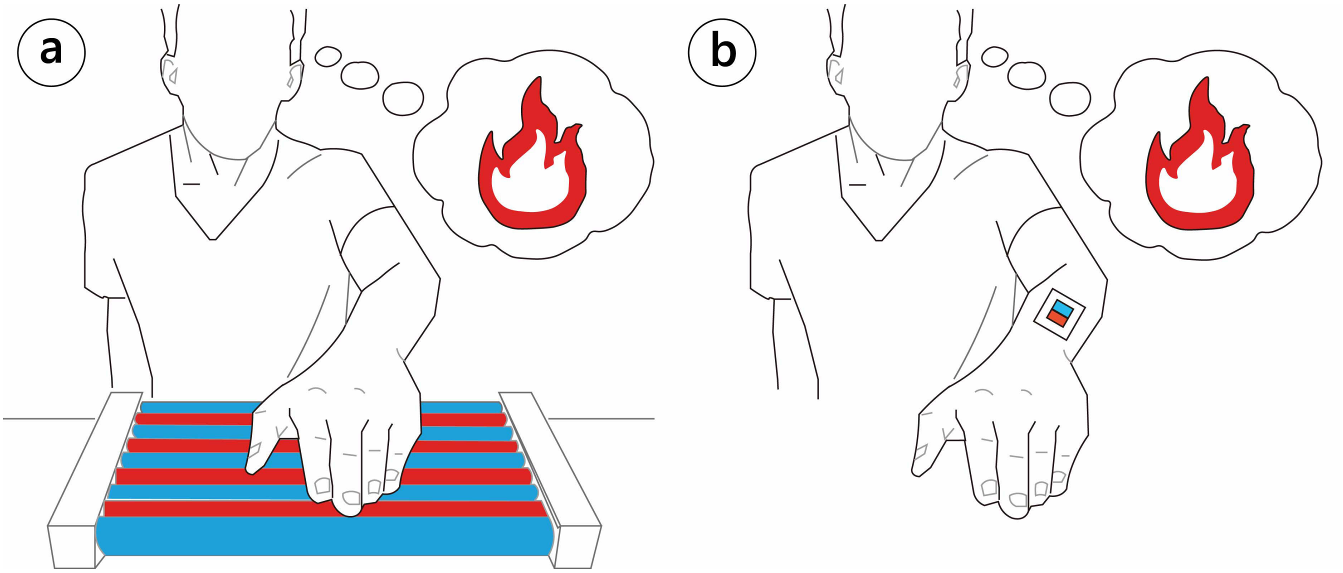

FIGURE 1. Research concepts. (a) Schematic showing how conventional TGI presentation methods involve bulky devices that are energy consuming. (b) Schematic of the proposed method using chemicals to present TGI, making it compact and energy-saving.

induction of TGI. Additionally, the effectiveness of this method was assessed by considering the timing and placement of chemical applications.

This study represents an extension and revision of the version presented at the IEEE Haptics Symposium in 2022 [17]. A preceding study [17] investigated the conditions necessary for chemically induced TGI, but it did not adequately address a critical element: "placement." Generally, TGI generation has prioritized increasing the thermal differential, overlooking the significance of placement owing to the physical limitations of Peltier elements. In contrast, chemical-based TGI enables effortless manipulation of stimulus placement, potentially leading to more effective TGI elicitation. Consequently, this research explores a method to enhance TGI by strategically altering the configuration of chemically infused gauze. The inclusion of these additional placement-centered experiments was aimed at examining new aspects of TGI, thereby offering a more sophisticated approach.

II. RELATED WORK

The purpose of this research was to create a TGI using chemicals for temperature sensation. We also evaluated the effectiveness of this approach by modifying the placement of the stimuli to change the perception of the TGI. This section describes the common presentation of temperatures for TGI induction, perceptual variations in TGI, and advances in tactile presentations using chemicals.

A. THERMAL PRESENTATION METHOD USED TO GENERATE TGI

The objective of this research was to generate the TGI using chemicals to create temperature sensations. Additionally, this study assessed the impact of altering the placement of stimuli on the perception of TGI. This section describes the standard practices in temperature presentation for TGI induction, explores perceptual variations in TGI, and discusses advancements in tactile presentations facilitated by chemical use.

Conventional physical methods for temperature presentation such as Peltier elements are prevalent in representing TGI. These elements are capable of both heating and cooling, and their silent operation has contributed to their extensive application in TGI displays and other thermally interactive systems [18], [19]. However, these devices pose certain limitations such as significant power consumption and the tendency for heat accumulation within the device during prolonged use, complicating the cooling of actuators after extended operation.

In contrast, water-based temperature presentation systems, which allow for the adjustment of water temperature, maintain nearly constant temperatures over extended periods owing to the high specific heat of water. Harper et al. demonstrated a TGI model utilizing a plastic tube through which water was circulated within a copper tube [20]. Although this system can cover larger skin areas and provide precise temperature control, the flexibility of the water tubing often results in bulky equipment.

An alternative approach by Nakajima et al. involved a non-contact TGI presentation using remote thermal manipulation. This method employed halogen lamps for heating and ultrasonic phased arrays for cooling via vaporization of a water mist [11]. Although innovative, this system is constrained by its substantial size, fixed application points, and limited range of presentation.

Our chemical-based approach for temperature presentation addresses these limitations. It directly stimulates receptors upon application, thereby obviating the need for actual thermal changes. This method offers an energy-efficient, miniaturized alternative for TGI induction, overcoming the challenges posed by traditional physical temperature presentation methods.

B. PERCEIVED CHANGES IN TGI

The TGI is characterized by two fundamental attributes. First, it creates a contrast in temperatures. Second, it involves placing heat and coolness next to each other. Extensive research has been conducted to explore the correlation between temperature disparities and TGI perception [2], [21]. Studies have revealed that the intensity of the burning sensation and pain escalates with an increase in the temperature difference between alternating hot and cold stimuli [22].

For instance, Leung et al. demonstrated that a lower temperature differential (22/38 °C and 24/36 °C) was perceived as TGI by only approximately 20 % of participants, whereas a more pronounced temperature difference (18/42 °C and 20/40 °C) elicited TGI in approximately 70 % of participants [23]. To chemically replicate this heightened temperature difference on the skin, the concentration of the chemical agents needs to be increased [24], [25], [26]. However, higher concentrations could potentially harm the skin and induce pain.

In this context, Experiment 3 focused on another pivotal aspect of TGI: placement. TGIs are typically produced by applying adjacent warm or cold stimuli. The majority of TGI studies have focused on a single series of stimuli applied to the forearm. For example, Lam et al. discovered that a pronounced TGI was generated by heating the ends of three bars while cooling the central bar [27]. Nonetheless, variations in the number of rods in a row (2–6) and the spacing between them (1–10 mm) were observed to pose negligible impact on TGI perception [28]. To date, the precise placement of hot and cold stimuli necessary to induce a robust TGI response remains to be conclusively determined.

C. CHEMICAL HAPTICS

Recent advancements in tactile presentation have been achieved using chemicals. The advantages of this method include its operation without the need for energy and its long-lasting effect. Brooks et al. demonstrated the induction of thermal sensations via the nasal administration of capsaicin and eucalyptol [13]. In a similar vein, Lu et al. utilized various chemicals including sanshool, cinnamaldehyde, and lidocaine to induce sensations such as tingling, stinging, and numbing in virtual reality environments [12]. This burgeoning field is known as "Chemical Haptics."

Further research has explored the combined effects of chemical and physical thermal stimuli. Jiang et al. [14] developed a method for pain induction through the cutaneous application of capsaicin, which was then modulated by thermal input using a Peltier device at the same site. This approach verified that heat stimulation augmented pain, while cold stimuli reduced it. However, these stimuli were localized at the same site, thus not resulting in TGI. Schaldemose et al. [29] investigated the modulation of perceived thermal thresholds and the consequent TGI when a physical temperature was applied directly to skin sensitized with capsaicin. Nonetheless, the temperature sensation was not solely induced by the chemicals. Previously, Chemical Haptics predominantly employed a single chemical for sensory feedback. This study expands upon this by using multiple chemicals to create novel sensory experiences.

III. EXPERIMENTS AND RESULTS

This study involved three experiments. Experiment 1 focused on combinations of chemicals, Experiment 2 investigated the effects of time differences, and Experiment 3 examined the influence of stimulus placement.

All experiments received approval from the Ethics Committee of the University of Electro-Communications, Japan (No. 21034).

A. EXPERIMENT 1: INVESTIGATION OF THE CONDITIONS UNDER WHICH TGI OCCURS

This experiment aimed to determine the specific conditions under which the TGI is elicited using chemicals. This procedure involved a comparative analysis of temperature perception and pain responses elicited by individual applications of capsaicin and menthol, a combined solution of both chemicals, and their adjacent applications.

1) CONDITIONS

The stimulus conditions were executed in four different configurations: a menthol solution alone (labeled as Menthol), a capsaicin solution alone (labeled as Capsaicin), a mixed solution of capsaicin and menthol (labeled as Mix), and adjacent applications of capsaicin and menthol (labeled as Adjacent), as shown in Fig. 2.

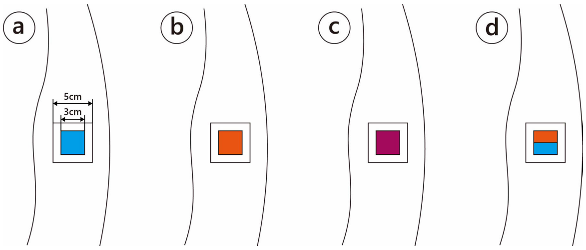

FIGURE 2. **Conditions for experiment 1.**

The experiments commenced with isolated applications of capsaicin and menthol on day 1, followed by experiments with mixed solutions and adjacent conditions on day 2. Upon application of capsaicin and menthol, a delay of several minutes was noted before sensation onset. We hypothesized that concurrent temperature changes are essential for TGI occurrence. Accordingly, capsaicin and menthol were administered to participants with a time delay, calibrated based on the first day's findings to closely match the onset of sensation.

2) PROCEDURE

The study involved ten participants–nine males and one female, aged between 21 and 26 years. The experiment was

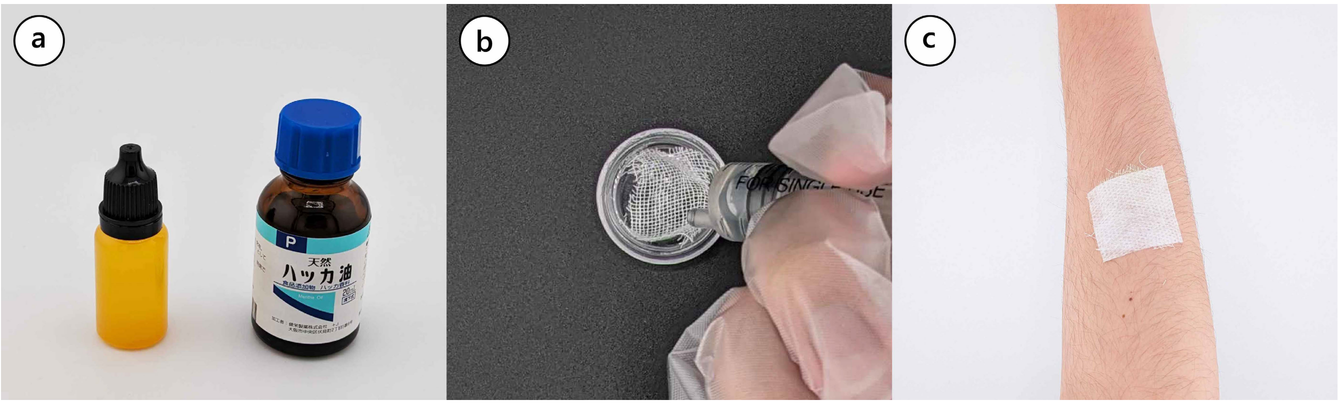

FIGURE 3. Actual system: (a) Used chemicals: capsaicin in the yellow bottle on the left, menthol in the brown bottle on the right. (b) The process of soaking a piece of gauze with chemicals. (c) Gauze applied to the participant's forearm, covered with a patch of adhesive bandage.

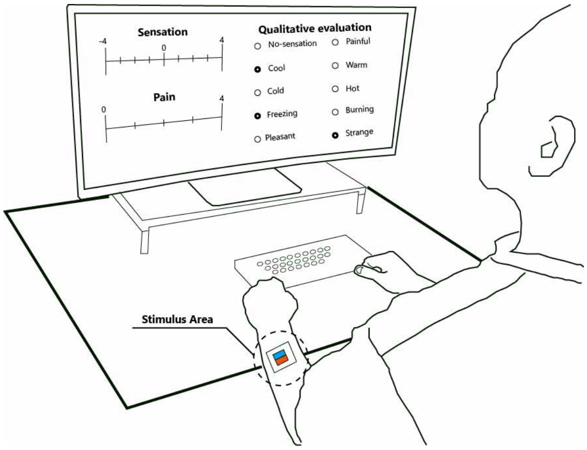

FIGURE 4. Schematic of a participant with the chemical applied to the lateral (dorsal) middle of the forearm undergoing stimulations.

conducted on two separate days, and the two conditions were measured daily in random stimulus order.

For the experiment, menthol oil (Kenei Pharmaceutical, menthol concentration 30 %) and a 5 % concentration capsaicin solution dissolved in 70 % ethanol in purified water were utilized (Fig. 3 (a)). These solutions were absorbed into a 3 cm square gauze (Fig. 3 (b)) and applied to the skin, as illustrated in Fig. 4. A 5 cm square adhesive bandage was used to cover the gauze, preventing it from drying and detaching from the skin during the experiment ((Fig. 3 (c))). The areas for warm and cold stimuli were maintained equal.

Participants applied the chemical to the lateral (dorsal) middle of the forearm and underwent stimulation for 30 minutes per condition. Every minute, they rated their temperature sensation on a 9-point Likert scale ranging from +4 (indicating "extremely hot") to -4 (indicating "extremely cold"), and their pain sensation on a 5-point Likert scale from 0 (representing "no pain") to 4 (representing "extremely painful"). Additionally, they qualitatively assessed their sensations upon solution application using 10 sensory descriptors: "no sensation," "cold," "cool," "hot," "warm," "burning," "freezing," "pleasant," "strange," and "painful."

3) RESULTS

Fig. 5 presents the outcomes of Experiment 1, employing a Likert scale with the vertical axis ranging from -4 to $+4$. This configuration restricted the depiction of pain scores to the graph's upper half. The menthol condition consistently exhibited low pain levels with minimal fluctuations, whereas the temperature perception diminished steadily. These findings underscore the effectiveness of menthol as a cooling agent without inducing pain. In contrast, the capsaicin treatment consistently escalated both pain and heat sensations, implying that capsaicin induces pain and creates a sensation of heat, with the pain sensation being more pronounced than the heat sensation. These outcomes align with those reported in previous studies [24], [25], [26].

The effects of the mixed and adjacent conditions, anticipated to induce TGI, were similar to those observed in the menthol and capsaicin conditions. Notably, the general trends for the adjacent and capsaicin-treated conditions were similar, although certain differences were observed in the initial half of the time series. Each condition was investigated with a focus on time.

Fig.6 displays the results recorded at 5 and 10 min after application, with error bars representing unbiased variances. The Friedman test revealed significant main effects for temperature sensation based on application conditions (After 5 min of application: $\chi^2 = 9.9474$, $p < 0.05$; After 10 min of application: $\chi^2 = 8.9333$, $p < 0.05$). Pain exhibited similar trends (5 min post-application: $\chi^2 = 5.55$, n.s.; 10 min post-application: $\chi^2 = 12.039$, $p < 0.01$). A Bonferroni-corrected t-test for multiple comparisons was conducted to determine the significance. 5 minutes after application, a significant trend was emerged in both the adjacent and capsaicin conditions ($p < 0.1$). After 10 minutes, significant trends were observed in the mixed solution and capsaicin application conditions ($p < 0.1$), with a significant difference in pain was observed between the menthol and adjacent conditions ($p < 0.05$). Notably, the adjacent condition reported the highest pain intensity 10 min after application.

Fig. 7 illustrates the temporal subjective response data across all participants for each experimental condition. This

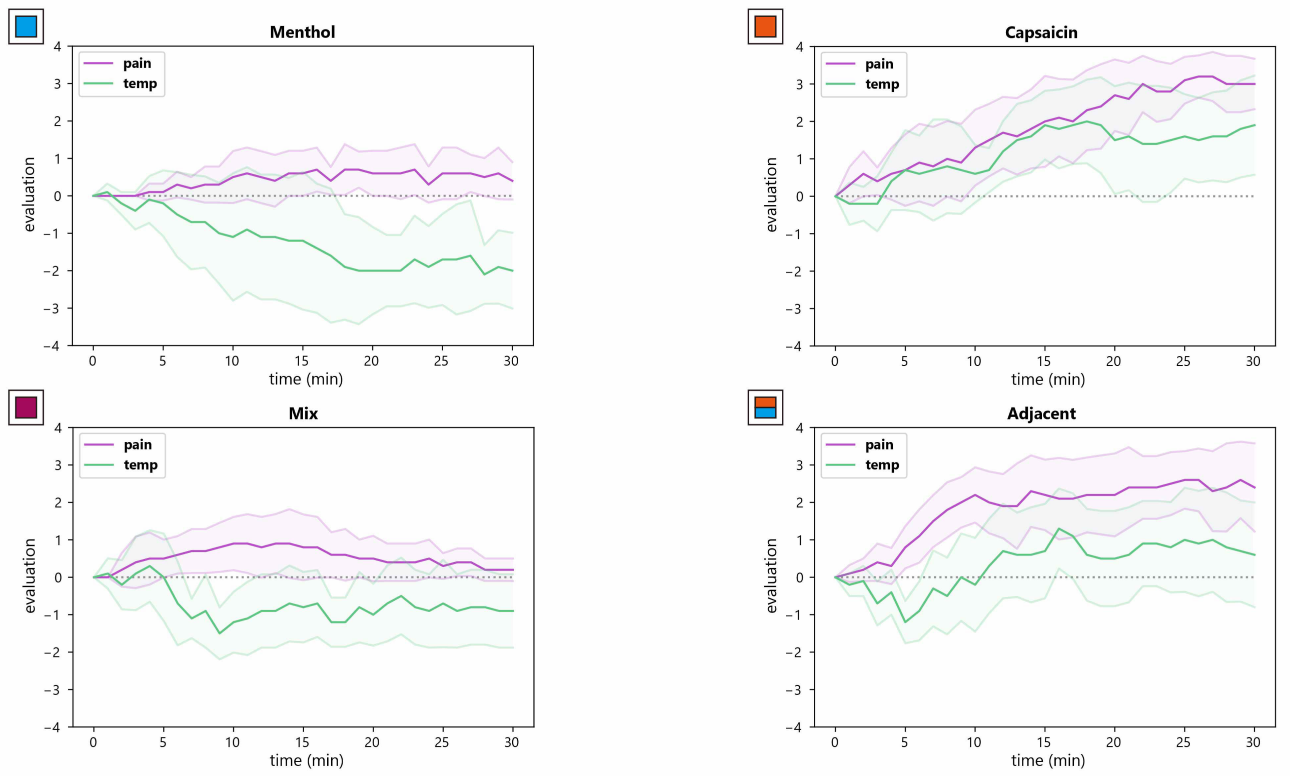

FIGURE 5. Results of experiment 1. Lines indicate the mean value and the bands indicate the 95 % confidence intervals.

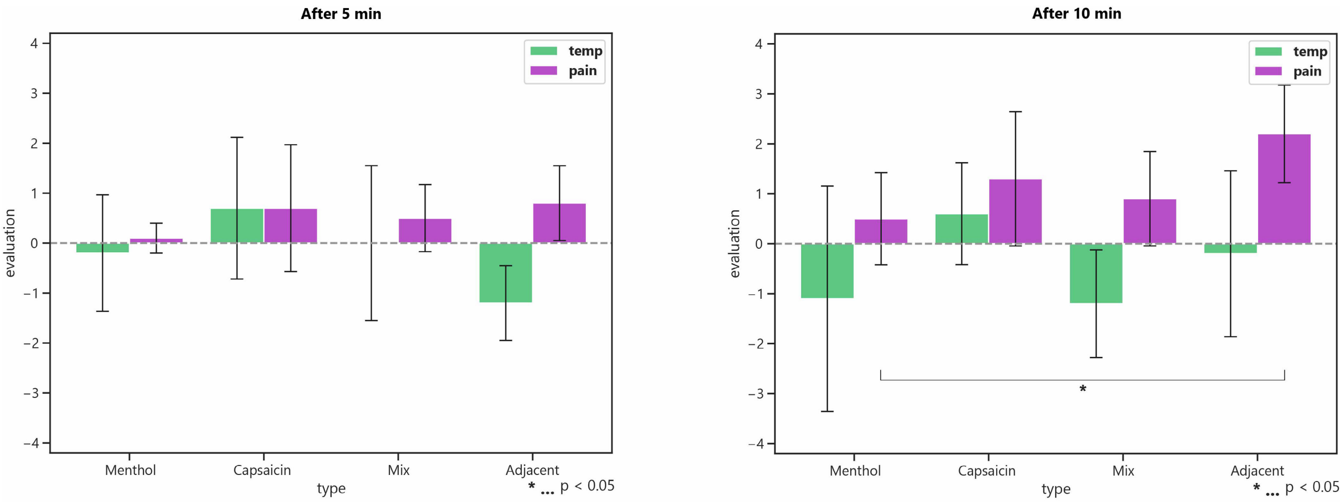

FIGURE 6. Result of temperature and pain sensation after 5 and 10 minutes under each condition of experiment 1.

study selectively highlights responses to thermal perception to aid comparative analysis. In the capsaicin condition, responses indicative of warmth, such as "warm," "hot," and "burning," were frequent, whereas in the adjacent condition, responses suggestive of coldness, such as "cool" and "cold," were common. The frequency of burning sensations in the adjacent condition was comparable to that in the capsaicin condition, yet expressions denoting warmth, such as "hot" or "warm," were absent, except "burning." These observations imply that the temperature sensations induced by capsaicin-only and adjacent application conditions differ. In both the menthol and mixed conditions, cold-related responses were predominant, with scarce reports of "burning," suggesting that the mixed conditions predominantly reflected the cooling effect of the menthol.

B. EXPERIMENT 2: EFFECT OF TIME DIFFERENCE

Experiment 1 revealed that the application of chemicals could elicit the TGI. However, this method was constrained by

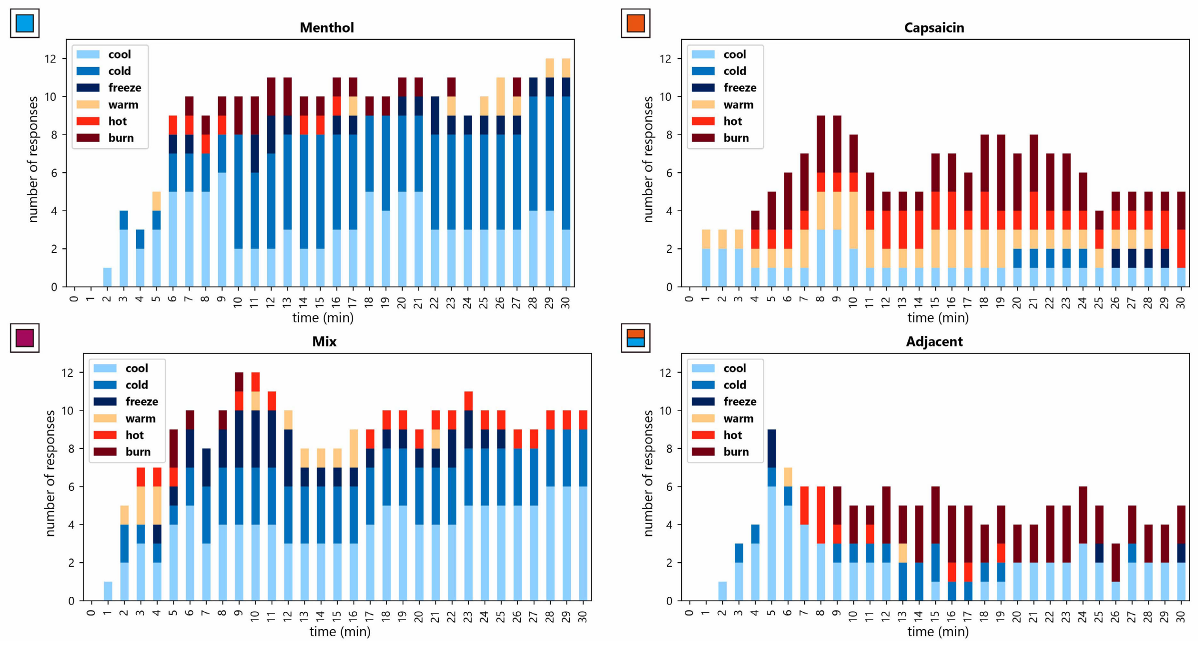

FIGURE 7. Subjective evaluation in each stimulus in experiment 1.

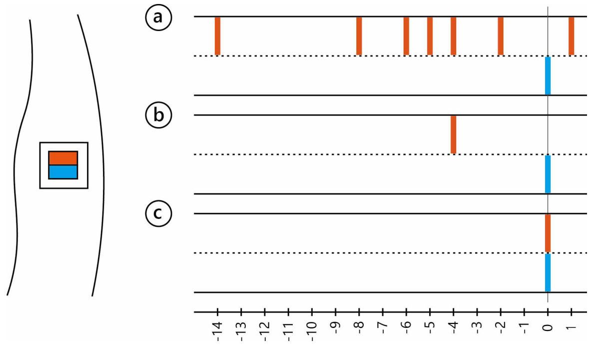

FIGURE 8. Conditions for Experiment 2: The horizontal axis represents on the application timing of menthol. Measurements are performed from the time of the last application of capsaicin or menthol. Multiple red lines indicate the timing of capsaicin application for each participant.

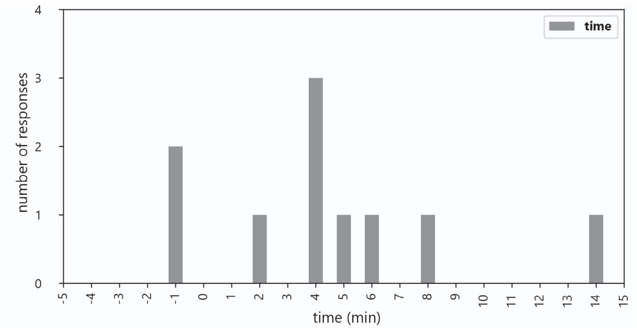

FIGURE 9. Difference in the time of onset of the menthol-induced cold sensation and the capsaicin-induced hot sensation for each participant. Menthol reacts faster when the value is positive; however, capsaicin reacts faster when the value is negative.

time gaps between the applications of different chemicals, which affected its practical applicability. Consequently, this experiment aimed to standardize the side-by-side application of substances, emphasizing varying time intervals. It evaluated temperature sensations and pain when chemicals were applied adjacently with distinct time intervals: individually tailored for each participant, standardized across all participants, and with no time difference.

1) CONDITIONS

Three stimulation conditions were employed in the experiment: application of adjacent substances with participant-specific time intervals (termed the individual condition), application with a uniform time interval for all participants (the unified condition), and application without any time disparity (the simultaneous condition), as depicted in in Fig. 8.

The time intervals for applying menthol and capsaicin in the individual conditions were based on the findings from Experiment 1. The unified condition utilized a consistent time interval for all participants. Fig. 9 illustrates the variation in timing for the onset of cold sensation from menthol and heat sensation from capsaicin as observed in Experiment 1. To effectively induce TGI in a broader participant base, a uniform application time interval was deemed preferable. Therefore, the selected time interval for this uniform application was established at the median and most common duration of 4 min. No time interval was implemented in the simultaneous conditions.

2) PROCEDURE

This experiment involved the same cohort of 10 participants as Experiment 1 and spanned two days, with one condition tested on the first day and two conditions on the second day.

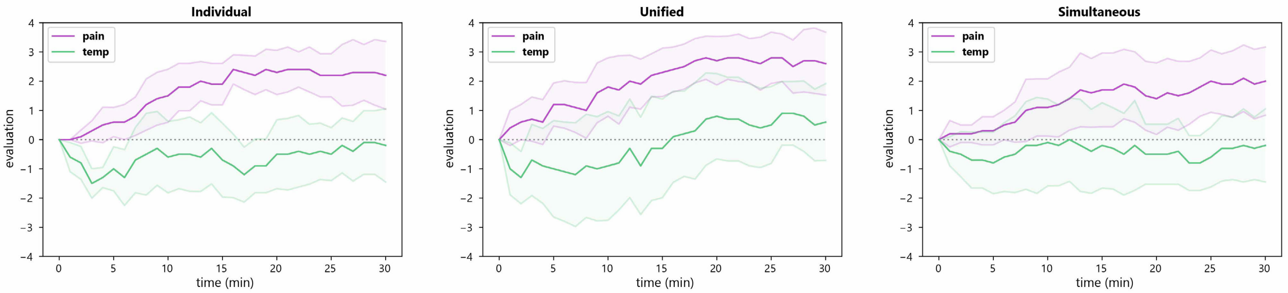

FIGURE 10. Results of experiment 2. Lines indicate the mean value and bands indicate the 95 % confidence intervals.

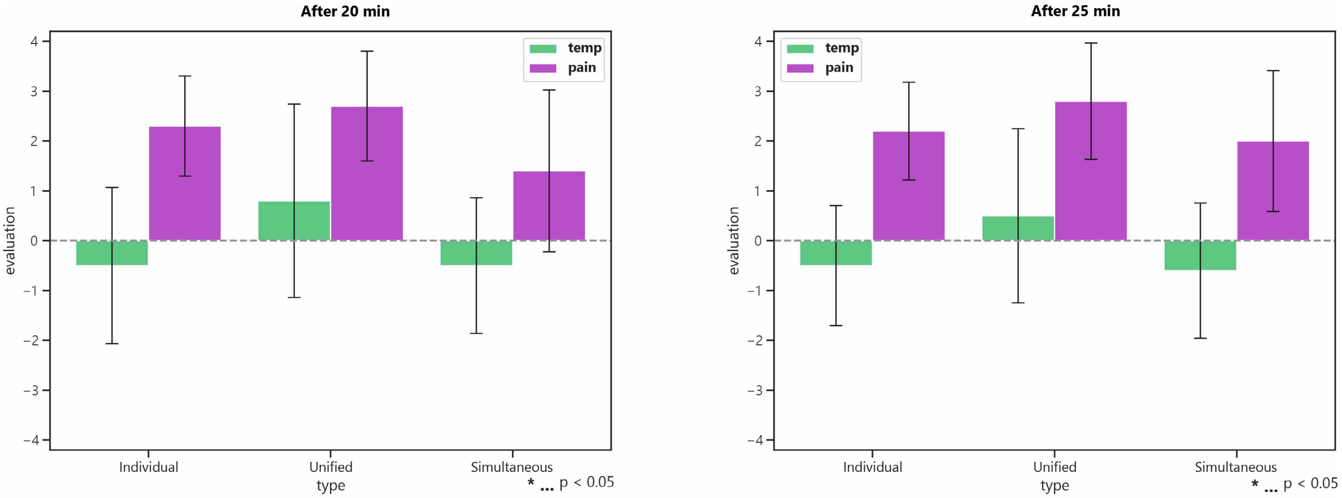

FIGURE 11. Result of temperature and pain sensation after 20 and 25 min under each condition of experiment 2.

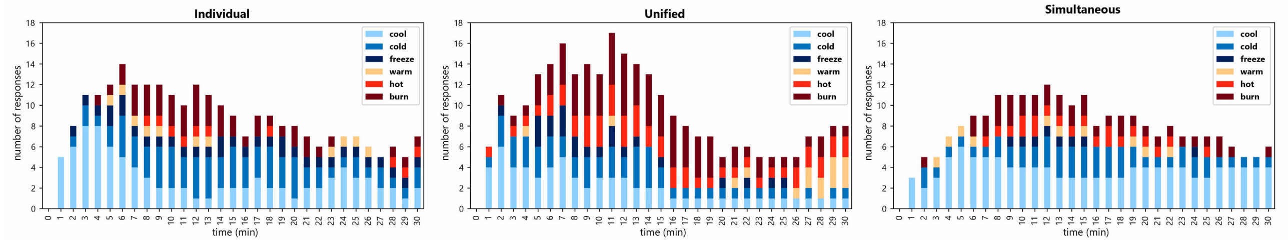

FIGURE 12. Subjective evaluation under each stimulus in experiment 2.

The methodologies employed were consistent with those applied in Experiment 1.

3) RESULTS

In Experiment 2, the individual condition was akin to the adjacent application from Experiment 1. Fig.10 illustrates the responses derived from the Likert scale, indicating that in the individual condition, the pain levels exhibited a monotonic increase, with minor fluctuations in temperature sensation. The simultaneous condition displayed patterns in pain and temperature perception similar to the individual condition. However, the unified condition demonstrated consistent increases in both pain and temperature sensations, with more pronounced differences observed later in the timeline.

Fig. 11 presents the results at 20 and 25 min after application. All conditions induced pain, with the most intense response noted in the unified condition. A Friedman test revealed no main effect for temperature sensation ($\chi^2 = 5.1724$, n.s.) but a significant main effect for pain ($\chi^2 = 6.2424$, $p < 0.05$) after 20 min. Conversely, at 25 min, no main effects were detected for both temperature sensation ($\chi^2 = 4.6667$, n.s.) and pain ($\chi^2 = 3.1515$, n.s.). Subsequent multiple comparison analysis using a Bonferroni-corrected t-test indicated prominent trends in the unified and simultaneous conditions at 20 minutes ($p < 0.1$), suggesting an intensified pain response in the Unified condition.

Fig. 12 displays the frequency of responses per minute for each subjective evaluation condition in Experiment 2. The individual and simultaneous conditions reported

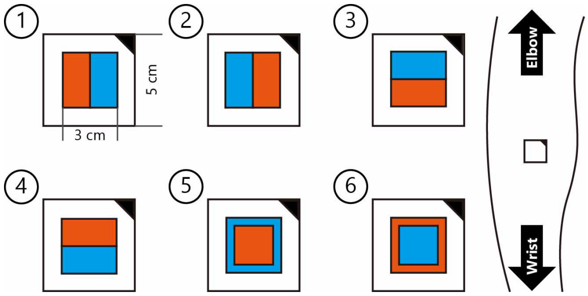

FIGURE 13. Conditions for experiment 3

similar frequencies of "burning" and "freezing" sensations, whereas the unified condition exhibited a higher incidence of "burning" sensations.

C. EXPERIMENT 3: EFFECTS OF PLACEMENT

Experiment 2 determined that simultaneous application of substances without a time gap could induce a weaker illusion. Practically, inducing a robust illusion without a time gap between applications is preferred. The TGI involves two primary aspects: creating a temperature differential and applying warm and cold stimuli alternately. In our approach, this differential is achieved by increasing the chemical concentrations. However, higher concentrations present a trade-off, potentially leading to skin invasiveness. Therefore, this study concentrates on alternative aspects of stimulus placement.

The aim of this experiment was to create a stronger TGI by varying the placement of the applied chemicals. A simplistic placement approach was employed to examine alterations in TGI perception.

1) CONDITIONS

Six stimuli were applied to the forearms in different configurations: transverse (1, 2), longitudinal (3, 4), and enclosed (5, 6), with capsaicin and menthol in different positions (Fig. 13).

2) PROCEDURE

The experiment was conducted on ten participants, comprising nine males and one female aged between 21 and 28 years. The experiment spanned six days, with one condition assessed daily.

The procedure mirrored those used in Experiments 1 and 2. Additionally, participants applied the chemical to the lateral (dorsal) middle of the forearm and underwent stimulation for 30 min per condition.

3) RESULTS

Fig. 14 displays the responses obtained using the Likert scale. In Condition 5, pain levels remained low with minimal fluctuation, while the temperature sensation exhibited a decreasing trend. Conversely, in all conditions other than Condition 5, pain levels increased monotonically, and there was an upward trend in temperature sensation from the 15 min mark, displaying a similar overall pattern. Despite these general trends, certain variations were noted in the latter half of the time-series data for conditions other than Condition 5, warranting a time-focused analysis for each condition.

Fig. 15 prensets the results after 20 and 25 min of application for each condition. These results indicated distinct pain sensations across different conditions. The variance in temperature sensation was substantial in all conditions except Condition 5, where participants' recognition between hot and cold was markedly different. The Friedman test revealed no main effect of placement on temperature sensation (After 20 min of application: $\chi^2 = 4.6939$, n.s.; After 25 min of application: $\chi^2 = 8.1973$, n.s.), while a significant main effect was observed for pain sensation (After 20 min of application: $\chi^2 = 15.721$, $p < 0.01$; After 25 min of application: $\chi^2 = 14.068$, $p < 0.05$). Therefore, the perception of pain sensation varied depending on placement. Significance for each combination was evaluated using multiple comparisons with a Bonferroni-corrected t-test. The results at 20 min indicated that Condition 5 exhibited lower pain levels than other conditions and was significantly lower compared to Condition 4. At 25 minutes, a marginally significant difference was observed between Conditions 1-5 and between Conditions 4-5 ($p < 0.1$). The average pain score in Condition 4 was higher than in other conditions, and although not statistically significant, it also differed from that of Condition 3, which only varied in orientation.

The number of responses to the subjective evaluation per minute for all the participants is shown in Fig. 16. To compare temperature sensations, only the number of responses for the subjective evaluation of the temperature sensation is shown presented. In Condition 5, there were no responses related to extreme temperature sensations such as "burning" or "freezing," and the majority of responses related to cold sensations such as "cool" or "cold." In particular, many respondents in Condition 4 felt a burning sensation compared to those in Condition 3 and the other conditions, where only the orientation was different.

These results indicate that the intensity of TGI-induced pain varies depending on the placement and orientation of stimuli. Condition 4, in which a warm stimulus was applied proximally and a cold stimulus was applied distally to the arm, produced the strongest TGI.

IV. DISCUSSION

A. GENERATION OF TGI BY CHEMICALS AND COMPARISON WITH INDIVIDUAL STIMULI

The experimental results demonstrate that when solutions are applied adjacently and chemically stimulate temperature sensations, they can induce pain. This sensation differs from when the solutions are applied separately. Qualitative evaluations indicated that participants experienced sensations of "burning" and "freezing." Prior research supports the notion that TGI can induce both types of pain sensation. Additionally, these results align with established TGI induction

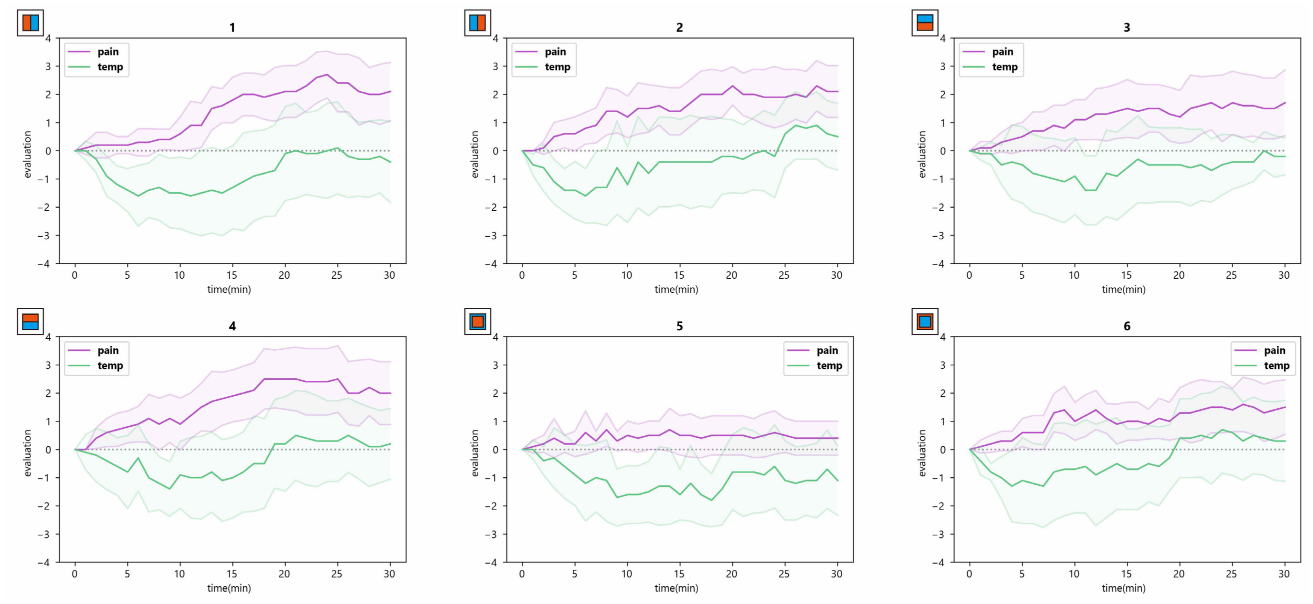

FIGURE 14. Time course of temperature and pain sensation under each condition: Lines indicate the mean values and bands indicate 95 % CI.

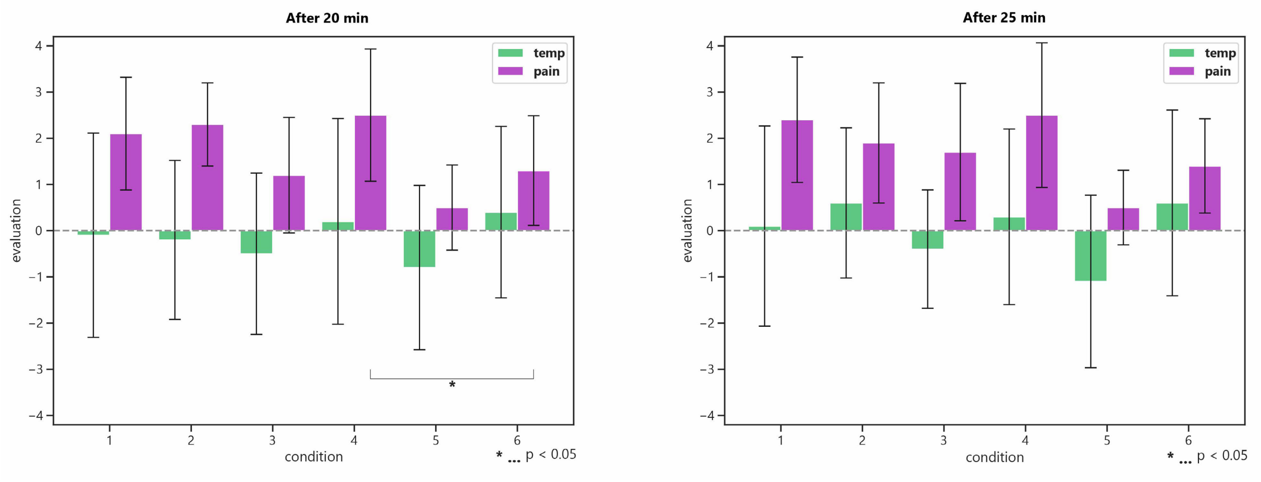

FIGURE 15. Result of temperature and pain sensation after 20 and 25 min under each condition of experiment 3.

methods involving proximal application of hot and cold stimuli. Thus, it is concluded that TGI can be effectively generated when chemicals are applied adjacent to each other, confirming the viability of using chemicals to induce TGI.

Experiment 1 revealed that the application of a mixed solution resulted in a trend similar to the menthol-only condition. Plausibly, the cooling stimulus of menthol affected the masking of pain, which aligns with a previous study [14] where pain was modulated by applying a cold stimulus with a Peltier element to the same skin area treated with capsaicin, suggesting that pain may be mitigated under mixed conditions.

B. EFFECT OF TIME DIFFERENCE

In the simultaneous condition of Experiment 2, the timing between the application of capsaicin and menthol and the onset of temperature sensation resembled that in the mixed condition. Consequently, there were fewer instances of "burning" or "hot" sensations reported compared to other conditions. The discuss that the warm stimulus of capsaicin was masked by the cold stimulus of menthol may be supported by the differences in pain onset and subjective evaluation responses between the simultaneous and mixed solution conditions.

Although TGI was elicited in all conditions of Experiment 2, a standardized four-minute delay produced a more pronounced effect than individually set times. This suggests that a universally applied four-minute delay, being the most common among participants, may offer a more effective measure for TGI elicitation.

C. OPTIMAL PLACEMENT OF HOT AND COLD STIMULI

The purpose of Experiment 3 was to investigate the placement of chemicals that strongly induces TGI. Using six

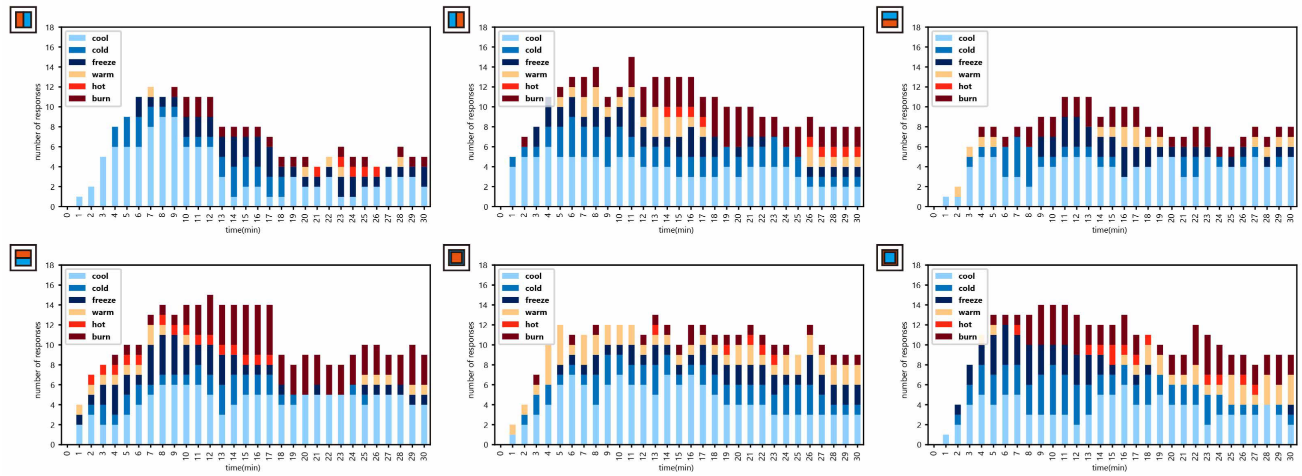

FIGURE 16. Subjective evaluation under each stimulus in experiment 3.

dichotomous thermal and cooling stimulus conditions, it was found that condition 4, which applied thermal stimuli to the proximal and cooling stimuli to the distal regions of the arm, significantly increased the perception of pain and burning. These results suggest that warm stimulation proximally to the arm and cold stimulation distally to the arm are optimal conditions for generating TGI using chemicals.

D. PLACEMENT OF WARM AND COLD STIMULI ON TGI GENERATION

In Condition 5, where capsaicin was placed at the center and menthol surrounded it, it was observed that the pain did not generate much pain based on the time variation and the results at each time point. In the subjective evaluation, there were few responses such as ‘‘burning’’ or ‘‘freezing’’ that typically occur when TGI is generated. In contrast, in all conditions except condition 5, pain occurred with time and at each time point, and subjective evaluations indicated a ‘‘burning’’ or ‘‘freezing’’ sensation. These results suggest that TGI was not generated in condition 5, while it was generated in the other conditions.

E. MECHANISM OF THERMAL PERCEPTION IN PLACEMENT

In Experiment 1, conditions involving a mixture of menthol and capsaicin were evaluated. Furthermore, as illustrated in conditions 5 and 6 of Experiment 3, temperature stimuli were presented in a manner where one stimulus encircled the other. These stimuli were anticipated to increase the generation of TGI by inducing sensations of warmth and cold in nearly the same location. However, these stimuli produced weaker illusions compared to other conditions. Consequently, it is imperative to circumvent the perceptual blending of cold and warm sensations when presenting temperature stimuli for effective TGI generation.

The results of the subjective evaluation indicated that Condition 4, where capsaicin applied proximally and menthol distally on the forearm, elicited a more intense TGI compared to Condition 3, which differed only in orientation. This prompted an inquiry into why merely altering the proximal and distal placement of hot/cold stimuli could result in such a disparity. Watanabe et al. researched to clarify the interplay between thermal referral and the positioning of warm and cold stimuli on the forearm [30]. Their findings revealed that the referral phenomenon, occurring when warm and cold stimuli are applied at significant distances from each other, is contingent upon the sequential arrangement of the warm and cold stimuli. Additionally, they observed that the locations of the warm and cold stimuli could be easily misperceived, particularly when the warm stimulus was applied distally and the cold stimulus proximally on the forearm. This misperception was attributed to the propensity for hot sensations to radiate towards the center of the body, and for cold sensations to disperse towards the periphery. This phenomenon is attributed to the tendency of hot sensations to radiate towards the body’s center and cold sensations towards the periphery. Based on these insights, it is plausible that in Condition 3, the hot and cold stimuli were perceived as intermingling, whereas in Condition 4, they were discerned as distinct. These results suggest that the appropriate placement of warm and cold stimuli is important for generating a strong TGI, and that careful consideration of the placement of these stimuli is necessary to minimize the perceptual mixing of warm and cold stimuli.

The skin surface is segmented into dermatomes, each innervated by sensory nerves emanating from a singular spinal nerve root. Prior research exploring the spatial boundaries of TGI indicated its occurrence both within and across dermatomes [31]. Francesca et al. employed warm and cold stimulation within and across skin segments, considering segmental distances between afferents like myelinated Aδ fibers and unmyelinated C fibers, which respond to innocuous cold and warmth [32]. The intensity of TGI is influenced by the segmental distance between these afferents. In our study, the greatest segmental distances were observed in conditions 1 and 2, where stimuli were applied transversely across the forearm, while the shortest distances were noted in conditions 3 and 4, with the stimuli oriented longitudinally along the forearm. This, the pronounced generation of TGI in Condition 4 aligns with these findings. The marked TGI in Condition 2 may be attributed to the stimulus' central placement on the forearm, straddling the boundary between lateral skin segments, and its application within a single skin segment without crossing it. For practical applications of this method, a placement that elicits strong, prolonged pain is preferable. In this experiment, the most intense TGI was observed under Condition 4, with stimuli conveniently administered within the same skin segment.

V. LIMITATIONS AND FUTURE WORK

The utilization of chemicals alone to represent temperature has inherent limitations, such as the prolonged duration required for the effects to subside and the difficulty of making adjustments. Consequently, this approach may be more suitable for applications like itch-suppressing patches rather than for representing rapidly fluctuating environments in VR applications. Furthermore, a combination of chemical and physical stimuli may be effective in pursuit of more rapid temperature representation. For instance, the use of resistance heating, which is spatially efficient and highly reactive, might provide a more rapid presentation for physical temperature expression than the slower time constant of a chemical stimulus such as capsaicin.

A limitation of these experiments was the small sample size and demographic skew towards male participants in their 20 s, potentially introducing bias. Factors such as aging and individual variations in skin and fat thickness might yield divergent results [33], [34]. Therefore, it is crucial to conduct future experiments encompassing a wider age range and including female participants.

Experiment 3 revealed that the intensity of the TGI is contingent upon the placement of stimuli. In response, more intricate placements could be explored, such as augmenting the divisions of warm and cold stimuli or contemplating a two-dimensional thermal array. Therefore, future plans include comparing the highly effective TGI-inducing placements identified in Experiment 3 with two-dimensional configurations like a grid layout. Further investigation will also delve into the effects of uneven distribution of warm and cold stimuli patches and whether more complex patterns can alter perceived sensations. Through these studies, we aim to enhance our understanding of the factors influencing TGI perception, potentially paving the way for novel pain management methods and medical technologies.

VI. CONCLUSION

This study investigated the feasibility of inducing TGI using chemicals instead of physical heat or cold stimulus. The experimental results confirmed that TGI can be generated by adjacently placing capsaicin and menthol. Moreover, applying these chemicals with a time delay yielded a more pronounced TGI than their simultaneous application. Modifying the placement of the stimuli also affected the perceived intensity of the TGI, with the most substantial effect observed when capsaicin was applied proximally and menthol distally on the forearm. These findings open up prospects for eliciting sustained and intense pain sensations without external energy sources and contribute to the understanding of human thermal sensation integration mechanisms.

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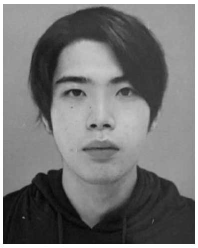

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