Conceptual Method of Temperature Sensation in Bionic Hand by Extraordinary Perceptual Phenomenon

Saeed Bahrami Moqadam¹ · Ahamd Saleh Asheghabadi¹ · Farzaneh Norouzi² · Hamed Jafarzadeh³ · Ali Khosroabadi⁴ · Afshin Alagheband⁵ · Ghazal Bangash⁶ · Negar Morovatdar⁷ · Jing Xu¹

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Abstract

Lack of temperature sensation of myoelectric prosthetic hand limits the daily activities of amputees. To this end, a non-invasive temperature sensation method is proposed to train amputees to sense temperature with psychophysical sensory substitution. In this study, 22 healthy participants took part besides 5 amputee participants. The duration time of the study was 31 days with five test steps according to the Leitner technique. An adjustable temperature mug and a Peltier were used to change the temperature of the water/phantom digits to induce temperature to participants. Also, to isolate the surroundings and show colors, a Virtual Reality (VR) glass was employed. The statistical results conducted are based on the response of participants with questionnaire method. Using Chi-square tests, it is concluded that participants answer the experiment significantly correctly using the Leitner technique (P value < 0.05). Also, by applying the “Repeated Measures ANOVA”, it is noticed that the time of numbness felt by participants had significant (P value < 0.001) difference. Participants could remember lowest and highest temperatures significantly better than other temperatures (P value < 0.001); furthermore, the well-trained amputee participant practically using the prosthesis with 72.58% could identify object’s temperature with only once time experimenting the color temperature.

Keywords Temperature perceptions · Leitner learning technique · Classical conditioning · Psychophysical sensory substitution · Extraordinary perceptual phenomenon · Bionic hand prosthesis

1 Introduction

The patients who are suffered from upper limb amputation expect that their prosthesis be similar functionally, as same as their missed limb [1]. There are performed impressive advancements in controlling the motion function in prostheses. Nevertheless, a closed-loop controlling method based on sensory feedback still is one of the current challenges in designing bionic hands [2]. Despite this, fewer efforts have been performed on retrieving sensation as a closed-loop sensory feedback system for these users. One of the attractive options for an advanced bionic hand could be sensing the temperature by the prosthesis and feedback it to users [3], which be useful in environmental interaction such as daily life activities. For instance, amputees are able to sense the cup temperature before drinking. Therefore, some attempts have been performed to feedback temperature sensation categorized as invasive and non-invasive methods. In the invasive manner, Targeted Muscle Reinnervation (TMR) and targeted sensory reinnervation methods to transmit

✉ Jing Xu
jingxu@tsinghua.edu.cn

- ¹ State Key Laboratory of Tribology, Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China
- ² Medical University of Mashhad, 13131–99137 Mashhad, Iran
- ³ Center for Computational and Data Intensive Science and Engineering (CDISE), Skolkovo Institute of Science and Technology (Skoltech), Moscow 121205, Russia
- ⁴ Department of Mechanical Engineering, Ferdowsi University, Mashhad 9177948974, Iran
- ⁵ Department of Electrical Engineering, Ferdowsi University, Mashhad 9177948974, Iran
- ⁶ Department of Computer Engineering, Ferdowsi University, Mashhad 9177948974, Iran
- ⁷ Clinical Research Unit, Imam Reza Hospital, Mashhad University of Medical Sciences, 13131–99137 Mashhad, Iran

neural sensory feedback somatotopically (which was consisted of the temperature feedback) to amputees have been used [4, 5]. However, the invasive methods have been lower considered due to their limitations and expenses than non-invasive ways. The non-invasive method also is categorized as somatotopically and non-somatotopically. The somatotopically is used phantom mapping generally on a residual limb (stump) to stimulate the cortical sensory homunculus of the missing limb in the cortex by a Peltier as stimulator [6]. Furthermore, the non-somatotopic method is categorized into modality match and non-modality match sensory substitution [7]. The Peltier has been used in modality match sensory substitution as a stimulator to generate warmth and cold. For example, Ino et al. applied a Peltier device for temperature perception on humans. However, the hazardous components, extra weight, high level of power consumption, time delay to response, and a prolonged time for changing cold and warmth are the disadvantages of this method that lead to inefficiency in daily application [8–11]. In the literature, the Peltier generally has been utilized as a temperature stimulator. Nevertheless, a heating pad (made of conductive metal yarn) also has been presented as a warmth stimulator [12]. Another method is a weak warmth sensation applied by Transcutaneous Electrical Nerve Stimulation (TENS) in high and low frequency on skin that can change skin's temperature about (1.60–1.69) °C which is warmer than the mean hand temperature [13]. However, it makes a low sensible temperature. These tiny changes are not functional for amputees in daily routine actions. The non-modality match sensory substitution in literature has presented as vibration to detect the intensity of sensed temperature [14]. The advantages of this method over previously mentioned methods are reducing the power consumption and extra-added weight, and time delay to the response. Moreover, disadvantages are lack of natural sensation of temperature, desensitization, and spatial interference between other stimulators.

The human perception consists of somatosensation and sensory perception. The somatosensation is the result of the cutaneous feedback receptors, which are stimulated by environment; while, the sensory perception is the outcome of the somatosensation processing which is received by bio-receptors [15]. In the human body system, the changes the temperature are sensed by the thermoreceptors where distribute in the cutaneous. Thermoreceptors are a part of receptive sensory neurons that are sensitive to changes in temperature. The warmth-sensitive thermoreceptors are called Raffini endings. Raffini endings are employing non-myelinated C-type fibers that have lower transmission speeds than other neural fibers. The warmth receptors are stimulated by changes in the temperature more than the body temperature, in which heat increases the discharge rate of the action potential. Moreover, the Krause end bulb receptors, cold receptors, are benefited both A- δ and C-fibers (with

the higher transport speed and thinly myelinated) [16]. Conversely, temperature changes at lower than the body temperature reduce their discharge potential [17]. While in cold receptors, the discharge operation of the action potential is performed in contrast to the warmth receptors [18]. The route of the thermoreceptors in the brain continues from the peripheral nervous system to the spinal cord and then to the thalamus and finally leads to the primary somatosensory cortex [19]. The brain perceives rapid and intense stimuli where pathways are similar to the temperature changes and pain sensation. Therefore, intense and rapid changes of temperature stimuli generate a sense of pain in the human perceptual experience [20].

Conditioning is one of the extraordinary perceptual phenomena that could be similar to psychophysical sensory substitution. It means that when a sensory pathway is stimulated, an involuntary response in another sensory pathway will express [21]. Conditioning is one of the brain-behavioral reflections, which can build the associations between stimuli and produce responses based on these associations. Conditionalization refers to a mind training method in which a Conditioned Stimulus (CS) multiple times is occurring with an Unrelated Stimulus (US) that consequently generates a known behavioral response or a new Conditioned Response (CR). The observed new CR to the stimulus trained in the behavior, before their continuous repetition appeared, was neutral on the behavior [22]. The origin of conditioning in the brain is haptic memory, which is a part of the sensory memory of the brain [23]. In sensory memory, most of the responses automatically happen reflected by stimulus factors [24]. Sensory memory consists of three sections: haptics memory, iconic memory, and echoic memory [23]. These branches of sensory memory make up our consciousness, emotions, and how to react to external stimuli. Haptics memory briefly records the somatosensory sense of touching objects such as force, pressure, temperature, pain, and itching [25]. The sensory memory records and holds the spatial and categorical stores of different types of processed and decodes the information of the objects, and it has a relatively high capacity to record up to twelve objects visually [26].

The human brain is composed of past, momentary, and futuristic (predictive) memory. Nevertheless, it seems that the brain is a chaotic system and cannot foresee its reactions. While applying some methods of mind-learning techniques, the brain would be able to give the desired behavioral feedback. However, on the other hand, consciousness comes with the repetition of sensory experiences [27]. According to brain theory about memory and prediction of spatial-temporal patterns, if multidimensional data are received by a memory system without sequences, some days later, 80%–90% of that data might be forgotten [28]. To evaluate the robust prediction in sequence memory, it needs to transmit the information from short-term memory to long-term

memory. Therefore, an efficient learning method is required to transfer patterns to long-term memory. In other words, learning will happen when essential data transmits from short-term memory to long-term memory [27]. Herman Ebbinghaus discovered scientific evidence about the learning/forgetting curve [29]. In the following, Sebastian Leitner [30] first had initiated the practical application of the theory of the learning-forgetting curve. Leitner S. in 1970 presented a learning method based on repetition. In this method, data pieces are documented and repeated at certain time intervals. After passing, at each interval the data are asked; if it remembers correctly, it proceeds to the next level; otherwise, the whole process repeat from the first level [30]. Another of the extraordinary perceptual phenomena is the psychological effects of colors on the human. In the psychological impacts of colors on the human, the function of the visual cortex is located in the occipital lobe to integrate information from subcortical areas, such as the lateral geniculate body located in the thalamus [31]. The visual cortex has two streams, the ventral and occipitoparietal streams. The ventral streams deal with the identification and recognition of objects. In addition, the dorsal (occipitoparietal) stream mediates in the location and movements of limbs and objects [32]. The ventral stream plays an essential role in this paper since it involves object recognition and has a connection to the medial temporal lobe (which is related to long-term memory) and the dorsal stream [32].

This paper attempts to show that using two mentioned extraordinary perceptual phenomena in humans can sense temperature without using any model of the sensory stimulator (such as the Peltier) by showing colors to amputees. The conceptual method of temperature sensation in a bionic hand by extraordinary perceptual phenomenon by the conditioning participants to color and temperature based on the Leitner technique will resolve the energy consumption challenge, time delay to response, extra weight, and prolonged time to changing the cold/warmth. The rest of the paper is arranged as follows: Sect. 2 presents the hardware and software for the proposed method evaluation; Sect. 3 describes the proposed method; the experimental results are analyzed and discussed in Sect. 4; and conclusion drawn in Sect. 5.

2 System Description

The system consists of two parts: the first part is the FUM bionic hand II is designed to test the virtual temperature sensation by extraordinary perceptual phenomena for amputees in this research. The second part is the software used in this paper to evaluate the concept of conditioning and mind learning (color temperature) as a Graphical User Interface (GUI).

2.1 FUM Bionic Hand II

To evaluate the presented method on amputee participants, a prosthetic hand, called FUM bionic hand II, has been developed. The developed prosthesis is an updated version of FUM bionic hand I [33] designed and inspired by the natural structure of human upper limb mechanisms, Fig. 1. The FUM Bionic Hand II has six Degrees of Freedom (DoF) generated by five linear actuators embedded inside the socket. In addition, a servomotor is installed at the palm of the prosthetic hand to rotate (abduction/adduction) the thumb. Furthermore, flat springs and elastic strips have been applied as ligaments at joints. The under-actuated anthropomorphic fingers of the prosthesis have shape adaptively with grasped objects due to implementing the tendon, spring, and pulley to transfer the motion.

The flexion/extension of fingers is performed by linear tension force provided by linear actuators using the two tendons opposite with the torsion spring (transmitted by stainless steel cable). The total weight of the hand, socket, and battery is about 1.25 kg and Mechanomyography (MMG) and Electromyography (EMG) signals voluntarily control the motion of each finger.

2.2 Android GUI Application of FUM Bionic Hand II

In this research, it is tried to expand it to a learning system by conditioning method. Therefore, two types of graphical user interface (GUI) applications have been designed for Windows and Android systems programmed by C# and JAVA, respectively, Fig. 2. These GUIs provide the same facilities for prosthesis users. Features of the applications are as follows: monitoring and calibrating biosignal (to control the prosthesis), supporting wireless connection port (WI-FI and Bluetooth), control of each finger, displaying the unique color based on sensed temperature (according to

Fig. 1 Prosthetic hand (FUM Bionic Hand II) was designed with capability of virtual temperature sensation according to Conditioning by the Leitner learning technique

Fig. 2 **a** Android application GUI designed by Java for monitoring temperature of the unique color and sensors calibration to make convenient accessibility to install smartphone on socket. **b** Windows

application GUI designed by C# to monitor temperature of the unique color and sensors calibration to make convenient accessibility to smartphones and laptops

this research), displaying applied force of the fingertip and positions of fingers, and selection of the grasping gesture modes options.

3 Methodology

Our study is carried out with the help of thirty healthy participants (college students) and five upper limb amputees with healthy vision, in a duration of 31 days, except eight healthy participants, who were excluded due to time limitation, the rest 22 healthy participants carried on till the end. The demographic data of the 22 healthy remaining participants and 5 amputees are in Table 1, respectively. The procedures of the experiment have been explained to all participants. The ethical approval is obtained by the institution review board of Tsinghua University. All participants completed informed consent. During the entire length of our study, all experiments have been conducted following relevant guidelines and regulations. The clinical trial's registration number is 20190088.

Each healthy and amputee participant sat on a chair. Healthy participants kept their three fingers in the water stored in the YECUP (Temperature Adjustable Mug) to somatotopically sensed temperature. The Android application of the mug was used to display and adjust (in real time) the temperature of the stored water. Healthy participants have put their fingers in the cup until they felt numbness in their fingers. For the amputee participants due to the limitation of using the mug (as temperature stimulator), an alternative method was implemented. A Peltier with a control system was mounted on phantom digits, Fig. 3, of the residual limb of the amputee participants to sense the temperature somatotopically. The Peltier was held on their phantom fingers until they felt numbness in their phantom fingers. When numbness has been felt, thermoreceptors have been adopted with the current sensed temperature. Functionally, thermoreceptors, when numbness occurs, do not stimulate until temperature changes occur [34].

In other words, during the thermal numbness, no sensory feedback information is transmitted to the Central Nervous System (CNS). In this study, the temperature was

Table 1 The demographic data of healthy and amputee participants

Healthy participants			Amputee participants		
Age	(mean±SD)	24.63±.31	Age	(mean±SD)	27±8.97
Gender N (%)	Male	19 (86.36)	Gender N (%)	Male	5(100)
	female	3 (13.63)		Female	-
Degree N (%)	Bachelor	15 (68.18)	Degree N (%)	Bachelor	4 (80)
	master	4 (18.18)		master	1 (20)
	PhD	3 (13.63)		PhD	-
Amputation Location			Amputation	A1	Wrist disarticulation
			Location	A2	Short below elbow
				A3	Very short below elbow
				A4	Very short below elbow
				A5	Long below elbow

Fig. 3 Mapping phantom digits on the residual limb to somatotopically stimuli the temperature sensory feedback onto the amputee participants

categorized in five ranges (0–15, 15–25, 25–35, 35–45, 45–48) °C [35, 36]. Each category has an indicator temperature, which is listed in Table 2.

Human neurons have logarithmic distribution in the spike intensity stimulus, so the temperature is increased logarithmically. The maximum temperature detected by thermoreceptors, without pain, is about 45 °C [37–39]. Therefore, the maximum selected temperature was 48 °C to investigate the effect of the pain on the quality of the learning. All of the participants had accepted 48 °C and they only touch it without numbness. Virtual Reality (VR) is used to show colors to the participants and isolate them from the environment. The colors were the key specification in presented method, because colored objects activate a pathway from visual cortex V1 to visual cortex V4.

Usually, colored objects activate more anterior parts of the fusiform gyrus, the hippocampus, and the ventrolateral frontal cortex. The iconic memory stores visual information for about 250 ms [40] and plays a key role in visual priming. It works quickly and unconsciously. Iconic memory holds obvious (vivid) images of stimuli [41]. Information from iconic memory connects to short-term memory via dorsal and ventral streams to recognize objects. The capacity of visual memory is about 30 s [42–44]. The human visual memory system is related to the Posterior Parietal Cortex (PPC). The PPC is a critical neural locus for the representation of

the visual world. The activity of the PPC is tightly correlated with the restriction of short-term visual memory [31]. Although their facts were implemented without considering cognitive factors such as memorizing, learning, and the cognitive systems of Helmholtz and Hering, who believed that “simultaneous lightness contrast is a result of miss judgment of illumination”[45].

To improve the reliability, monitoring the unique color temperature to virtual temperature sensation was based on the attention of the subjects, as referred to in the results of Zeki S. and Marini L.’s research [26]. Stimulation from the retinal ganglion cells travels to the primary visual cortex (V1) in the occipital Lobe via several tracts and nuclei (through the optic nerve to the optic chiasm, then through optic tracts to the thalamus and lateral geniculate nucleus) [43, 46]. Information flows through V1, V2, and V4 to process color/raw visual input without consideration to memory and learning. The inferior temporal cortex processes shapes and forms of objects [46, 47]. So, five colors were selected based on a color spectrum according to [48] as shown in Fig. 4.

With using Leitner learning technique, learning had five steps. Each step had a distinct duration in Fig. 5(a) as shown below:

- Step 1: one day after experiencing the color temperature
- Step 2: two days after step 1
- Step 3: four days after step 2
- Step 4: eight days after step 3
- Step 5: sixteen days after step 4

The temperature indicator has been set by the android application of YECUP for healthy participants. Furthermore, the Peltier’s temperature was adjusted by a controller system for the amputee participants. The related color to the temperature was shown by VR for both groups of participants. In each step, the healthy participants put their fingers in the mug until they felt numbness as shown in Fig. 5(b). Moreover, the Peltier was put held on to the amputees’ phantom finger zone until they were felt numbness as shown in Fig. 5(c).

The participants were informed about the temperature indicator the related color before the experiment.

Table 2 The categorized temperature in five ranges and their indicator temperature

Temperature category	(0–15) °C	(15–25) °C	(25–35) °C	(35–45) °C	(45–48) °C
Indicator temperature	10 °C	20 °C	30 °C	40 °C	48 °C

Fig. 4 Colors that were shown on VR, each color is indicator of each temperature range. From left, dark blue (DB), blue (B), light blue (LB), yellow (Y), red (R)

Fig. 5 **a** Five-step tests of the Leitner learning technique. **b** The situation of each healthy participants when they were in conditioning procedure. **c** The situation of each amputee participants during con-

ditioning based on Leitner technique. The rooms where testing and conditioning took place were same and quiet

Participants were then evaluated in five steps. In each interval, they observed the relevant colors in the GUI designed for FUM bionic hand II. The total duration of the test was 31 days that the participants had to pass steps among 31 days. In case of giving a wrong answer, they had to repeat the experiments and start it again from step one on the remaining days. At the end of the test, we calculated the percent of participants (who could complete the steps in 31 days). A percentage of participants, who had to start over it again due to the wrong answers, missed their time to complete remained steps of the test in the remaining days. Furthermore, each return to step one was considered an error. Equation (1) shows the total days lost due to the error(s), missed days, where the participant had to start it again.

$$\sum_1^n a_n b_n = \text{Missed days}, \quad (1)$$

where “ n ” is the number of steps (1–5), “ a ” is the number of the day of each step (1, 3, 7, 15 or 31) and “ b ” is the number of errors occurred in each step. We calculated the final step that the participants reach after 31 days (the end of the study) by:

$$31 - \sum_1^n a_n b_n = \text{Step range}. \quad (2)$$

For descriptive data, the mean, Standard Deviation (SD), frequency, and percentage were used and the tables were drawn. Quantitative variables were expressed as mean SD and qualitative variables in terms of numbers and percentages. For cases of normal distribution of quantitative data, parametric tests were used. A 95% confidence interval was used to express the estimation accuracy. SPSS (Statistical Program for Social Sciences, version 22) is used for data analysis.

4 Results and Discussion

Twenty-two healthy and five amputee participants with demographic data in Table 1 took part in this experiment. Five colors including red (for 48 °C), yellow (40 °C), light blue (30 °C), blue (20 °C), and dark blue (10 °C) are used in our experiment. Furthermore, we had five steps or intervals in our study including step 1 (from days 1 to 2), step 2 (from days 3 to 6), step 3 (from days 7 to 14), step 4 (from days 15 to 30) and step 5 (day 31). On day 1, day 3, day 7, day 15, and day 31, the participants were asked about the temperature they felt by showing them each color. If a participant gave a wrong answered on any day, he/she had to start over from the first step otherwise; he/she would go to the next step. Each response given at an interval (previously defined) determined the stage of an individual. We evaluated the percentage of correct answers in each step, specifically, to improve the accuracy of evaluation, each of the steps of the experiment separately has been performed on each color, which is shown in Table 3 for healthy, and amputee participants.

According to obtained results, all participants have answered correctly after passing 1 day of the experience of the color-temperature perception. After 3 days, 100% of healthy participants have answered correctly for red color. Furthermore, 100% of amputee participants after 3 days have been answered correctly for the red color. The red color plays an essential role in our experiment because it has two cognitive loads, pain and color (one of the extraordinary perceptual phenomena), on participants. The healthy participants who reached the final step after 31 days at separate color intervals are 3 in DB, 2 in B, 2 in LB, 3 in Y, and 10 in R. Moreover, 1 in DB, 0 in B, 0 in LB, 1 in Y, and 2 in R have been obtained from amputee participants. More

Table 3 The percentage of correct answer in each step in each color for participants

Healthy participants						Amputee participants					
	Step 1 (day 1)	Step 2 (day 3)	Step 3 (day 7)	Step 4 (day 15)	Step 5 (day 31)		Step 1 (day 1)	Step 2 (day 3)	Step 3 (day 7)	Step 4 (day 15)	Step 5 (day 31)
DB	100	90.9	68.2	31.8	13.6	DB	100	80	40	40	20
B	100	95.5	31.8	22.7	9.1	B	100	80	60	40	0
LB	100	72.7	31.8	18.2	9.1	LB	100	60	60	20	0
Y	100	81.8	31.8	18.2	13.6	Y	100	80	60	40	20
R	100	100	95.5	90.9	45.5	R	100	100	60	60	40

details of all steps based on colors are shown in Fig. 6 for healthy participants and for amputee participants are shown in Fig. 7.

In addition, for indicating the distribution, median, spread, and overall range of recorded data in Fig. 8 and Fig. 9 are presented for healthy and amputee participants respectively.

Using Chi-square tests, it is concluded that participants answer the experiment significantly correctly using the Leitner technique (P value < 0.005). The total error for each color is estimated and a significant difference in the errors of each color is noticed. The most errors were seen for light blue (LB), and the least was for red (R) color (P value $= 0.001$), Table 4.

It is concluded that conditioning for temperatures near the body temperature (LB) is more difficult to evaluate than the highest (R) and lowest (DB). By applying the “Repeated Measures ANOVA”, it is noticed that the time of numbness was different at different temperatures except at (25–35 °C) vs. (45–48 °C) in healthy participants. Furthermore, (0–15 °C) vs. (35–45 °C), (0–15 °C) vs. (45–48 °C), and (15–25 °C) vs. (35–45 °C) the time of numbness were different in amputee participants, Table 5. Moreover, the minimum, maximum, and mean level of the time of the numbness were measured in these two groups and the results are expressed at Fig. 10.

To evaluate this experiment in daily routine activities, the amputee participant who had the best performance during the experiments was selected to perform an additional test. Five bottles of water at different temperatures (indicator temperatures) had been prepared to use as a stimulator for the thermosensors embedded on the finger of the prosthetic hand. We asked the amputee participant to wear VR and observe the android application. We randomly put each of the five bottles onto the thermosensors. To the best of our knowledge, no similar study has introduced the effect of conditioning on virtual temperature sensation by psychophysical sensory substitution.

Next, the selected participant observing displayed colors by the Android GUI application of prosthesis reports us the range of the bottle's temperature. The reported result of the amputee participants is shown as the confusion matrix shown in Table 6.

In this paper, a sensed temperature virtually by psychophysical sensory substitution (conditioning and Leitner learning technique) on the healthy and amputee participants has been implemented. This paper is proposed to overcome the limitations of using hardware temperature stimulators on prostheses used in other non-invasive methods. This method can work with low energy consumption, no time delay to response, no extra weight, and no prolonged time to changing the cold/warmth. This paper on studying human psychological characteristics and implementing them on

Fig. 6 The percentage of correct answer in each step in each color for healthy participants

Fig. 7 The percentage of correct answer in each step in each color for amputee participants

Fig. 8 Distribution, median, spread, and overall range of correct answer recorded data from healthy participants

Fig. 9 Distribution, median, spread, and overall range of correct answer recorded data from amputee participants

participants suggests a novel method to make closed-loop feedback controlling by the prosthesis. Although this method is proposed for virtual temperature sensation, it has the potential to perform for other sensory feedbacks. Generally (today), amputees controlling their upper limb prosthesis by visual and auditory feedback (observing the prosthesis during grasping and hearing the changes noise of the DC motor of the prosthesis). On another side, commercial bionic hands with sensory feedback do not exist in the market yet. Also, the available upper limb prostheses are expensive for amputees. Therefore, our proposed method is suggested an easy way to have a closed-loop sensory perception for amputees based on their mental ability. The advantage is that amputees do not need to pay a lot to add this option to their prostheses. Besides, without adding extra weight, they can use their previous prosthesis. The prepared GUI also can be used in smartphones making it more convenient for amputees. In addition, by referring to achieve results, for all colors, the average of healthy participants who could pass the fourth step was 36.6%, and in amputee participants was 40%. However, both groups of participants had correctly answered the red temperature in step five with a high level of precision than other colors (45.5% of healthy and 40% of amputee participants). Achieving a high level of accuracy to the correct answer to the red color at the fifth step by once time experiencing of the experiment indicates that augmenting the cognitive load on colors might be enhanced the learning quality in our proposed method. Furthermore, although the well-trained amputee participant with only once time experience the color temperature, could practically 72.58% identify the temperature of objects by the proposed method, still needs to perform more experiments on amputees to evaluate the repeatable accuracy.

Moreover, during somatotopically sensing the temperature by fingers, the time of numbness at participants in each color was different. The time of numbness in healthy participants by increasing the temperature and closing to the body temperature was decreased; in contrast, in amputee participants it was increased. The reasons for the different reactions are not clear, and it needs to perform more experiments. Nevertheless, it might be due to applying different kinds of stimulators (Peltier rather than water) in groups. By putting the fingers in the water, the water surrounds the fingers and stimulates them in three dimensions, whereas the Peltier can only stimuli the surface of the skin in one dimension on the phantom digits zone. Besides, the difference in time of the numbness at groups might be one of the side effects of limb amputation. In addition, the virtual temperature sensation by extraordinary perceptual phenomena for the first time was tested on more than ten participants. The user only uses his/her laptop or mobile phone to access controlling, monitoring, calibration, and evaluate temperature virtually just by observing colors. And disadvantages are dependence on observing the monitor of laptop/mobile phone, that it can be solved by installing five range colors of Light Emitted Diode (LED) on the socket in the feature, and delay time occurred by mind training procedure.

However, the disadvantage of the proposed method may be in the long term being in constant contact with these colors and temperatures may affect virtual sensation. However, our goal is to apply practical, non-invasive, inexpensive, and more convenient methods on upper limb prostheses to find a robust closed-loop feedback sensation and feel like a natural limb. Although, the only method that directly focuses on inducing temperature on amputees was generating heat on the limb according to with temperature sensed

Table 4 Total errors for each color

Healthy participants				Amputee participants			
Dark blue	<i>N</i>	Valid (amount of participants)	22	Dark blue	<i>N</i>	Valid (amount of participants)	5
		Missing	0			Missing	0
		Mean	2.82			Mean	1.4
		Median	3.00			Median	1.00
		Std. Deviation	1.918			Std. Deviation	0.8
		Minimum	0			Minimum	1
		Maximum	7			Maximum	3
Blue	<i>N</i>	Valid	22	Blue	<i>N</i>	Valid	5
		Missing	0			Missing	0
		Mean	4.91			Mean	1.33
		Median	5.00			Median	1.00
		Std. Deviation	2.486			Std. Deviation	0.47
		Minimum	0			Minimum	1
		Maximum	9			Maximum	2
Light blue	<i>N</i>	Valid	22	Light blue	<i>N</i>	Valid	5
		Missing	0			Missing	0
		Mean	4.82			Mean	1.75
		Median	5.00			Median	2.00
		Std. Deviation	2.648			Std. Deviation	0.43
		Minimum	0			Minimum	1
		Maximum	11			Maximum	2
Yellow	<i>N</i>	Valid	22	Yellow	<i>N</i>	Valid	5
		Missing	0			Missing	0
		Mean	4.18			Mean	1
		Median	4.00			Median	1.00
		Std. Deviation	2.594			Std. Deviation	0
		Minimum	0			Minimum	1
		Maximum	10			Maximum	1
Red	<i>N</i>	Valid	22	Red	<i>N</i>	Valid	5
		Missing	0			Missing	0
		Mean	1.18			Mean	0.75
		Median	1.00			Median	0.50
		Std. Deviation	1.868			Std. Deviation	0.82
		Minimum	0			Minimum	0
		Maximum	6			Maximum	2

by thermo-sensing elements that were put on the prosthetic hand [49, 50]. A comparison of previous investigations that used temperature inducing is shown in Table 7. In Table 7, invasive and non-invasive methods have been had applied to evaluate temperatures sensed by electronic skins and other types of thermosensors.

Moreover, in this experiment, we faced on some limitations such as the use of only one kind of measurement. Participants are asked about what they feel, but which can be evaluated by accurate methods like Functional Magnetic Resonance Imaging (fMRI) or Electroencephalography (EEG) to map activities of the brain's areas. Moreover, since we had a short time because of the spreading of the

Coronavirus Disease (COVID-19) pandemic, it is recommended to repeat this study for a longer duration. This experiment could be happened in an isolated room with different lights and room temperature so that the participants can sense deeply.

5 Conclusion

In conclusion, the lack of temperature sensation of the myoelectric prosthetic hands limits the daily activities of amputees. To this end, a non-invasive temperature sensation method is proposed to train amputees to sense temperature with psychophysical

Table 5 Repeated measures ANOVA followed by Tukey post hoc test was used for analysis

Tukey's multiple comparisons test	Mean Diff	95% CI of diff	Adjusted <i>P</i> Value
Healthy participants			
Tem1 (0–15 °C) 10 °C vs. Tem2 (15–25 °C) 20 °C	11.39	6.846–15.93	< 0.0001****
Tem1 (0–15 °C) 10 °C vs. Tem3 (25–35 °C) 30 °C	29.78	25.37–34.18	< 0.0001****
Tem1 (0–15 °C) 10 °C vs. Tem4 (35–45 °C) 40 °C	21.06	16.02–26.09	< 0.0001****
Tem1 (0–15 °C) 10 °C vs. Tem5 (45–48 °C) 48 °C	30.28	25.70–34.86	< 0.0001****
Tem2 (15–25 °C) 20 °C vs. Tem3 (25–35 °C) 30 °C	18.39	15.48–21.30	< 0.0001****
Tem2 (15–25 °C) 20 °C vs. Tem4 (35–45 °C) 40 °C	9.667	5.969–13.36	< 0.0001****
Tem2 (15–25 °C) 20 °C vs. Tem5 (45–48 °C) 48 °C	18.89	16.35–21.43	< 0.0001****
Tem3 (25–35 °C) 30 °C vs. Tem4 (35–45 °C) 40 °C	– 8.722	– 10.53 to – 6.918	< 0.0001****
Tem3 (25–35 °C) 30 °C vs. Tem5 (45–48 °C) 48 °C	0.5000	– 1.717 to 2.717	0.9568
Tem4 (35–45 °C) 40 °C vs. Tem5 (45–48 °C) 48 °C	9.222	6.533–11.91	< 0.0001****
Amputee participants			
Tem1 (0–15 °C) 10 °C vs. Tem2 (15–25 °C) 20 °C	6.8	3.6887–9.9113	< 0.01**
Tem1 (0–15 °C) 10 °C vs. Tem3 (25–35 °C) 30 °C	17	12.879–21.120	< 0.01**
Tem1 (0–15 °C) 10 °C vs. Tem4 (35–45 °C) 40 °C	3.4	0.143–6.656	0.3089076
Tem1 (0–15 °C) 10 °C vs. Tem5 (45–48 °C) 48 °C	– 5	– 7.785– – 2.214	0.058218
Tem2 (15–25 °C) 20 °C vs. Tem3 (25–35 °C) 30 °C	10.2	6.270–14.129	< 0.01**
Tem2 (15–25 °C) 20 °C vs. Tem4 (35–45 °C) 40 °C	– 3.4	– 6.411– – 0.389	0.3089076
Tem2 (15–25 °C) 20 °C vs. Tem5 (45–48 °C) 48 °C	– 11.8	– 14.294– – 9.305	< 0.01**
Tem3 (25–35 °C) 30 °C vs. Tem4 (35–45 °C) 40 °C	– 13.6	– 17.645– – 9.554	< 0.01**
Tem3 (25–35 °C) 30 °C vs. Tem5 (45–48 °C) 48 °C	– 22	– 25.67– – 18.32	< 0.01**
Tem4 (35–45 °C) 40 °C vs. Tem5 (45–48 °C) 48 °C	– 8.4	– 11.07– – 5.72	< 0.01**

** indicates a 0.01 significance level, **** indicates a 0.0001 significance level

sensory substitution. The conceptual method of temperature sensation in a bionic hand by extraordinary perceptual phenomenon is presented based on the psychophysical sensory substitution (principles of the human behavior), extraordinary perceptual phenomenon, and intelligence system theory to make a closed-loop controlling system for amputees. Therefore, healthy participants were experience temperature with their fingers while putting them in temperature adjustable mug and observed indicated color

at the GUI application by VR glasses. Besides, by mounting a Peltier onto the phantom digit zone of amputee participants, similar to the healthy participants, have been used the VR glasses to observe indicate color for them. Learning process based on Leitner technique during 31 days with 5 steps. In this research, two factors can affect mental training quality. In this research, three factors can affect mental training quality; type of the sensory stimulator, location of the stimulation, and the extra cognitive

Fig. 10 The time of numbness of participants in each temperature, the time of numbness (The time adaptively of fingers with temperature) for temperatures near human body temperature was more than other temperatures

Table 6 The performance of practical test of the proposed method by the amputee

Temperature	Tem1	Tem2	Tem3	Tem4	Tem5	Recall
Tem1	20	4	1	0	0	0.77
Tem2	6	13	5	0	0	0.57
Tem3	0	4	15	6	0	0.56
Tem4	0	2	6	17	0	0.74
Tem5	0	0	0	0	25	1.00
Precision	0.80	0.54	0.60	0.68	1.00	Accuracy = 72.58%

Table 7 Comparison of temperature stimulation methods on human sensation

Ref	Location	No. of participants	No. of sensors /actuators	Range of feedback level
[51]	Upper arm	One healthy	One Peltier element + thermocouple	extreme hot or cold
[52]	Biceps	One healthy	One Peltier element	hot (40 °C), lukewarm (35 °C), not much (30 °C), a little cold (20 °C), and cold(15 °C)
[9]	Left hand	One healthy	One Peltier element	Hot, Mild, Cold
[53]	Fingertip	One healthy	One Peltier element + PID	hot, or cold
This paper	Fingers and phantom digits	22 healthy + 5 Amputees	Water + one Peltier + colors	Five ranges(10–20–30–40–48)°C

load that might be generated during the experiment (such as the pain sensation). The advantages of the proposed method are the perception of the temperature only by a laptop or mobile phone is required without electronic components and extra batteries and solves the low energy consumption, time delay to response, additional weight, and prolonged time to changing the cold/warmth. The proposed method in the future could be implemented for other types of sensory feedback, and this method has enough potential for clinical application without any side effects.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethical Approval Approval was obtained from the institution review board of Tsinghua University. The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

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