ThermAirGlove: A Pneumatic Glove for Thermal Perception and Material Identification in Virtual Reality

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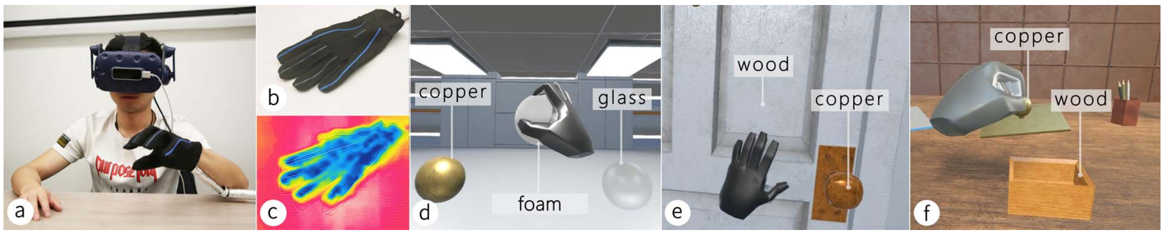

Figure 1: (a) a user wearing ThermAirGlove (*TAGlove*) and grasping the virtual object in VR, (b) the RGB image of *TAGlove*, (c) the thermal image of *TAGlove* filled with cold air, (d-f) Examples of *TAGlove* applications in virtual scenes, left to right: three virtual spheres with different materials, a wood door with a copper handle, a wood box with a copper lid.

Abstract

We present ThermAirGlove (*TAGlove*), a pneumatic glove which provides thermal feedback for users, to support the haptic experience of grabbing objects of different temperatures and materials in virtual reality (VR). The system consists of a glove with five inflatable airbags on the fingers and the palm, two temperature chambers (one hot and one cold), and the closed-loop pneumatic thermal control system. Our technical experiments showed that the highest temperature-changing speed of *TAGlove* system was 2.75°C/s for cooling, and the pneumatic-control mechanism could generate the thermal cues of different materials (e.g., foam, glass, copper, etc.). The user-perception experiments showed that the *TAGlove* system could provide five distinct levels of thermal sensation (ranging from very cool to very warm). The user-perception experiments also showed that the *TAGlove* could support users' material identification among foam, glass, and copper with the average accuracy of 87.2%, with no significant difference compared to perceiving the real physical objects. The user studies on VR experience showed that using *TAGlove* in immersive VR could significantly improve users' experience of presence compared to the situations without any temperature or material simulation.

Index Terms: Human-centered computing—Virtual reality; Human-centered computing—Haptic devices

1 Introduction

Recently, the topic of haptics in virtual reality (VR) has been attracting a large amount of research interest. The main goal of haptic feedback in VR is to improve the realness of the simulated scenario through touch. When we touch a real-world object, we can learn about the properties of its material through thermal cues. For instance, under the same room temperature, touching metal feels cooler than touching wood or plastic. As the skin of human fingers is usually warmer than the objects under the room temperature (24 - 26°C), the thermal perception of the material mainly comes the responses of cold thermoreceptors in the skin. The thermal conductivity and heat capacity are different among different materials [13], so the material composition of the object can be inferred through the decrease in skin temperature.

While a significant amount of research efforts have been focused on providing the kinesthetic force-based feedback and simulate the sizes/shapes of objects in VR [2, 4–6, 27, 36, 38, 39, 48–50], it is still challenging to perceive the virtual objects with similar size/shape yet different materials/temperatures. For example, two virtual cups with the same shape, one of which is made of steel and the other is plastic, will feel the same based on the force feedback in VR, while in the real world, the steel cup feels cooler than the plastic one. Ho's research [14] has showed that people could identify different real-world materials with significantly different thermal properties, ranging from foam, glass, wood, to copper. There are two key thermal cues for distinguishing different materials: the initial temperature-changing rate and the total changing amount in skin temperature throughout the contacting process. The materials with high contact coefficients, such as copper, could generate a higher initial cooling rate and a larger total temperature-changing amount in skin during the heat transfer process. In addition, the rigid ceramic Peltier-based thermoelectric cooler (TEC) can provide thermal cues to simulate the perception of materials and support material identification. This technique could potentially be applied to VR scenario, to provide thermotactile sensation of a user's hand grasping virtual objects. However, directly attaching multiple rigid TEC modules on a user's hands may result in movement restriction, and affect the user experience in VR.

In this paper, we present ThermAirGlove (*TAGlove*), a pneumatic glove that can provide on-hand thermal feedback in VR. The *TAGlove* system (Fig. 2) consists of a glove with five inflatable airbags attached on the fingers and the palm, two temperature chambers, and the pneumatic and thermal control system. By mixing the air in the room temperature and the air from the hot and the cold chambers, the system can achieve thermal signals in different intensities. Besides simulating VR objects in different temperature, *TAGlove* could simulate the thermal transient of hand-material contact and provide the thermal sensation of grasping objects in different materials (Fig. 1d-f), and support users' material identification in VR. Our technical experiments validated the thermal signals generated by the *TAGlove* system and the maximum temperature changing speed could achieve 2.75°C/s within the first two seconds. The results of the user-perception experiences showed that 1) the *TAGlove* system could provide five distinct levels of thermal feedback (ranging from very cool to very warm); and 2) *TAGlove* could support users'

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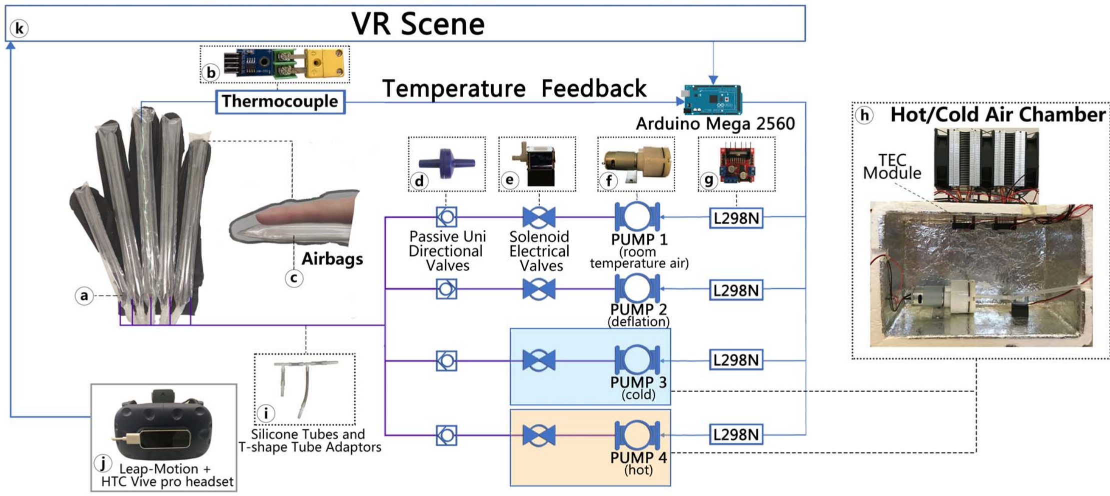


Figure 2: System Diagram of *TAGlove*: (a) *TAGlove*, (b) thermocouple, (c) inflatable airbags inside the glove, (d) passive uni-directional valves, (e) solenoid electrical valves, (f) air pumps, (g) L298N motor driver, (h) hot and cold air chambers, (i) silicone tubes and T-shape tube adaptors, (j) Leap-Motion device with the HTC Vive pro headset, (k) VR scene in Unity.

material identification among foam, glass, and copper with the average accuracy of 87.2%, with no significant difference compared to perceiving the real physical objects. The user studies on VR experience showed that using *TAGlove* in immersive VR could significantly improve users' experience of presence compared to the situations without any temperature or material simulation.

This paper makes the contributions in five folds:

- The *TAGlove* system with controllable pneumatic thermal feedback;
- The temperature-tracking experiments validating the thermal signals generated by *TAGlove*;
- The user-perception experiments evidencing *TAGlove*'s support on different levels of thermal-intensity perception;
- The user-perception experiments evidencing *TAGlove*'s support on virtual material identification;
- The user studies validating *TAGlove*'s capability of improving the experience of presence in VR compared to the conditions without thermal feedback.

2 Related Work

TAGlove was highly inspired by existing research on thermal haptics in HCI (Human-Computer Interaction), especially VR. We would also review previous research on simulating different materials through thermotactile feedback.

2.1 Thermal Feedback in HCI & VR/AR

In the early studies on thermal feedback for HCI, extensive research have been focused on the design of useful features of thermal display [18], and new thermal components to integrate with mobile devices [42] and to reduce reaction time [33, 34].

Wilson et al. conducted a series of research on thermal feedback in HCI, which provided essential design insights for on-hand thermal design [9, 10, 43, 44]. Following Wilson et al.'s insights, Tewell et al.'s research showed that thermal feedback enhanced the affective perception of text messages [40] and could facilitate navigation [41]. Singhal and Jones [37] evaluated thermal pattern recognition on the hand and arm with a single thermoelectric module, and proposed the model-based approach for designing thermal icons. More recently, researchers started investigating the thermal feedback in wearable accessories, such as finger ring [51], bracelet [25], earhook [23], etc.

Thermal feedback could also contribute to the immersive user experience in VR/AR, to simulate virtual temperatures [29, 35], season experience [30], wetness [24], and work as directional cues in VR [26]. Takaki et al. [22] presented a wearable haptic display that generates force and thermal feedback for augmented-reality applications. Han et al. developed HydroRing [11], a finger-worn device which could provide concurrent force, vibration and temperature feedback through a liquid medium. Among these research, there is no investigation focusing on simulating hand-material contact in VR, the real-world counterpart of which is an important haptic experience. The technique of TEC modules may potentially be applied to VR scenario, to provide the on-hand thermal sensation of touching virtual materials. However, directly attaching multiple rigid TEC modules on a user's whole hands for object grabbing in VR may restrict the fingers movement, and affect the user experience in VR. Compared to rigid TEC modules, *TAGlove* generates the on-hand thermal feedback by controlling the air temperature in the flexible airbags, without restricting the hand movement. One may argue that it is hard to control and maintain the temperature of air due to its heat capacity, and the liquid-based solution [11] could be a better alternative for high-speed thermal display [32]. We considered that the liquid-based solution might create weight illusion to the user. Recently, Xu et al. [46] implemented a non-contact cold thermal display by controlling low-temperature air flow. Thus, we chose to adopt the air-based solution for *TAGlove*.

2.2 Material Identification by Thermal Cues

There have been studies focusing on controlling thermal cues to support material identification in the real world. As one of the early studies, Caldwell and Gosney [3] used Peltier devices to model the thermal transient of a 40°C robotic hand contacting ice, heated iron, aluminum block, and foam. Their experiments showed that subjects could identify each material with accuracy above 80%. Taking a similar hardware setting, Ino et al. [17] showed that the recognition results for the simulated materials presented using the thermal display were equivalent to those measured with real materials. The experiments by Jones and Berris [19] further suggested that the temperature cues could be used to discriminate between materials, but only when the thermal properties were large. Later, Ho and Jones [13] adopted the semi-infinite body model [21] to simulate the thermal transient process of hand-material contact, and further proved the effectiveness of the semi-infinite body model for temperature control and supporting material identification.Adopting the same model for temperature control, Yang et al. [47] found that the spatial summation of thermal perception could improve the accuracy of temperature-based material discrimination. Richter et al. [31] proposed a prototype of haptic interface that reproduced five kinds of materials (aluminum, glass, rubber, polyacrylate and wood) on the touchscreen with thermal feedback. With their device, subjects could perform material identification with an average accuracy of about 50%. More recently, Gabardi et al. [8] designed a finger-worn thermotactile device, with an embedded Peltier module and a linear electromagnetic actuator. The device controlled the thermal feedback based on the semi-infinite body model, and produced the temperature trend of hand contacting with urethane, glass, and copper. Their experiments showed that subjects could identify the three simulated materials in an average accuracy of 76.19%.

These existing research suggested the feasibility of material identification/discriminination through thermal cues based on the semi-infinite body model. However, it is still unclear that how the thermotactile material simulation could be integrated into a wearable form factor with less constraint on the palm and fingers movement, and its effectiveness in improving immersive VR experience is still unexplored. In this paper, we present the design of *TAGlove* with five embedded airbags providing pneumatic thermal feedback in VR. Our experiments showed that *TAGlove* supported reliable material identification, and the thermal feedback for temperature and material simulation significantly improved the immersive VR experience.

3 *TAGlove* System Description

We designed the *TAGlove* system consisting of a pneumatic glove, two temperature chambers, and the pneumatic temperature control system. Fig. 2 illustrates an overview of the *TAGlove* system.

3.1 Pneumatic Glove

We designed a pneumatic glove embedded with five airbags on the fingers and the palm as shown in Fig. 2a. Each airbag was in the shape of a rectangle with the width of 2cm, and made of 0.2 mm non-elastic PE sheets, which ensured the closed contact with skin and would not skin temperature when contacting. To cover all the fingers and the palm area, we designed the length of the thumb airbag as 12cm and 20cm for the airbags of the other fingers. The height of inflated airbags is 1.5cm, so the total volume of the five airbags is 276mL, where the size is suitable for most people. Based on our empirical tests, the current system could full inflate all the airbags within 0.5s, and maintain the pressure at averagely 40 kpa inside the inflated airbags during the temperature-changing stage. The airbags connected to two peltier-driven temperature chambers, one hot and one cold, through the air-pump system. A type-K thermocouple (Fig. 2b, sampling frequency: 5Hz) was attached on the airbag on the middle finger to acquire the real-time temperature as the feedback for the closed-loop control.

3.2 Temperature Chambers

As shown in Fig. 2h, we designed and made the two temperature chambers using two foam boxes and four peltier modules. The volume of each foam box is 7L and its inner size is 340x220x160 (mm), which is the common size of foam boxes (similar to the mailing box) in the market. Each chamber contained two 40×40 (mm) peltier elements (Model NO.: TEC-12706), each of which was attached to a $90 \times 90 \times 160$ (mm) heat sink and three electric fans (12V0.15A). Each peltier module was connected to an individual power supply (12V6A) through the relay circuits with temperature sensors. One temperature chamber maintained the temperature at 68°C which was below the normal softening temperature of foam, and the other maintained at 2°C which was above the icing temperature, during inflation and deflation process. We also covered the inner surface of each temperature chamber with the foil for heat preservation.

3.3 Pneumatic Thermal Control System

The pneumatic thermal control system was based on an Arduino Mega 2560. Each pump was controlled by an external motor-driver circuit (L298N, Fig. 2g) with an external power supply of 24V5A, and each solenoid valve was controlled through a relay circuit. The peak flow of the air pump is 15L/min. We used three air pumps (Fig. 2f) to mix the hot, the cold and the room-temperature air into the airbags, and mainly used the pump in the room-temperature for maintaining the air pressure. We also used one pump for deflation. For reducing the heat transfer during the air-pumping process, the cold and the hot pumps with solenoid valves (Fig. 2e) were placed into the temperature chambers, and the silicone tubes (Fig. 2i) were wrapped with thermal insulation materials. The closed-loop control system diagram is shown in Fig. 3, the VR application detected the object-grabbing/touching action, and triggered the temperature tracking process. Taking the temperature reference of the thermal cue as the set point and the measured temperature reading of the thermocouple as the feedback, the micro-controller controlled the pneumatic control system to mix the air from the cold and the hot chambers and the room-temperature air, to achieve the target point of air temperature in the *TAGlove* airbags.

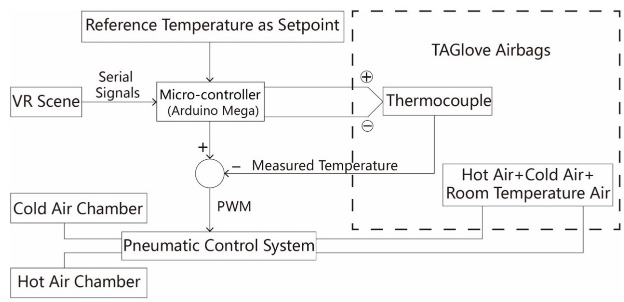


Figure 3: Closed-loop temperature control system for *TAGlove*.

While being integrated with VR, the system tracks the user's hand movements using Leap-Motion, and triggers the pneumatic thermal control system when the user's hand touches/grabs the virtual object.

4 Thermal Performance Evaluation: Temperature Tracking

We first evaluated *TAGlove*'s performance on generating different levels of thermal feedback in the temperature-tracking experiments.

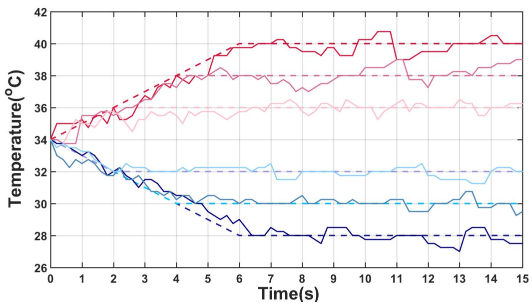
4.1 Thermal Parameter Test

Regarding *TAGlove*'s performance in temperature tracking, we first measured the step response of temperature change for a set of thermal feedback that combined the parameters that were commonly used in existing thermal research [10, 40, 43], including two directions of change (DoC: warming and cooling), two rates of change (RoC: 1°C/sec - slow or 2°C/sec - fast), and three intensities of change (IoC: 2°C, 4°C and 6°C). A common neutral skin temperature of 34°C was set as the start temperature as this is within the defined "neutral zone" of the thermal sensation [18] and has been used in other studies [10, 43, 44]. Therefore, there were in total 2 directions $\times$ 2 rates $\times$ 3 intensities = 12 thermal stimuli, see Table 1.

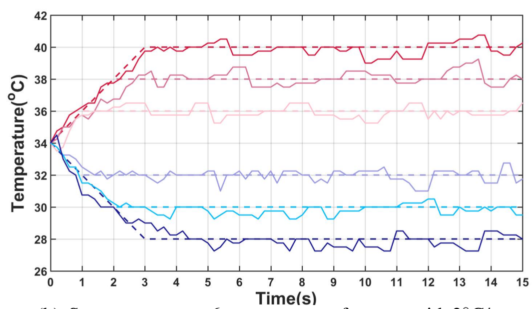
In the temperature tracking experiment, we implemented the PID algorithm to evaluate the performance of the system in tracking temperature references. We set up the sampling period of the temperature control system as 0.2s, in order to achieve precise responses and fast dynamics for both the cooling and the heating phases. Fig. 4 illustrates the system step responses to the temperature references of the twelve thermal stimuli. The results showed that the overall mean absolute error (MAE) of the temperature-changing proportional stage (i.e. before reaching the target temperature) was 0.37°C, and 0.31°C

Table 1: Stimuli by DoC, RoC, and IoC.

	Warm		Cool	
Intensity	1°C/sec	2°C/sec	1°C/sec	2°C/sec
2°C	36°C (36slow)	36°C (36fast)	32°C (32slow)	32°C (32fast)
4°C	38°C (38slow)	38°C (38fast)	30°C (30slow)	30°C (30fast)
6°C	40°C (40slow)	40°C (40fast)	28°C (28slow)	28°C (28fast)



(a) Step responses to 6 temperature references with 1°C/sec



(b) Step responses to 6 temperature references with 2°C/sec

Figure 4: Step responses of the temperature-control system of *TAGlove*: the dotted lines were the theoretical temperature data, and the solid lines were the measured data from *TAGlove*.

for the stable stage. The overall maximum measured error (MME) during the proportional stage was 0.95°C, and 0.95°C for the stable stage. Table 2 shows all MAEs and MMEs of each thermal stimulus.

4.2 Thermal-based Material Simulation

We adjusted the parameters of PID control algorithm on our system and then measured the step responses of temperature change simulating user's hand contact with three different materials (foam, glass and copper). In order to accurately replicate the typical heat transfer processes of human skin contacting different materials by controlling the airbag temperature, we modelled the temperature of the airbags in *TAGlove* with the common hand temperature (34°C) as the starting point, since the airbags were closely in contact with the fingers and the palm. We assumed the virtual materials were placed in the common room temperature (26°C). When the contact with a virtual material occurs, the airbags temperature will drop to simulate the transient heat-flux of the skin-material contact, and the rate of temperature dropping is correlational to the thermal conductivity of the material (Table 3).

To calculate the temperature references, we adopted the semi-infinite body model [21] that takes into account the influence of the thermal contact resistance. After the contact of skin and material occurs, Equation 1 and 2 calculated the temperature transient of both the skin and the object surfaces respectively.

Table 2: MAEs and MMEs of the thermal signals.

			Proportional Stage		Stable Stage	
DoC	RoC (°C/s)	IoC (°C)	MAE (°C)	MME (°C)	MAE (°C)	MME (°C)
Cool	1	2	0.16	0.45	0.24	0.75
		4	0.41	1.15	0.22	0.75
		6	0.40	1.00	0.31	1.00
	2	2	0.29	0.60	0.29	1.00
		4	0.16	0.50	0.27	0.75
		6	0.59	2.00	0.35	1.00
Warm	1	2	0.31	0.70	0.32	1.50
		4	0.43	1.05	0.39	1.00
		6	0.45	1.15	0.38	1.00
	2	2	0.46	1.05	0.30	0.75
		4	0.49	1.10	0.36	1.25
		6	0.31	0.70	0.34	1.00

Table 3: Thermal properties of human skin [16] and materials [47].

Material	Thermal Conductivity $k[W/m\cdot K]$	Density $\rho[kg/m^3]$	Specific heat $c[J/kg\cdot K]$
Skin	0.37	1000	3770
Foam	0.026	70	1045
Glass	1.4	2500	750
Copper	401	8933	385

$$
\begin{aligned}
T_s(t) &= \frac{A}{B}\left\{1-e^{\alpha_s B^2 t} erfc[B(\alpha_s t)^2]\right\}+T_{s,i},\\
A &= \frac{-(T_{s,i}-T_{o,i})}{k_s R_{s-o}}, B=\frac{1}{k_s R_{s-o}}[1+\frac{(k_s\rho_s c_s)^{1/2}}{(k_o\rho_o c_o)^{1/2}}].
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
T_o(t) &= \frac{C}{D}\left\{1-e^{\alpha_o D^2 t} erfc[D(\alpha_o t)^2]\right\}+T_{o,i},\\
C &= \frac{T_{s,i}-T_{o,i}}{k_o R_{s-o}}, D=\frac{1}{k_o R_{s-o}}[1+\frac{(k_o\rho_o c_o)^{1/2}}{(k_s\rho_s c_s)^{1/2}}].
\end{aligned} \tag{2}
$$

where $T_{s,i}$, $T_{o,i}$, and $T_s(t)$, $T_o(t)$ are respectively the initial temperatures and the transient temperatures as functions of time t. R_{s-o} is the thermal contact resistance computed as: $R_{s-o}=(0.37+k_o)/(1870k_o)[m^2K/W]$. k_s, k_o represent the thermal conductivity; ρ_s, ρ_o are densities; c_s, c_o are specific heat values. Finally, α_s, α_o are thermal diffusivity coefficients computed as: $\alpha_{s,o}=k_{s,o}/(\rho_{s,o}c_{s,o})[m^2/s]$. Subscripts s and o refer to *skin* and *object* respectively.

As the airbags were closely in contact with the user's hand, we adopted the skin temperature calculated by Equation 1 as the references for the airbag temperature control. The results of tracking the temperature references for material simulation are shown in Fig. 5. We observed the overall MAE within the first 2 seconds of 0.28°C for the reference simulating copper, 1.28°C for glass, and 0.41°C for foam (grand average 0.66°C). The MAE of the following time (2 to 10 seconds) was 1.01°C for copper, 0.39°C for glass and 0.27°C for foam (grand average 0.56°C). The MME was 0.74°C for the reference simulating copper, 2.76°C for glass, and 0.73°C for foam (grand average 1.42°C) in the temperature-changing proportional stage. The MME was 1.89°C for the temperature reference simulating copper, 1.40°C for glass, and 0.75°C for foam (grand average 1.35°C) in the stable stage.

With the validated thermal signals, we then conducted the user-perception experiments, to investigated users' perception of the thermal feedback in different levels, and their capability of material discrimination using *TAGlove*.

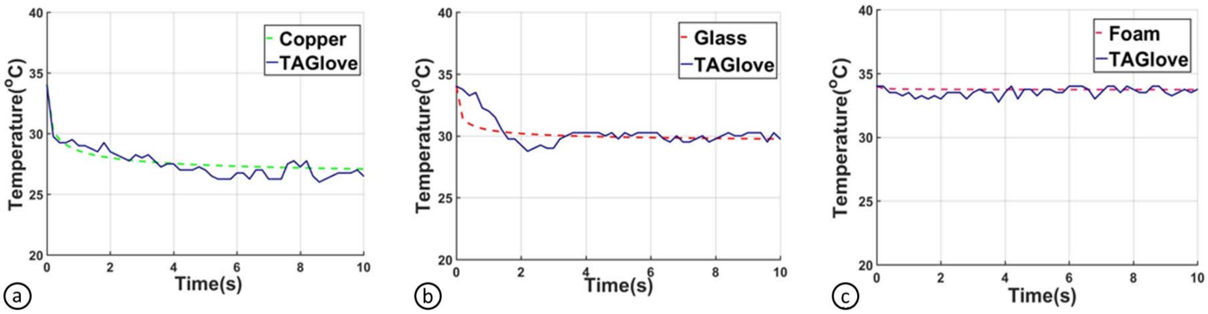


Figure 5: Step responses to the temperature references for material simulation: (a) copper, (b) glass, (c) foam. The dotted lines are the theoretical temperature data, and the solid lines are the measured data during the closed-loop control process.

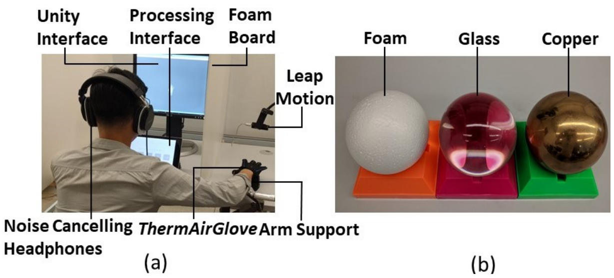


Figure 6: (a) Setup of the study environment, (b) Real foam, glass, and copper balls for material identification.

Figure 7: The participant-response interfaces for user-perception experiments of *TAGlove*: (a) thermal stimuli intensity rating. (b) material identification.

5 User-Perception Experiment 1: Thermal-Stimuli Intensity Rating

In the first user-perception experiment, we investigated how users perceived the thermal stimuli provided by *TAGlove* in different directions, rates, and intensities of temperature change. We adopted the methodology of subjective intensity rating which has been applied and validated in the research of thermal feedback in HCI [9, 44].

5.1 Participants

Twelve participants, all right-handed, were recruited from a local university. The average age was 25.2 years old (SD = 2.14). Three of them had experience with thermal user interface before.

5.2 Apparatus and Stimuli

Fig. 6a shows the setup of the study environment, including the *TAGlove* system, a Windows-based touch tablet for the participants inputting their responses, and an external 21” monitor for displaying the time information. The participant wore *TAGlove* on his/her right hand which was placed behind a large cardboard to avoid visual bias. In addition, the participant rested his/her arm on an arm support fixed on the table, to minimize possible fatigue. The participant also wore a pair of noise-cancelling headset to avoid auditory bias.

The set of the thermal stimuli included the twelve combinations of temperature parameters in Table 1. As the skin temperature of the participants ranged from 33.5°C to 34.75°C, averagely 33.85°C (SD = 0.46), the neutral starting temperature of 34°C would be closed to overall skin temperature, producing no sensation of warm or cool. We also included the neutral temperature of 34°C (34n) in the stimuli set, so the test set included 13 stimuli (i.e., 28fast, 28slow, 30fast, 30slow, 32fast, 32slow, 34n, 36fast, 36slow, 38fast, 38slow, 40fast, and 40slow).

5.3 Experiment Design

A within-subject design was used with three independent variables: direction of change (DoC), intensity of change (IoC), and rate of change (RoC). We measured participants’ subjective ratings of thermal intensity and the trial-completion time as the dependent variables. In each trial, a thermal stimulus presentation comprised of a 10s stimulus followed by a 40s deflation period for the skin temperature naturally return to the neutral temperature. There were no visual or auditory cues during the stimulus. The monitor in front of the participant showed the count-down process, and the tablet screen remained blank during the 10s stimulus. After the stimulus, the slider (Fig. 7a) was presented for the participant to rate his/her perceived intensity in a continuous scale from Very Cold (slider value: 1.00) to Very Hot (slider value: 5.00), and the slider value for Neutral is 3.00. Each participant performed the experiment in one sitting, including breaks. Each stimulus was repeated for three times, and presented in random order. The experiment lasted for around 1 hour. In total, each participant did a total of 13 stimuli × 3 repetitions = 39 trials.

5.4 Procedure

The experimenter began with introducing the logistics of the experiment, and then instructed the participant to fill a pre-questionnaire with demographic information. The experimenter then helped the participant to put on the glove that best fits his/her hand. Each experiment session contained one training block and one testing block. In the training block, the experiment system randomly selected five stimuli for the participant to practice the intensity-rating tasks. After the training block, the thermal feedback was turned off, and the participant took off the glove for 5 minutes, to allow the skin to return to the same temperature measured before the training block. The experimenter then helped the participant put on the glove, and all the 39 stimuli were presented in random order. The participants were instructed to provide their ratings as fast as possible, and click the Next button to finish the current trial.

5.5 Results

5.5.1 Subjective Intensity Ratings & Trial-Completion Time

Before the statistical analysis, we post-processed the participants’ subjective intensity ratings by subtracting the original rating values by 3 and taking the absolute values of the subtraction results. This approach has been used in other HCI research related to thermal feedback [9, 44]. Therefore, the processed intensity ratings ranged from 0.00 (Neutral) to 2.00 (Very Intense). Fig. 8 shows the descriptive results of subjective intensity ratings.

A multi-factorial repeated-measures ANOVA was performed on the intensity ratings, and the results showed a significant effect of IoC on the subjective intensity ratings ($F(2, 22) = 10.47$, $p < 0.005$, $\eta_p^2 =$

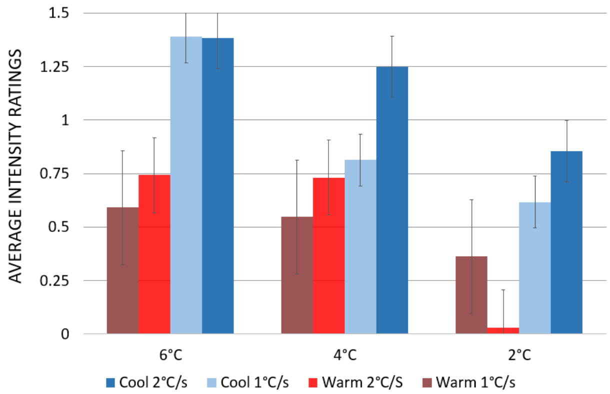


Figure 8: Average intensity ratings of the thermal stimuli.

0.488). Post-hoc pairwise comparison showed significant differences in the intensity ratings between 2°C and 4°C ($p < 0.005$) and 2°C vs. 6°C ($p < 0.005$), while there was no significant difference between 4°C vs. 6°C. RoC also had a significant effect on the intensity ratings (F(1, 11) = 5.79, p <0.05, $\eta_p^2 = 0.345$). The higher RoC (2°C/sec) was rated significantly more intensive than the lower ROC (1°C/sec, $p < 0.05$). In addition, DoC placed a significant effect on the intensity ratings (F(1, 11) = 7.00, p <0.05, $\eta_p^2 = 0.389$). Post-hoc pairwise comparison showed that the cooling process was rated significantly more intensive than the warming process ($p < 0.05$). One possible reason is that cold receptors outnumber warm receptors in the skin, and the differential threshold for cooling is usually lower than that of warm one [20].

While the independent variables yielded significant effects on the subjective intensity ratings, the multi-factorial repeated-measures ANOVA showed that they did not significantly affect the trial-completion time (Overall Mean = 4.45s, SD = 1.42). This could be due to that the participants might have made their decision on the rating within the 10s stimulus period, so they can select the slider's value quickly once the stimulus stopped.

5.5.2 Thermal Feedback Clustering

Besides the multi-factorial repeated-measures ANOVA on the intensity ratings, we performed a k-means clustering process to categorize the thirteen tested thermal stimuli into different levels. The goal of the clustering process was to minimize the within-cluster difference and maximize the between-cluster difference of the intensity ratings. The results showed that the thirteen thermal stimuli could be divided into five clusters as shown in Table 4. The repeated-measures ANOVA showed that the clustering results had a significant effect on the intensity ratings (F(4,44) = 31.48, $p < 0.0005$, $\eta_p^2 = 0.741$), and there was no significant difference among the stimulus within the same cluster. Post-hoc pairwise comparison showed a significant difference in the intensity ratings between all clusters.

Table 4: Results of K-Mean clustering of the thermal feedbacks. The values in the brackets are the standard deviations.

Cluster ID	Stimuli	Average Intensity Rating
C1	28fast, 28slow, 30fast	1.66 (0.13)
C2	30slow, 32fast	2.17 (0.16)
C3	32slow, 34n, 36slow	2.56 (0.12)
C4	36fast	2.97 (0.14)
C5	38slow, 38fast, 40slow, 40fast	3.72 (0.15)

These results suggested that *TAGlove* could generate five different levels of thermal stimuli that received significantly different subjective intensity ratings from the users. In addition, considering the power consumption for different thermal parameters, the power requirement increases as the IoC and the RoC increase. The clustering result suggested a set of power-friendly parameters. That is, for one particular cluster of thermal intensity, future design could consider the stimulus with the lowest values of IoC and RoC. For instance, it consumes less power to use 30fast than 28fast and 28slow to achieve the thermal intensity of Cluster 1, and 38slow could be the power-friendly setting for Cluster 5.

6 User-Perception Experiment 2: Material Identification

Besides the user-perception experiment on different levels of thermal intensities, we also investigated the feasibility of performing material identification based on the temperature signal of *TAGlove*.

6.1 Participants

We recruited twelve participants, and none of them participated in the previous perception experiment. The average age was 25.3 years old (SD = 2.19). The skin temperature of the participants ranged from 33°C to 34.75°C, averagely 33.83°C (SD = 0.54). All of them are right-handed.

6.2 Apparatus and Stimuli

We adopted the experiment setup similar to the previous experiments. In this experiment, we stimulated the participant grabbing the 10cm sphere of a particular material with his/her dominant hand. Therefore, we developed a Unity3D-based experiment system with the LeapMotion device above the table. The device tracked the participant's hand movements and controlled the movements of a virtual hand accordingly. When the system detected the collision between the virtual hand and the virtual sphere, it activated the thermal cues accordingly. The Windows-based touch tablet and the external monitor only displayed the time information and the input interface (Fig. 7b), and the hand-tracking process performed in the back-end. Besides the virtual sphere-grabbing system, we also included the condition of grabbing real materials, with three real spheres of copper, glass, and foam, as shown in Fig. 6b. All these real spheres were in the diameter of 10cm.

There were two groups of material stimuli: the real objects and the temperature signals of *TAGlove*. The real-object stimuli included the touch of the foam, the glass, and the copper balls, and they were used as the ground-truth condition for material discrimination. The *TAGlove* stimuli included the thermal signals for material simulation as shown in Fig. 5.

6.3 Experiment Design

We adopted a within-subject design with two independent variables: the type of stimuli, and the type of material. We measured three dependent variables: the accuracy of material discrimination, the trial-completion time, and the subjectively perceived workload. In each trial, the participant was instructed to keep the grabbing posture without lifting the ball for 10s with the activated thermal cue. After the 10s stimulus, three buttons with the names of the materials were presented on the touch tablet to collect the participant's response. There was a 40s break between two trials, for the skin to naturally return to the resting temperature. Each participant performed the experiment in one sitting, including breaks. The two types of stimuli, real and *TAGlove*, were presented to the participants in two sequential sub-sessions in a counter-balanced order. Within each group of stimuli, each material was repeated for five times, and presented in a random order. The experiment lasted for around 40 mins. In total, each participant did a total of 2 types of stimuli $\times$ 3 materials $\times$ 5 repetitions = 30 trials.

6.4 Procedure

We followed the similar procedure of "Introduction - PreQuestionnaire - Training - Testing" in the previous perception experiments.

During the training, the participants were first instructed to freely experience the material stimulus as much as possible until they reported that they were familiar with the three stimuli. Then they entered another stage for the training block, in which the participant practiced identifying five random material stimuli without data recording. In between the training block and the testing block, the thermal feedback was turned off, and the participant took off the glove for 5 minutes, to allow the skin to return to the same temperature measured before the training block.

After the break, the experimenter helped the participant put on the glove again, and started the testing block. There were no visual or auditory cues when stimuli were presented. The participants were instructed to touch the real spheres without picking up them (see more details in the video), and provide their choices after the end of the stimulus as fast as possible, then click the Next button to confirm and complete the trial. The task of material perception requires the participant to physically feel the thermal cue and mentally recognise the material type. Therefore, after finishing all the trials for one condition, the participant was asked to fill the NASA-TLX questionnaire [12] to rate his/her perceived workload, to investigate if *TAGlove* creates additional workload for the participant.

6.5 Results

6.5.1 Accuracy & Trial-Completion Time

A multi-factorial repeated-measures ANOVA on the accuracy showed no significant effect of the type of stimuli ($\eta_p^2 = 0.024$), meaning that there was no significant difference in terms of accuracy yielded by the real-object and the *TAGlove* material stimulation. The small effect size indicated a small to moderate effect of the type of stimuli on the accuracy. There was an significant effect of the type of material on the accuracy (F(2,22)=6.31, $p < 0.05$, $\eta_p^2 = 0.365$). Post-hoc pair-wise comparison showed that the participants identified foam and glass significantly more accurately than copper (foam vs copper: $p < 0.005$, glass vs copper: $p < 0.05$). As shown in Fig. 9, in both conditions of *TAGlove* and real objects, the participants tended to confuse copper and glass. This because these two materials have more similar thermal properties when compared to foam.

	TAGlove			Real Objects		
	Copper	Glass	Foam	Copper	Glass	Foam
Copper	**90.0%**	6.67%	0.03%	**80.0%**	18.3%	1.67%
Glass	18.33%	**81.67%**		13.33%	**86.67%**	
Foam		10.0%	**90.0%**			**100%**

Figure 9: Confusion table for material discrimination: row is the stimuli and the column is the participants' response.

The multi-factorial repeated-measures ANOVA on the response time showed no significant effect of the type of stimulus nor the type of material (*TAGlove* copper: Mean = 2.37s, SD = 0.84; *TAGlove* glass: Mean = 2.22s, SD = 0.84; *TAGlove* foam: Mean = 2.31s, SD = 0.90; real copper: Mean = 3.05s, SD = 0.98; real glass: Mean = 2.77s, SD = 0.73; real foam: Mean = 2.65s, SD = 0.64).

6.5.2 Task Workload

We performed a pair-wise Wilcoxon Signed Ranks Test on the NASA-TLX questionnaire responses to compare the perceived workload of the real-object and the *TAGlove* material stimulation. The results showed no significant difference between these two types of material stimulation for all the questionnaire items and the total score of the NASA-TLX questionnaire. In addition, the effect sizes (values of r) for all the comparison were smaller than 0.2, indicating the type of stimulation had a small effect on the perceived workload, showing the *TAGlove* system brought no significantly additional workload for the participants compared to the real-material situation. Fig. 10 shows the descriptive results of the NASA-TLX questionnaire.

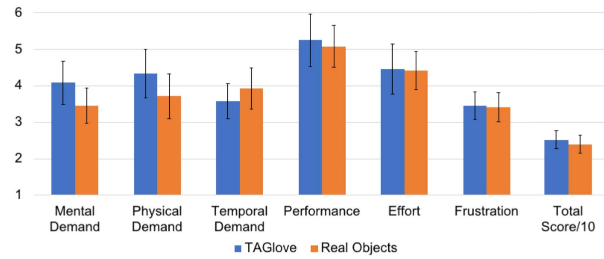


Figure 10: Average NASA-TLX ratings for material identification.

7 User Study on VR Experience with *TAGlove*

With the user-perception experiments validating the effectiveness of the thermal signals generated in *TAGlove*, we further conducted the user studies to investigate how *TAGlove* could affect users' sense of presence in immersive VR.

7.1 Participants

Twelve participants, with an average age of 25.3 years old (SD = 3.34), were invited. To avoid potential bias in the participants' subjective ratings, we adopted the following strategies as suggested in [7]: 1) all these participants did not attend the previous experiments; 2) the study facilitator was from the same ethnic group as the participants; 3) the facilitator did not know the participants in person beforehand, and did not explicitly disclose any personal association with the system. One participant stated that he never tried HMD-based VR before, while the rest had tried HMD-based VR for a few times. The average skin temperature was 33.89°C.

7.2 Apparatus

We developed a VR application using Unity3D 2018 (Fig. 11). The application used HTC Vive Pro HMD, a Leap-Motion hand-tracking device, and the *TAGlove* system. The Leap-Motion device supported free-hand interaction in the game. There were five virtual objects in the VR game: three spheres in different materials (i.e., foam, glass, and copper), and two cups of water (i.e., warm and cool). There were three modes of object manipulation: 1) using the bare hands without *TAGlove* (denoted as *BareHand*), 2) wearing *TAGlove* with inflating the room-temperature air only, without any temperature or material simulation (denoted as *TAGlove_F*), 3) wearing *TAGlove* with controlled pneumatic thermal feedback for temperature and material simulation (denoted as *TAGlove_TF*).

7.3 Task and Procedure

Each session included one participant and one experimenter. The experimenter first taught the participant how to grab virtual objects using bare-hand movement. The participant then went through three sub-sessions of VR interaction representing three modes of object manipulation. In each sub-session, he/she could freely interact with the virtual objects by picking up, touching, moving, and rotating the objects, and the goal of the game is to put the virtual objects into the boxes with the correct labels. After each sub-session, the participants responded to the haptic-related questions from the presence questionnaire [45], and moved to the next mode. The visual and auditory feedback was the same across the three modes, and the three modes was presented in a Latin-square-based counterbalanced order. At the end of the study, the participant was asked to propose a few potential scenarios that *TAGlove* can be applied.

7.4 Results

Friedman Test showed the type of the control mode significantly affected the perceived naturalness of the interaction ($\chi^2(2) = 16.19$, $p < 0.0005$), consistency of VR and real world ($\chi^2(2) = 19.3$, $p <$ 0.0005), capability of touch-based exploration ($\chi^2(2) = 18.59$, $p <$

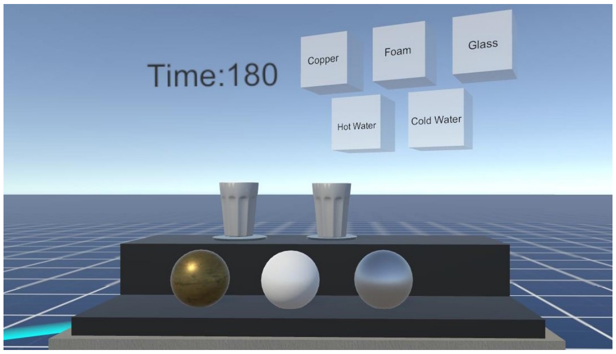


Figure 11: The virtual scene for the user study.

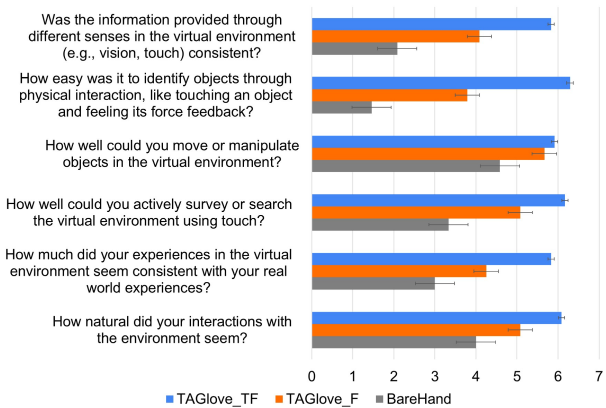


Figure 12: Questionnaire responses on the haptic experience.

0.0005), ease of object identification through touch ($\chi^2(2) = 23.53$, $p < 0.0005$), and consistency of the multisensory information in VR ($\chi^2(2) = 19.96$, $p < 0.0005$). Post-hoc pairwise Wilcoxon Signed Ranks Test showed that *TAGlove_TF* yielded significantly higher ratings of all these questionnaire items than *BareHand* and *TAGlove_F*, and *TAGlove_F* was significantly higher rated than *BareHand*. There was no significant difference among these three conditions for the participants' responses to the question on the capability of freely exploring the virtual environment, and this may indicate that the hardware setting of *TAGlove* (e.g. tubes) did not place constraints on user's hand movement in VR. Fig. 12 illustrates the comparison among these three conditions. While experiencing the *TAGlove_TF*, one participant commented, *"I can distinguish copper, glass, and foam by just looking at them, but the different temperature feelings of grabbing them make me feel more real."* Another participant mentioned, *"The feel of the temperature especially helped me figure out which is warm water and which is cool water, because they look very similar."* Regarding to the on-hand airbags, one participant commented that he did not quite feel the inflated airbags affecting his experience in VR.

8 Discussion

The above experimental results showed the capability of *TAGlove*. Here we discuss some possible use cases of *TAGlove* that we collected during the VR user studies. One straight-forward application is entertainment, such as VR gaming and multimedia. The participants also mentioned that the thermal feedback of virtual materials contact might contribute to skill training (e.g., fire escape, surgery, etc.). This echoed with existing research suggesting that the haptic feedback could potentially facilitate motor skill acquisition and transfer in VR training [1, 28]. Another interesting application from the participants was that *TAGlove* could be used by visually impaired users in VR, to enhance their VR exploration.

We also identified a few limitations in our current system. Firstly, while *TAGlove* could achieve five distinct clusters of thermal feedback, the range of the intensity ratings (i.e., from 1.6 for C1 to 3.7 for C5 as shown in Table 4) did not fully cover the rating spectrum (i.e., 1.0 to 5.0). This indicates that the current system may not achieve the cases that are perceived as extremely hot/cold by the participants. This could be due to the heat transfer between the air in the tube and the environment during the pumping process. This could be solved with better insulation in the future. In the current work, we did not measure the warm and the cool thresholds for *TAGlove*, or test the just noticeable difference (JND) for *TAGlove*. Therefore, more comprehensive studies need to be done to evaluate the user perception of *TAGlove* and pneumatic thermal feedback in a general sense. In addition, the current control of the thermal signal (Fig.4) may seem to be a little unstable. This could be due to the sensitivity of the thermocouple, and the control mechanism can be improved using the thermal sensor with higher response speed.

Secondly, we mainly tested copper, glass, and foam for material identification, as they are largely different from each other in terms of thermal properties. This followed the results of existing real-world material discrimination research that the subjects could discriminate two materials with the ratio of the contact coefficients exceeded three [15]. Hence, for different types of metal which own contact coefficients with little difference, such as copper, aluminium, and steel, it is difficult to discriminate these materials only through thermal cues even for the real-world objects. In the future, we plan to experiment with more types of materials covering a wider range of thermal properties within the distinguishable range of humans.

Last but not least, the current *TAGlove* system mainly focuses on controlling the pneumatic thermal signal, but there is no closed-loop control mechanism for the air-pressure feedback. In addition, we did not focus on the weight of the object in the current work. While it may be possible to generate simultaneous weight and thermal feedback using liquid, it is challenging to control these two liquid-based feedback concurrently. On the other hand, the force feedback can be offered by exoskeleton or mechanical structures which can be integrated with the pneumatic thermal feedback in the future work. We will also incorporate the pressure sensor into the *TAGlove* airbags to achieve different levels and patterns of the force feedback, and investigate how the on-hand pneumatic force feedback could enhance the haptic perception on other material properties of virtual objects, such as softness and roughness.

9 Conclusion

In this paper, we present ThermAirGlove (*TAGlove*), a pneumatic glove with embedded airbags which provides on-hand thermal feedback in VR. Besides simulating VR objects in different temperatures, *TAGlove* could generate the thermal cues of different materials by controlling the air temperature. A series of user-perception experiments showed that the *TAGlove* system could provide five distinguishable levels of thermal sensation (ranging from very cool to very warm), and the thermal feedback could support users' material identification, with no significant difference compared to perceiving the real physical objects. The user studies on VR experience showed that using *TAGlove* in immersive VR could significantly improve users' experience of presence compared to the current VR settings in the commercial markets. The user studies also suggested the thermal feedback played a vital role in the improvement of VR experience.

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