# Too Hot to Handle: An Evaluation of the Effect of Thermal Visual Representation on User Grasping Interaction in Virtual Reality

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## ABSTRACT

Influence of interaction fidelity and rendering quality on perceived user experience have been largely explored in Virtual Reality (VR). However, differences in interaction choices triggered by these rendering cues have not yet been explored. We present a study analysing the effect of thermal visual cues and contextual information on 50 participants' approach to grasp and move a virtual mug. This study comprises 3 different temperature cues (baseline *empty*, *hot* and *cold*) and 4 contextual representations; all embedded in a VR scenario. We evaluate 2 different hand representations (*abstract* and *human*) to assess grasp metrics. Results show temperature cues influenced grasp location, with the mug handle being predominantly grasped with a smaller grasp aperture for the hot condition, while the body and top were preferred for baseline and cold conditions.

### Author Keywords

Virtual Reality, Grasping Metrics, Hand Tracking, Hand Interaction

### CCS Concepts

•**Human-centered computing** → *Interaction design theory, concepts and paradigms;* **Virtual reality; Gestural input; Human computer interaction (HCI);** User studies;



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## INTRODUCTION

Immersive headsets have experienced an unprecedented growth in consumer availability [60], with companies such as Facebook, Microsoft or Samsung enabling accessible VR experiences for the masses. The sector's growth prospects reflect its potential to reshape the way people communicate [64, 91], play [43], work [45, 50] and learn [38, 107], achieving high levels of immersion [10].

Intuitive interaction in immersive environments plays a key role in increasing presence [36] which in turn can improve the overall user quality of experience. Seamless interactive VR systems often rely on hand interaction due to their multiple degrees of freedom [78] and human ability to use hands for acquiring and manipulating objects [2, 41, 63, 94]. Previous studies have shown that bare hand interaction (i.e. without the use of supplementary wearables) is linked to ease of access and naturalness. This is due to the absence of constraints imposed by wearable devices and its potential in delivering natural, intuitive and effective interaction in immersive environments [37, 49, 56, 73, 97]. When creating new bare hand interactive systems, several studies rely on predefined sets of gestures for natural interaction [22, 103, 104]. These interactions have predominantly been designed by researchers for optional recognition rather than for naturalness, being often arbitrary and not intuitive enough [66]. Therefore, one of the interaction challenges in VR is to improve the intuitive nature of interaction by improving natural grasping quality [67], thus mimicking the behaviour our human hands have in real environments [88].

Previous literature has explored the essential influencing factors to grasping real objects, with these being texture, hardness, weight and temperature/thermal conditions [5, 46]. Rendered textures and perceived hardness of objects and their effect on usability and user perception have been widely explored in immersive systems, with authors exploring texture repre-


(a) Abstract (b) Human (c) VR Scenario (d) Basic (e) Label (f) Glass (g) Context Objects

**Figure 1. Conditions under study, with 1(a) and 1(b) showcasing the human hand representations and 1(d), 1(e), 1(f) and 1(g) showcasing the VR environment conditions alongside visual thermal cues.**

sentations using *"custom-made"* haptic actuators [5, 7, 32]. Additionally, thermal haptic feedback has been used to supplement immersive environments. Recent studies have applied thermal haptic feedback in differing configurations, namely, around the wrist [61], to augment emotions [89], show directional cues for users [62], guide user behaviour [90] and evaluate users' perception [5, 108]. However, the effect of visual thermal cues for grasping interaction in VR has not been explored.

We present the first study evaluating thermal cues and their effect on grasp metrics in VR. Across 50 participants we report on user grasp aperture, grasp type and grasp location on the object under different visual thermal cues. We further evaluate four different contextual representations of the virtual environment to assess the influence of thermal visual feedback on grasp interaction. Findings from this study can be used as guidelines for interaction design, helping developers and designers to select the most suitable visual cues for facilitating an intuitive interaction with virtual objects and support improved natural interaction design for VR.

## RELATED WORK

### Hand Interaction in VR

Hand interactions in VR were initially developed using instrumented gloves [29], which inspired the development of wearable equipment such as wireless data gloves [44], markers [94] and electromyographic armbands [96, 106]. Wearable devices have been widely used for hand interaction methods, however, they inherently constrain human motion [101] and they have been often linked to discomfort [87], time-consuming configuration and problems with wider user adaptation [35].

As a result of these constraints, researchers have considered systems that do not require the full instrumentation of the hand [41] or devices that allow bare hand interaction [2, 34, 103]. Hand based interaction that enables users to manipulate objects as if they were real is known as grasping [3, 16]. This natural interaction with objects in VR plays an important role in increasing immersion in virtual environments [36], however is still one of the ongoing interaction challenges in VR [67].

#### *Grasping*

Researchers have investigated human's approach to grasping real objects, aiming at understanding certain aspects of human hand usage [72, 79], as well as classifying grasps in a discrete set of types [21, 28, 39]. However, this knowledge cannot be applied directly to virtual grasping, as it has been identified that users interact with virtual objects differently than they interact with real objects [54, 92, 98]. Therefore, virtual grasping has extensively been explored as a technical and computational challenge [12, 13, 88].

It has been identified that object characteristics as shape and size influence the grasp choice when grasping real objects [25], as well as virtual objects [3, 4]. However, VR commonly lacks physical sensations of friction and weight to the hand [12], key constraints considered in grasping real objects.

### Visual Representations

The main feedback cue in VR environments is the visual rendering [19]. Therefore, a number of works take advantage of the easiness with which visual cues can be controlled and evaluated in VR.

#### *User Representation*

The use of avatars and avatar representation in VR has received significant attention from the research community exploring how it effects the sense of body ownership [59, 84] and agency [40] as they allow users to locate their own body pose within the virtual environment.

Furthermore, additional visual aspects such as human-likeness [48, 52], gender [82] or transparency [15, 42] of the virtual representation have shown to influence ownership illusion as well as user performance.

The human hand is a powerful physical tool through which people interact with the surrounding world [30]. It has been identified that perceived naturalness of virtual hands can have a significant effect on perceived user presence [82] as well as own-body perception and immersion [48].

*Environment Representation*

One important facilitator of immersion in VR is fidelity, the degree of accuracy with which a system recreates real-world experiences [14, 20, 55, 100], with high levels of interaction fidelity being preferred for virtual object manipulation [75]. Multi-sensory feedback has proved to generate high levels of fidelity in VR [23, 32, 33, 80], with an increased number of works using haptic feedback devices to stimulate other sensory channels [1, 7, 51, 58, 95, 105]. However, providing haptic feedback generally requires complex hardware, while still being limited [18, 47].

As an alternative, researchers rely on the concept of the kinesthetic visual capture [86], the dominance of vision over proprioception, to efficiently deceive user experience through visual cues in the environment [65].

Rietzler *et al.* [74] used visual cues to induce the haptic sensation of weight. They used perceivable tracking offsets of the virtual hand, nudging the user to lift the arm higher to perceive some form of additional exertion. To create the illusion of resistance of wind in VR, Pusch *et al.* [70, 71] used visual hand displacements. Their results show that the majority of participants felt a force that was pushing their hands. Rosas *et al.* [77] investigated how different types of visual cues for textures change depth perception. They found that textures with a pseudo-random distribution of circles provide the highest reliability in discriminating the distance of objects in motion. Biocca *et al.* [11] investigated sensory illusions in a virtual environment, and identified that when manipulating the visual analogue for a physical force, a virtual spring, users reported haptic sensations of *"physical resistance"*, even though the interface included only visual representations. Vigier *et al.* [93] studied the role of visual cues (sky aspect, shadows, sun location and light effects) on climate perception (season, daytime and temperature) in virtual urban environments. Their results prove the feasibility of suggesting complex climatic perceptions and thermal feelings using just visual representations.

Although the effect of visual representations of the virtual environment on human perception has been investigated, its effect on wider interaction patterns such as grasp choice in VR is unknown.

## STUDY DESIGN

### Apparatus

We built a custom experimental framework using the Oculus Rift DK2 VR Head Mounted Display (HMD) and the Leap Motion hand tracking device. The Leap Motion was mounted on the front of the HMD facing the participants' hands, to facilitate hand interaction. Additionally, we used a Logitech Pro 1080p HD webcam positioned on top of the Oculus DK2, to record participants' hand from the user's perspective at all times. The system was developed using C#, Unity 2018.2 and Leap Motion 4.0 SDK. The virtual interaction space was 60 cm x 60 cm x 60 cm. The setup and equipment are shown in Fig 2.

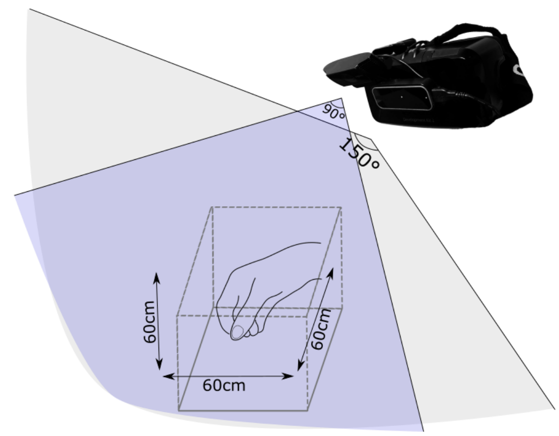



**Figure 2. System configuration displaying the custom experimental framework: Leap Motion and Logitech Pro 1080p HD camera attached to the Oculus Rift DK2.**

### Environment

The experiment was conducted in a controlled environment under laboratory conditions at location N 52° 28.35′ E 53° 5.87′ in July 2019. The average outdoor temperature was 22.4°C (SD 3.8)[1] and the indoor controlled environment temperature was constant 20°C to minimise the potential inference of environmental and weather conditions in the results of the presented study. The test room was lit by a 2700k (*warm white*) fluorescent with no external light source.

The virtual environment showed a virtual desk with its surface aligned to a seating position, as in Figure 1(c). The virtual mug was placed at the centre of the table, changing its texture and content as presented in the next subsection and in Figures 1(d)-1(g). Additionally, the scenario showed a window, which changed views in between conditions.

### Conditions

*Hand Representation*

Following Schwind *et al.* definitions [82], for hand representations we selected an *abstract* hand model that was extracted from the Leap Motion SDK and was represented as a set of cylinders and spheres representing bones and joints respectively (please refer to Figure 1(a). For the *human* hand condition we chose an androgynous model, following Schwind *et al.* recommendation for avoiding noticeable gender characteristics in human hands [82] (please refer to Figure 1(b)).

*Thermal Representations*

For this study, we chose a 3D mug as the interaction object, due to its familiarity in everyday tasks, as well as the variations of grasping it proposes. Won *et al.* [102] showed that the colour red is associated to hot concepts, blue to cold and green to reliable and safe. For the mug, we used the yellow colour, as it is the only one of the primary colours that was not associated to any connotation that may influence the study results.

[1]Weather data collected from: https://www.accuweather.com/en/gb/birmingham/b5-5/july-weather/326966 *(last accessed September 2019)*

(a) Cold (b) Hot (c) Empty

**Figure 3. Thermal representations for the virtual mug. 3(a) shows the cold condition with ice cubes and a clear liquid, 3(b) shows the hot condition with coffee steam coming out of the top and 3(c) shows the empty condition with no content.**

- **Cold:** The mug content in this condition was a set of ice cubes inside a clear blue liquid (as in Figure 3(a)).
- **Hot:** The mug content was rendered as a brown liquid simulating coffee with steam coming from the top of the mug (as in Figure 3(b)).
- **Empty:** An empty mug with no content inside (as in Figure 3(c)).

We chose the colours of the liquid (blue for cold and brown for hot) based on previous literature showing that surfaces whose dominant frequencies are towards the blue end of the spectrum are perceived as cold, and those towards the red end of the spectrum are perceived as hot [8].

### *Virtual Environment*

The environment surrounding objects has shown to influence interaction choice [99], therefore, to evaluate this in the context of the study, we explore different contextual representations to support the thermal cues above.

- **Basic:** Presents a simple yellow mug, in all 3 temperature conditions. As in Figure 1(d) the only visual difference between the thermal conditions is the rendered content inside the mug.
- **Content Label:** Presents a mug with a label attached to it, informing about the contents inside as in Figure 1(e).
- **Glass:** Presents a see-through mug in a transparent texture as in Figure 1(f). This allows the user to see the content of the mug through the mug itself, mimicking a glass texture.
- **Context Objects:** Presents the mug used in the basic condition accompanied by other contextual objects to support the thermal representation as in Figure 1(g). These accompanying objects were presented behind the mug, 10 cm away from its original position in both z and x axes. The accompanying items were a coffee espresso machine for the *hot* condition, ice bucket for the *cold* condition and an empty bucket for the *empty* condition. The view from the window also changed depending on the thermal cues, displaying a snowy landscape for the *hot* condition, a beach for the *cold* condition and a forest for the *empty* condition.

## Task

Participants were instructed to pick and move the virtual mug from the origin location to a target location situated on the left of the original object and displayed as a 3D semi-transparent virtual mug in a different colour, as in Figure 4.

**Figure 4. Interaction environment displaying the virtual mug (yellow virtual mug) and the target position (semi-transparent green virtual mug).**

## Participants

A total of 50 participants (21 females, 29 males) from a population of university students and staff members volunteered to take part in this study. Participants ranged in age from 18 to 50 (M=25.5, SD=14.57). All participants were right-handed, to ensure they interacted with the mug under the same conditions (i.e. the handle in the same orientation with respect to their dominant hand).

All participants performed the experiment tasks under both hand conditions(*abstract* and *human*). Participants completed a standardised consent form and were not compensated. Visual acuity of participants was measured using a Snellen chart, each participant was also required to pass an Ishihara test to check for colour blindness. Participants with colour blindness and/or non corrected visual acuity of $< 0.80$ (where 20/20 is 1.0) were not included in this study.

Participants were asked to self-assess their level of experience with VR systems, with 16 participants reporting to have an average level of experience, 31 reported being novice to the technology and 3 self-labelled themselves as experts. Participants did not have any previous experience with hand tracking sensors.

## Protocol

### *Pre-test*

Prior to the study, participants were given a written informed consent form, where the test protocol and main aim of the study were described. Additionally, participants completed a pre-test questionnaire enquiring about their background level of experience with VR systems and hand recognition sensors.

### *Calibration*

Before each test, the test coordinator followed manufacturers' guidelines to help participants fit the HMD in the most suitable and comfortable way. The camera attached to the Oculus DK2 (Fig. 2) was adjusted each time to ensure the participants' hand was in the field of view of the devices.

### *Training*

Participants were trained to pick and move a neutral object (a cube) from its original position to a target position, to familiarise themselves with the VR environment and hand interaction space. Thermal cues were not included at this stage of the study. Participants spent 7-10 minutes training with the system until they felt comfortable with the task and the apparatus.

*Test*

Once participants were comfortable with the interaction space and the overall VR environment, they were presented with the main experimental task. Each participant completed 24 tasks(2 hand representations × 3 temperature cues × 4 environmental conditions as shown in Fig 1). The order of the hand representation conditions were counterbalanced; half participants started with *human* hand (Fig. 1(b)) and the other half with the *abstract* hand (Fig. 1(a)). Thermal and environmental conditions were then presented in randomised controlled order. Participants were asked to pick and move the virtual mug the way they felt most intuitive to them and instruct the test coordinator when they were happy with their hold. Hand tracking data was then recorded from the Leap Motion device, while an image was captured of both the VR scenario and from the Logitech webcam.

*Post-Test*

After each hand representation condition, participants were asked to complete the Igroup Presence Questionnaire (IPQ) and a set of tailored questions asking about their experience during interaction with the virtual object in different conditions.

### Metrics

*Grasp Aperture*

We capture $X$, $Y$, $Z$ positions of finger joints during the interaction using the Leap Motion. We use the Grasp Aperture ($GAp$) defined in equation 1 from the grasp model presented in [3].

$$GAp = \sqrt{(P_x - B_x)^2 + (P_y - B_y)^2 + (P_z - B_z)^2} \quad (1)$$

Where $GAp$ is the distance between the index and the thumb fingers in the x, y and z axes, and $P_x$, $P_y$ and $P_z$ are the coordinates of the index finger tip, and $B_x$, $B_y$ and $B_z$ are coordinates of the thumb tip.

*Labelling*

Two trained rater academics labelled all grasps individually; following the methodology described in [17]. The grasp types used for labelling are those in the Human GRASP taxonomy [28]. Additionally, raters labelled the grasp location of the mug as explained in section *Grasp Location*. The raters came from a computer science background and were familiar with human grasping literature. Raters were asked to label both the real view captured by the webcam and the virtual view captured in Unity when the object was grasped. The difference in the parameters between raters were analysed by rater 1, who made a final decision about which rater's assignment was correct as in [27, 17].

*Grasp Type*

The full set of grasps used for labelling are those by Feix *et al.* in the Human GRASP taxonomy [28]. This taxonomy divides grasp types in three main categories: power, intermediate and precision. *Power grasps* are linked to stability and security and distinguished by large areas of contact between the hand and the object [21]. *Precision grasps* are commonly defined by the object being held between the finger tips, allowing an increased level of manipulation [53]. *Intermediate grasps* present elements of power and precision roughly in the same proportion, enabling a finer representation of grasp types [28].

*Grasp Location*

An object can be manipulated in different ways. For each way it is manipulated, there might be different proportions of the object relevant for the actual grasp. Therefore, Feix *et. al.* introduce the concept of grasped location, which they define as the local part of the object specific to the grasp instance (see Figure 5). An object can have multiple grasp locations, and humans will chose a grasp location based on the task and other parameters [26].

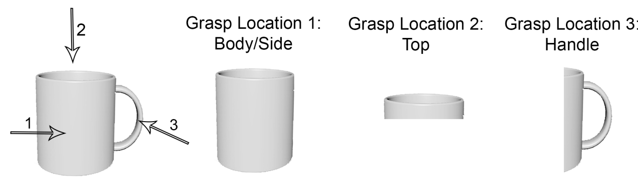



**Figure 5. Grasp locations as by the Human Grasp Taxonomy [26] for the virtual mug used in this study.**

*Presence Questionnaire*

The IPQ is a scale for measuring the sense of presence experienced in VR. When compared to other presence questionnaires, IPQ has shown to provide the highest reliability [81]. We used the IPQ to assess presence for each hand condition; *human* and *abstract*. The questionnaire is structured in 4 sub-scales: General Presence (PRES), Spatial Presence (SP), Involvement (INV) and Experience Realism (REAL), with 14 items in total, rated in 7-point scale (1-no feeling of presence, 7-strong feeling of presence). The scores for each sub-scale as well as the overall score are calculated by averaging their 7-point scores.

*Post-Test Questionnaire*

The post-test questionnaire consisted of tailored questions asking about the perceived usefulness of thermal visual cues. We used the post-test questionnaire, interview and observation to assess the perceived usefulness of visual cues for each hand condition.

### Hypotheses

Following the current literature defined in this paper we propose the hypotheses listed below:

- **$H_1$:**The thermal visual cues of the object have an effect on the grasp metrics (i.e. aperture, location and type).
- **$H_2$:**The visual representation of the hand have a effect on the grasp metrics.

### Statistical Analysis

The Shapiro-Wilk [85] normality test found the data to be not normally distributed. We test for significance between the conditions and the metrics described using a non parametric Friedman test [31]. 95% Confidence Intervals (CI) and pair-wise Effect Sizes (ES) are reported following a non dichotomous statistical approach [24].

## RESULTS

### Grasp Aperture (GAp)

A comprehensive analysis of grasp aperture with Effect Sizes (ES) and 95% Confidence Intervals (CIs) per temperature representation and scenario conditions is presented in Table 1 for the *abstract* hand and in Table 2 for the *human* hand.

#### *Hand Representations*

No statistically significant differences were found between the *abstract* and *human* hand visualisations for any of the environment conditions under study when comparing them pairwise by thermal cue for all the available scenarios (i.e. Hot *abstract vs.* hot *human*, empty *abstract vs.* empty *human* and cold *abstract vs.* cold *human*).

#### *Environment Conditions*

- **Basic:** Statistically significant differences were found between temperature representations for the *abstract* hand, with medium ES shown between the *empty* and *hot* conditions and between the *cold* and *hot* conditions (Table 1). Statistically significant differences were also found in the *human* hand condition, with large ES between the *empty* and *hot* conditions and medium ES between the *cold* and *hot* conditions, as shown in Table 2.

- **Content Label:** Both hand conditions presented statistically significant differences between temperature representations, with large ES shown between the *empty* and *hot* conditions (Tables 1 and 2). The *human* hand condition showed a medium ES between *cold* and *hot* conditions.

- **Glass:** Only the *human* hand presented statistically significant differences between the temperature representations, presenting large ES between the *empty* and *hot* and between the *hot* and *cold* conditions (Table 2).

- **Context Objects:** Statistically significant differences were presented between temperature representations in the *human* hand condition with large ES between the *empty* and *hot* conditions and medium ES between the *cold* and *hot* conditions (Table 2).

Overall grasp aperture showed statistically significant differences for visual thermal cues in every condition under study with the *human* hand interaction while it only presented statistically significant differences in *basic* and *content label* conditions for the *abstract* hand model.

### Grasp Location

Grasp location was defined as the preferred location for the grasp as in Figure 5. A comprehensive analysis of grasp location differences between visual thermal cues for all environment conditions is presented in Table 1 for the *abstract* hand and in Table 2 for the *human* hand. These tables present the statistical differences, Effect Sizes (ES) and visual heat-maps for the grasp location. Heat-maps are calculated to show the mid point between the thumb, and index finger during grasp.

#### *Hand Representations*

As with the grasp aperture no statistically significant differences were found between the *abstract* and the *human* hand visualisations for any of the context conditions under study when comparing them pairwise by temperature for all the available scenarios (i.e. *Hot abstract vs. hot human*, *empty abstract vs. empty human* and *cold Abstract vs. cold human*).

#### *Environment Conditions*

- **Basic:** Statistically significant differences were found between temperature representations for the *abstract* hand, with medium ES shown between the *empty* and *hot* conditions and between the *cold* and *hot* conditions (Table 1). Statistically significant differences were also found in the *human* hand condition, with large ES between the *empty* and *hot* conditions and between the *cold* and *hot* conditions (Table2).

- **Content Label:** Both hand conditions presented statistically significant differences between temperature representations, with large ES showing between the *empty* and *hot* conditions and medium ES between the *cold* and *hot* conditions as in Tables 1 and 2.

- **Glass:** Both hands presented statistically significant differences between the temperature representations, with medium ES between the *empty* and *hot* and between the *hot* and *cold* conditions (Tables 1 and 2).

- **Context Objects:** Statistically significant differences were presented for both hands with medium ES between *empty* and *hot* conditions (Tables 1 and 2).

Overall, statistically significant differences were presented for both hands across all environmental conditions with larger effect sizes between the *empty* and *hot* conditions and *cold* and *hot* conditions for both the *abstract* and the *human* hand. The results suggest a change in the location of the grasp for the *hot* content condition across all environmental conditions, which is consistent with the visual density representation in the heat-maps, where the *hot* conditions present a higher density of grasps around the *handle* area.

### Grasp Types

In this section we report on grasp choice patterns for each grasped location (see Figure 5). Figure 6 presents grasp choices based on hand conditi on and mug content representation. A total of 1200 instances (50 participants $\times$ 2 hand representations $\times$ 4 environmental conditions $\times$ 3 visual thermal cues) were labelled according to the methodology presented in the *Labelling* section. Each hand representation received 600 instances that were further analysed in the following paragraphs based on the grasp locations presented in Figure 5.

- **Grasp Location 1 *(Handle):*** 53.16% (355 instances) of the *abstract* hand data and 64% (380 instances) of the *human* hand data were located in the handle of the mug.

  - *Abstract hand:* Out of the 355 instances, 43.38% (154 instances, see Figure 6) of them belonged to *hot* content conditions while 31.54% (112 instances) were for *cold* content and the remaining 25.07% (89 instances) for *empty* conditions.

**Table 1. Abstract Hand - Grasp aperture and grasp location statistics, displaying effect sizes (|ES|) and 95% confidence intervals (CI) where H stands for Hot content, C for Cold content and E for Empty mug conditions.**

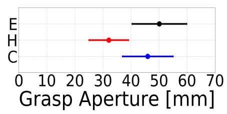
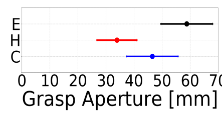
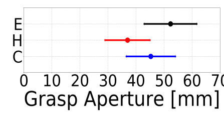
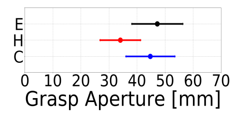
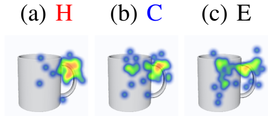
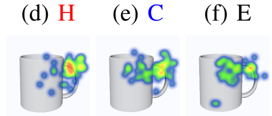
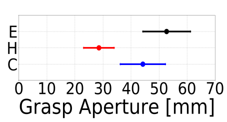
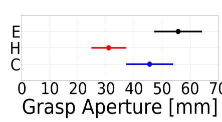
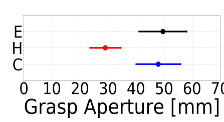
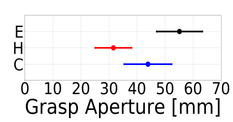
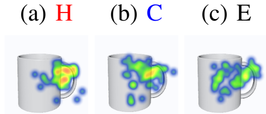
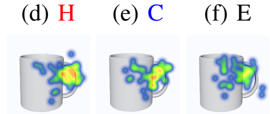
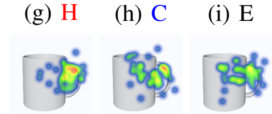
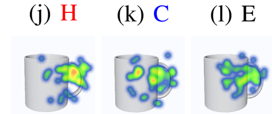
| | | Basic | Content Label | Glass | Context Objects |
|---|---|---|---|---|---|
| **Grasp Aperture** | $p$ | $(\mathbf{Stat = 8.68},$ $\mathbf{p = 0.01})^*$ | $(\mathbf{Stat = 13.0},$ $\mathbf{p = 0.02})^*$ | $(Stat = 1.74,$ $p = 0.06)$ | $(Stat = 1.48,$ $p = 0.47)$ |
| | \|ES\| | **E** *vs.* **H** = 0.67<br>**E** *vs.* **C** = 0.13<br>**C** *vs.* **H** = 0.50 | **E** *vs.* **H** = 0.86<br>**E** *vs.* **C** = 0.38<br>**C** *vs.* **H** = 0.44 | **E** *vs.* **H** = 0.50<br>**E** *vs.* **C** = 0.22<br>**C** *vs.* **H** = 0.28 | **E** *vs.* **H** = 0.46<br>**E** *vs.* **C** = 0.08<br>**C** *vs.* **H** = 0.38 |
| | 95% CI |  |  |  |  |
| **Grasp Location** | $p$ | $(\mathbf{Stat = 17.86},$ $\mathbf{p < 0.01})^*$ | $(\mathbf{Stat = 23.51},$ $\mathbf{p < 0.01})^*$ | $(\mathbf{Stat = 13.03},$ $\mathbf{p = 0.01})^*$ | $(\mathbf{Stat = 8.22},$ $\mathbf{p = 0.02})^*$ |
| | \|ES\| | **E** *vs.* **H** = 0.72<br>**E** *vs.* **C** = 0.17<br>**C** *vs.* **H** = 0.54 | **E** *vs.* **H** = 0.84<br>**E** *vs.* **C** = 0.29<br>**C** *vs.* **H** = 0.48 | **E** *vs.* **H** = 0.65<br>**E** *vs.* **C** = 0.23<br>**C** *vs.* **H** = 0.40 | **E** *vs.* **H** = 0.52<br>**E** *vs.* **C** = 0.06<br>**C** *vs.* **H** = 0.45 |
| | Heat-maps | (a) H (b) C (c) E<br> | (d) H (e) C (f) E<br> | (g) H (h) C (i) E<br> | (j) H (k) C (l) E<br> |

**Table 2. Human Hand - Grasp aperture and grasp location statistics, displaying effect sizes (|ES|) and 95% confidence intervals (CI) where H stands for Hot content, C for Cold content and E for empty mug conditions.**

| | | Basic | Content Label | Glass | Context Objects |
|---|---|---|---|---|---|
| **Grasp Aperture** | $p$ | $(\mathbf{Stat = 26.28},$ $\mathbf{p < 0.01})^*$ | $(\mathbf{Stat = 22.84},$ $\mathbf{p < 0.01})^*$ | $(\mathbf{Stat = 7.8},$ $\mathbf{p = 0.02})^*$ | $(\mathbf{Stat = 11.68},$ $\mathbf{p = 0.03})^*$ |
| | \|ES\| | **E** *vs.* **H** = 0.95<br>**E** *vs.* **C** = 0.27<br>**C** *vs.* **H** = 0.65 | **E** *vs.* **H** = 0.96<br>**E** *vs.* **C** = 0.35<br>**C** *vs.* **H** = 0.58 | **E** *vs.* **H** = 0.82<br>**E** *vs.* **C** = 0.05<br>**C** *vs.* **H** = 0.79 | **E** *vs.* **H** = 0.90<br>**E** *vs.* **C** = 0.38<br>**C** *vs.* **H** = 0.46 |
| | 95% CI |  |  |  |  |
| **Grasp Location** | $p$ | $(\mathbf{Stat = 27.18},$ $\mathbf{p < 0.01})^*$ | $(\mathbf{Stat = 26.69},$ $\mathbf{p < 0.01})^*$ | $(\mathbf{Stat = 21.5},$ $\mathbf{p = 0.02})^*$ | $(\mathbf{Stat = 13.67},$ $\mathbf{p < 0.01})^*$ |
| | \|ES\| | **E** *vs.* **H** = 0.98<br>**E** *vs.* **C** = 0.14<br>**C** *vs.* **H** = 0.79 | **E** *vs.* **H** = 0.95<br>**E** *vs.* **C** = 0.38<br>**C** *vs.* **H** = 0.60 | **E** *vs.* **H** = 0.75<br>**E** *vs.* **C** = 0.05<br>**C** *vs.* **H** = 0.71 | **E** *vs.* **H** = 0.62<br>**E** *vs.* **C** = 0.19<br>**C** *vs.* **H** = 0.40 |
| | Heat-maps | (a) H (b) C (c) E<br> | (d) H (e) C (f) E<br> | (g) H (h) C (i) E<br> | (j) H (k) C (l) E<br> |

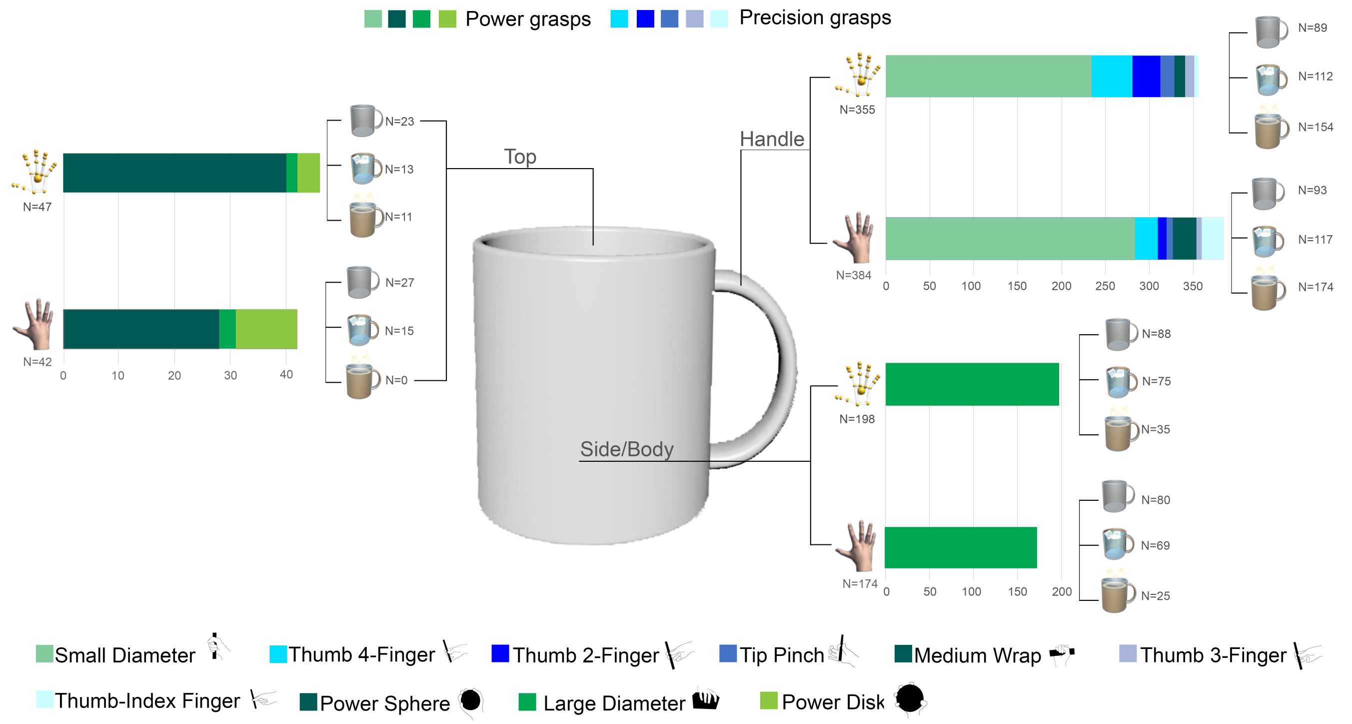



**Figure 6. Grasp type choice for each grasped location; N represents the number of instances for which that grasp location was chosen, for each temperature condition. Grasp types are categorised in *Power* (variations of green) and *Precision* (variations of blue).**

- *Human hand:* Handle grasps for the *human* hand were divided as follows: 45.31% (174 instances as in Figure 6) for the hot conditions, 30.46% (117 instances) for the cold conditions and the remaining 24.22% (93 instances) for the empty conditions.

The main grasp choice for this location was the Small Diameter grasp for both hand conditions. This grasp belongs to the *Power Grasp* category defined in the *Grasp Types* section, thus a stable grasp enabling the firm grip of the virtual mug. The remaining grasps belonged to the *Precision Grasp* category, enabling a precise grasp of the mug using the fingertips. All grasp choices identified in the dataset for the *handle* location are reported in detail in Figure 6.

- **Grasp Location 2 *(Top)*:** A total of 47 instances (7.83% of the dataset) for the *abstract* hand and 42 (7% of the dataset) for the *human* hand conditions were located around the *top* of the mug.
  - *Abstract hand:* Out of the 47 instances, 23.40% (11, see Figure 6) belonged to *hot* content conditions while 27.66% (13 instances) were for *cold* content and the remaining 48.94% (23 instances) for *empty* conditions.
  - *Human hand:* 35.71% (15 instances) for the *cold* conditions and the remaining 64.28% (27 instances) for the *empty* conditions. No grasps were recorded in this area for the *hot* condition in the *human* hand visualisation.

All grasps recorded in the *top* of the mug for both hand conditions belonged to the *Power Grasp* category as defined in the *Grasp Types* section. Figure 6 displays grasp choice in more detail.

- **Grasp Location 3 *(Body/Side)*:** 33% (198 instances) of the *abstract* hand condition and 20% (174 instances) of the *human* hand condition were grasps recorded in the *body/side* of the mug.
  - *Abstract hand:* Out of the 198 instances, 17.67% (35 as in Figure 6) of them belonged to *hot* content conditions while 37.88% (75 instances) were for *cold* content and the remaining 44.44% (88 instances) for *empty* conditions.
  - *Human hand:* 14.36% (25 instances as in Figure 6) for the *hot* conditions, 39.65% (69 instances) for the *cold* conditions and the remaining 45.97% (80 instances) for the *empty* conditions.

The only grasp type recorded in this area was a Large Diameter grasp, from the *Power Grasp* category. This grasp is categorised by large areas of the hand in direct contact with the object, enabling a firm grip which is in alignment with the location of the grasp in the virtual mug.

### IPQ

The IPQ Presence Questionnaire showed no statistically significant differences between the hand representations under study, with the *abstract* hand obtaining an average score of (M=4.54, SD=1.02) and the *human* hand (M=4.75 SD=1). None of the sub-scales of the questionnaire showed any statistically significant results. Presence scores by sub-scale are presented in Figure 7.

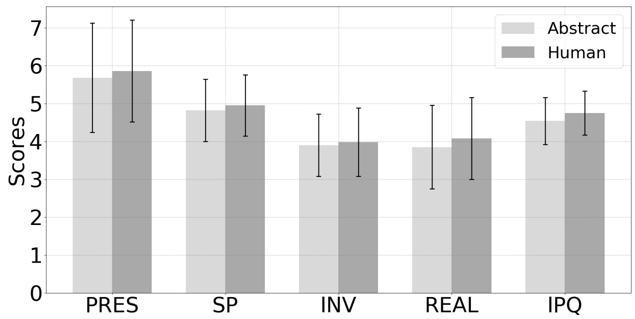



**Figure 7. Scores for IPQ sub-scales and overall IPQ score for *abstract* and *human* hand conditions; a score equal to 7 represents the highest feeling of presence while 1 represents the lowest.**

### Post-Test Questionnaire

Participants were asked to complete a post-test questionnaire to gain a better understanding of their perceptions while interacting with the thermal cues, the environment and hand representations.

Participants reported *ice* and *steam* visual cues from the thermal representations section in Conditions as the strongest visual cue supporting their grasping behaviour. However, these are the cues they were more familiar with, as they were present in all environment conditions under study for both hand representations.

Following these remarks, participants were asked if they felt their grasp location and type was influenced by the different thermal representations or the environment. 37 participants (*abstract* hand) and 36 participants (*human* hand) reported that grasp location was influenced by mug content. Additionally, 29 participants (*abstract* hand) and 37 (*human* hand) reported that the visual thermal representation influenced the location where they grasped. Some participants reported *"I used the handle because I did not want to get burnt or my hand to be too cold."* [P34] or *"I used the handle for hot content to avoid being burnt"* [P28] while other participants reported *"Not necessarily as I wasn't too concerned about burning my hand (because it is robotic [sic]), therefore, didn't matter how I grasped the mug "* [P03].

Some additional comments included: *"With real hand, I almost expected the mugs to have different weights with respect to the amount of liquid in each mug. This was to a greater extent than the abstract hand."* [P11], *"I felt that the simulation with the human hand made me feel the need to be careful in case I burnt myself a lot more than when using the robot hand simulation."*[P24],*"I first thought that it was my hand and I realised that it was not only by looking at the short nails."*[P47].

Overall, participants reported that mug content and thermal cues have a stronger impact on their grasp choice and location than other environmental cues such as changes in the environment or in the hand representation.

## DISCUSSION

We present a study to evaluate the influence of visual thermal cues on VR grasp type, aperture and location. Our results show how visual thermal feedback had an influence on grasp aperture ($GAp$), grasp location and grasp type, thus we accept the hypothesis $\mathbf{H_1}$ that thermal visual cues have an effect on grasp metrics. Additionally, our results correlate with prior work studying grasp patterns for real objects, therefore showing that visual thermal feedback has an effect on grasping approach [69] and indicating a connection between grasping approaches across both VR and real environments.

Our results shown that visual representations of temperature influenced $GAp$ for all conditions under study when using the *human* hand (Figure 1(b)) and for the *Basic* (Figure 1(d)) and *Content Labels* (Figure 1(e)) conditions when using the *abstract* hand. Participants grasped the virtual mug with a smaller $GAp$ in the hot condition compared to cold and empty for both hand representations (*abstract* and *human*).

Grasping instances presenting a small $GAp$ were predominantly located around the *handle* of the virtual mug, showing the influence of the size of the grasped location on the grasp pattern when interacting with virtual objects. This correlates with grasping real objects, where the aperture of the grasp is primarily influenced by the size of the grasped location [26]. Participants predominantly used the *handle* as a grasp location in both *hot* and *cold* conditions, while grasp location choice varied between *body/side*, *top* or *handle* for the *empty* condition. This shows that the visual representation of content inside the mug influenced user's behaviour when grasping, and therefore could illustrate a strong functional correlation between the shape of the grasped location and the manner in which it is generally grasped by the hand which has been shown in real object grasping [76]. Similarly, our results highlighted that the object shape and the chosen grasped location had an influence on the grasp used. Participants predominantly chose a Large Diameter for *body/side* (cylinder shape) and a Power Sphere for *top* (disk shape) on the mug.

As with previous studies [66, 101], participants did not show an awareness of the number of fingers involved while interacting with the system. Commonly, users presented different variations of the thumb-finger grasp for the same grasp location; notably variations of Thumb-Index Finger, Thumb 2-Finger, Thumb 3-Finger, Thumb 4-Finger when grasping the *handle*. Differences in grasp type were identified between the *human* and *abstract* hand conditions; for instances where the *handle* was chosen, participants used a *power* grasp in 80.72% of the instances in the *human* hand condition, while choosing *power* grasps in only 69.29% of the instances in the *abstract* hand condition. This result suggests that users intuitively performed a grasp that could normally hold a heavy object more often with the *human* hand than with the *abstract* hand, with *power* grasps being associated with stability and security when grasping real objects[21].

When comparing between conditions, ES was generally smaller for the *abstract* hand than for the *human* hand, however, there were no significant statistical differences between hand representations for grasp data. The IPQ scores did not present statistically significant differences in perceived presence between hand representations. This finding is contrary to popular literature [83], and therefore we reject our hypothesis $\mathbf{H_2}$ for the effect of hand representations on grasp metrics. However, during the interview and post-questionnaire within the study, participants emphasised higher levels of attachment to the *human* hand condition.

Throughout the study, participants were not specifically instructed that grasping type, location and aperture were under study and were therefore free to interact with the virtual mug as they felt suitable. However, they could have experienced the *Good Subject Effect*. Notably, this is found when participants can respond to an experiment in ways that they believe confirm the hypothesis of the study [57]. Although we believe our methodology negates this effect, it can not be ruled out completely. Therefore, future work should consider masking the temperature representations or embedding the "*pick and move*" task in a more complex task or environment and further assess current results. Additionally, future studies could integrate colour and context variations, building up the current knowledge in grasping presented in this evaluation.

Overall, we presented the first study into understanding the influence of visual thermal cues on grasping patterns, with practical implications for the VR interaction design community:

- **Grasp aperture:** Visual thermal feedback on an object had an influence on grasp aperture ($GAp$) showing smaller apertures for visual representations of hot content. This insight should be considered for interaction virtual object design in VR environments where the user needs to manipulate thermally variable objects (i.e. welding training scenarios as in [9, 68]).

- **Grasp location and type:** Objects representing a weight or content showcased grasp location differences when compared to the *empty* mug condition, with users presenting a higher density of *precision* grasps in the *handle* area. Participants performed more precise grasps for triggering the interaction when the mug had content, therefore suggesting that the perceived weight, content and/or fragility of an object had an effect on grasp choice and location. This interaction insight is useful for designers creating VR environments that require direct interaction with objects, specially for training (i.e. VR training environments in construction and manufacturing [6]). In these scenarios, the form and shape of objects need to be considered, with objects being designed to specifically encourage this user selection of precision grasps and thus facilitating a more precise and finer manipulation.

## CONCLUSION

The presented study evaluates the influence of visual thermal cues in VR on grasping. We report on a within participants study to evaluate how thermal cues (*empty hot* and *cold*) affect user grasp metrics, notably grasp location, grasp aperture ($GAp$) and grasp choice. Our results illustrate that visual thermal feedback in VR can have an influence on user grasp location when aiming to pick up and translate objects of different content (i.e a mug with hot coffee or cold water). Additionally, we report on the influence on grasp metrics such as grasp aperture and grasp type and show that higher effect sizes can be observed between the *hot-cold* and *hot-empty* conditions. While future work could analyse other virtual objects or thermal cues, our findings present the first study into understanding the influence that visual cues have on user grasping in VR.

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