A Grasp on Reality: Understanding Grasping Patterns for Object Interaction in Real and Virtual Environments

Andreea Dalia Blaga* Maite Frutos-Pascual † Chris Creed‡ Ian Williams§

DMT Lab
Birmingham City University

Abstract

Grasping is the most natural and primary interaction paradigm people perform for every-day manual tasks in reality. However, while grasping real objects in Real Environments (RE) has been highly explored in literature, there is a recent emerging trend to explore the complications and nuances of hand interaction including grasping in Virtual Environments (VE). While this is leading towards a richer body of work to understand users' approach to grasping in VE, a direct comparison between grasping real objects in RE and grasping virtual representations of real objects in VE has not been explored before. To address this gap, we perform a user study (n=20) on 7 representative real objects and their virtual twins from the *"Yale–Carnegie Mellon University–Berkeley Object and Model Set"*. We report on 840 grasp instances collected during a grasp and translate task across RE and VE. We present initial results on the observed differences between RE and VE grasping across the different objects using the *grasp type* metric from real grasping studies. We explore the rationale for any observed differences between the RE and VE and present indicative trends for VE grasping. Finally, we propose methods and approaches for furthering work within VE grasping for improving the natural grasping interface.

Index Terms: Human-centered computing—Human-Computer Interaction (HCI)—Interaction Paradigms—Gestural Input; Human-centered computing—Human-Computer Interaction (HCI)—Interaction Paradigms—Virtual Reality;

1 Introduction

Grasping is the primary and most frequent physical interaction technique people perform in everyday life [17]. It is defined as every static posture at which an object can be held securely with a single hand [15]. Researchers have highly focused on understanding, studying and classifying aspects of human hand usage when interacting with objects, with the aim of replicating grasping for robotic arms [26]. Moreover, researchers took advantage of humans' ability to use hands for acquiring and manipulating objects with ease [24, 34] and have implemented grasping of virtual objects, aiming to achieve natural, intuitive interactions in Virtual Reality (VR). Aiming to mimic reality as closely as possible, grasping interactions have received increased attention from the VR community [6, 7]. However, virtual grasping is still a challenge, users often being trained to use particular grasps [3], or with the design considerations and grasping constraints being applied from the body of knowledge available in real object grasping. To achieve natural and intuitive systems, there is a need to understand grasping patterns for VR and how these patterns differ to grasping approach in reality. Comparing virtual and real environments is a common approach for improving existing systems by analysing differences between Virtual Environments (VE) and Real Environments (RE) and has been previously used for understanding spatial presence [18], sense of touch [27] or training transfer [28]. However, a direct comparison between grasping approach in VE against grasping approach in RE has not been conducted yet. To address this, we conducted a study where we ask participants to grasp and translate 7 physical objects in RE and their virtual twins in VE. We collected and labelled a total of 840 grasps. We report on the *grasp type* metric as in the work of [12] and [14] to compare the results and provide an overview of grasping trends in VR and their differences against grasping real objects.

This paper is structured as follows; Section 2 presents an overview of grasping real objects and interaction in VR. Section 3 presents the experiment design, section 4 focuses on user study and section 5 describes the methodology for labelling the grasps collected during the experiments. Section 6 presents the hypothesis of the study, section 7 presents the results and section 8 discussion and conclusion.

Id	Object	x(mm)	y(mm)	z(mm)
(a)		36	36	190
(b)		80	80	82
(c)		26	26	26
(d)		18	121	18
(e)		50	97	82
(f)		87	200	14
(g)		58	95	190

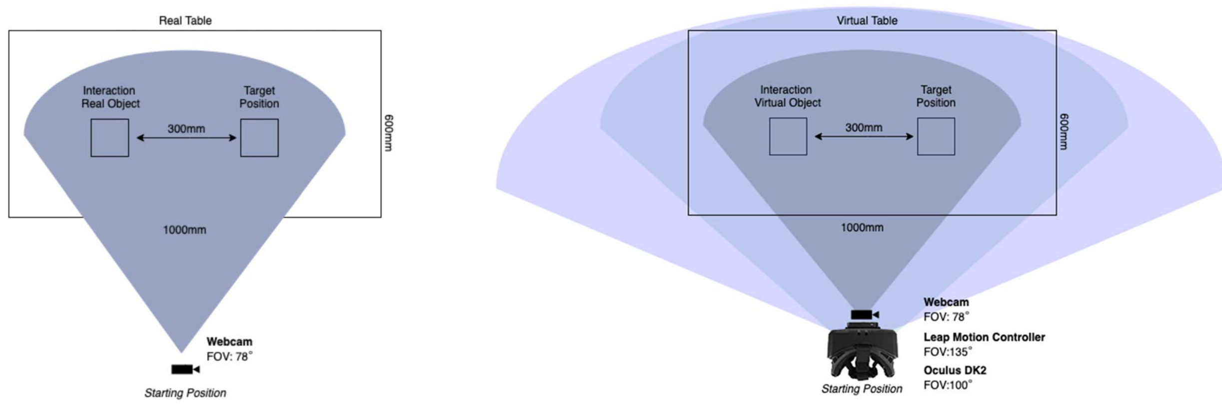
Table 1: Objects chosen for the study with dimensions. The objects are chosen from the *"Yale–Carnegie Mellon University–Berkeley Object and Model Set"*, which present the most frequently used objects in research [5]. In this paper, we refer to these objects by their name in YCB Model set [5] as follows: (a) Banana, (b) Mug, (c) Lego, (d) Marker, (e) Potted Meat Can, (f) Scissors, (g) Mustard.

2 Background

2.1 Grasping Real Objects

Researchers have investigated human's approach to grasping real objects, aiming at understanding certain aspects of human hand usage [26]. Taylor and Schwarz [30] presented a taxonomy of

*e-mail: andreea.blaga@mail.bcu.ac.uk
†e-mail:maite.frutos@bcu.ac.uk
‡e-mail:chris.creed@bcu.ac.uk
§e-mail:ian.williams@bcu.ac.uk



(a) RE Experimental Environment

(b) VE Experimental Environment

Figure 1: Experimental Environment; (a) RE Experimental Environment consisted of the Logitech Webcam, with a FOV of 78°. The physical table was 600 mm $\times$ 1000 mm, with the physical objects positioned on it, 300 mm away from the target position. (b) VE Experimental Environment consisted of the Oculus DK2, with the Leap Motion Controller and Logitech Webcam attached to the HMD as in [12]. The virtual table was 600 mm $\times$ 1000 mm, with the virtual objects positioned on it, 300 mm away from the target position. The webcam had a FOV of 78°, the Leap Motion Controller a FOV of 13°, and Oculus DK2 a FOV of 100°. The starting position was consistent for both (a) RE and (b) VE.

grasp types focusing on six main grasp types: Cylindrical, Tip, Hook, Palmar, Spherical and Lateral grasps. Slocum and Pratt [32] focused on understanding the loss of functional hand use due to injuries, reduced these six types to three functional components of the hand: Grasp, Pinch and Hook. Napier later suggested a scheme where grasps were divided into *Power* and *Precision*, considering the stability and security of the hand while grasping [9, 22]. Further, Landsmeer's [19] revision led to the presentation of new grasp types and variations such as the Writing grasp, Dynamic tripod or the Adduction grasp. Cutkosky and Howe [11] and Cutkosky and Wright [9] focused on power requirements in their taxonomies, extending the work of Napier [22]. Later, Elliot *et al.* [21] investigated and classified ways of manipulating objects using the hand and Cutkosky [10] focused on grasping tools and metal parts. This leads to a rich body of work which categorises and classifies human grasps to support a wider level of application of grasping in RE.

2.2 Hand Interaction in VR

To achieve natural and intuitive interactions in VR, researchers use the hand, the most powerful tool through which we interact with the surrounding world, as the main interaction tool [1]. Hand interactions were initially developed using instrumented gloves [16], however, it has been shown that wearable devices inherently constrain human motion for meaningful human-computer dialogue [35] being often linked to discomfort, time-consuming configurations and user adaptation [17]. As a result of these constraints, researchers have considered freehand interactions [36]. Current freehand interactions often rely on predefined sets of gestures for natural interaction [36], however, it has been shown that they are often arbitrary and not intuitive [25]. Therefore, researchers have looked at physical interactions, which proved to be more intuitive, and showed higher interaction performance when compared to gesture-based interactions [37]. Virtual grasping has been highly explored, however, the approaches followed in previous work [33] rely on computed grasps, often using the grasping knowledge from real object grasping, notably the work detailed in Section 2.1, therefore not taking into account humans' grasping actions in VR. To address this, previous work looked at understanding grasping patterns directly in VR [12], however, this work only focused on grasping patterns in VE, without directly comparing grasping patterns in RE against VE. Direct comparisons between real and virtual environments have been conducted before for assessing spatial presence [18] or sense of touch [27], showing significant differences in performance and user behaviour between the two environments. Yet, a direct comparison of grasping in RE against grasping in VE has not been conducted.

3 Experiment Design

3.1 Task

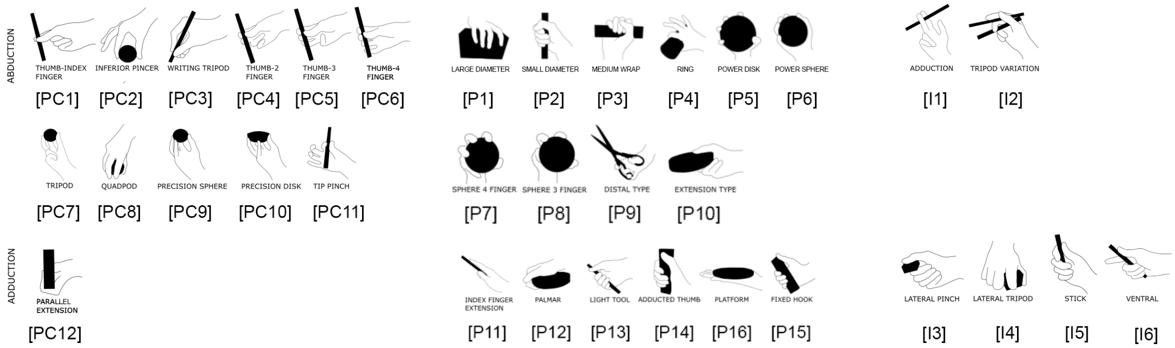
We implemented an object translation task on the x axis of the Cartesian coordinate system, positive direction for both experimental conditions (RE and VE as in Fig. 1). The task was consistent across conditions, with participants being asked to move the object to the target position, which was positioned 300 mm away from the object to be grasped in both RE and VE (see Figure 1).

3.2 Apparatus

We recorded the grasps in both environments, using a Logitech Pro 1080p HD camera with a Field of View (FOV) of 78°. To attach the camera in the optimal position, we conducted pilot tests to find the position and angle for which the camera would record participants' hands at all times. We used a physical table (RE) and a virtual table (VE) of 600 mm $\times$ 1000 mm for placing the real and virtual objects on it. The starting position was the same for all participants. Figure 1 shows an overview of the experimental environment.

RE: We attached the camera on user's forehead using a head strap (GoPro Head Strap). The camera was centered on the user's forehead and tilted by 30° to record participants' hands during the interaction.

VE: We followed the methodology detailed in [12] using the Oculus DK2 VR headset and the Leap Motion device. The Leap Motion Controller was attached to the HMD, facing the user's hands. We then attached the camera on top of the Oculus DK2, facing participants' hands and recording all the grasps during the VE experiment. The virtual interaction space was 600 mm $\times$ 600 mm $\times$ 600 mm



(a) Precision grasps (b) Power grasps (c) Intermediate grasps

Figure 2: Grasps from (a) Precision, (b) Power, (c) Intermediate category, subdivided in *Thumb Adducted* and *Thumb Abducted* as in [12] and [14].

(based on Leap Motion Controller FOV). The system was developed using C#, Unity 2018.2 and the Leap Motion 4.0 SDK.

3.3 Objects

For a direct comparison between RE and VE in terms of the grasping approach, we used the same set of objects for both environments: physical objects for RE and virtual 3D representations for VE. We selected 7 representative objects from the *"Yale–Carnegie Mellon University–Berkeley Object and Model Set"*, which present the most frequently used objects in research [5]. The selected objects are presented in table 1, along with the object dimensions for each object (in mm). To ensure size is consistent across RE and VE conditions, we resized the 3D models to match the size of the physical objects, using scale-related settings in Unity (2018.2).

4 User Study

4.1 Environment

The experiment was conducted prior to the COVID-19 pandemic in a controlled environment. The test room was lit by a 2700k (*warm white*) fluorescent with no external light source.

4.2 Participants

A total of 20 right-handed participants (12 males and 8 females), ranging in age from 19 to 65 (M = 33.25, SD = 11.98) and from a population of university students and staff members volunteered to take part in this study. Participants were asked to self-assess their level of experience with VR systems, with 6 participants reporting to have an average level of experience, 11 reported being novice to the technology and 3 self-labelled themselves as experts. Participants did not have any previous experience with hand tracking sensors. All participants completed both conditions of the experiment and a standardised consent form. 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 not compensated.

4.3 Protocol

4.3.1 Training

Participants underwent initial hand interaction and task training to familiarise themselves with the environments. The training task was a representative version of the tasks in the user study, where participants were asked to grasp and translate a cube object, both in RE and VE. For this, we used a physical cube in RE and a 3D virtual representation of the cube in VE (50mm $\times$ 50mm $\times$ 50mm).

4.3.2 Test

Each participant performed both conditions: RE and VE. Half participants started with RE and the other half with VE. The 7 objects were randomised for each condition with the starting position being consistent for all objects. Each participant grasped every object three times, with a total of 21 grasps (7 objects $\times$ 3 repetitions) performed per participant both in VE and RE.

RE: Participants were seated in front of the physical table, wearing the head strap as presented in Section 3.2. The test coordinator placed the objects in front of the participant, in randomised order, one at a time. The test coordinator informed participants when they could start the grasp and translate task.

VE: We followed the protocol in [12], used for understanding grasping patterns in VR. Participants were seated, wearing the Oculus DK2 (Section 3.2). For each task, a virtual object appeared on the virtual table. As in [12] a *Wizard of Oz* methodology is applied where participants are instructed to grasp the virtual object the way it felt most intuitive, notifying the test instructor when they were happy with their grasp. The trigger for the interaction is then controlled by the test coordinator, allowing the capture of intuitive user grasps, not being constrained by an automatic interaction trigger.

5 Grasp Labelling

A total of 840 grasps were recorded during the experiment (20 participants $\times$ 2 conditions $\times$ 7 objects $\times$ 3 repetitions). To label the grasps collected we followed the methodology of [12]. Two academic members of the staff with background in computer science and familiar with grasping literature were trained to annotate the grasps. The metric used for labelling is *Grasp Type*. First, raters labelled all grasps individually. They were asked to pick one *Grasp Type* for each grasp instance, having the option to choose "cannot classify". Further, the differences in the parameters between raters were analysed by rater 1, who made a final decision about which rater's assignment was correct as in [14]. The full set of grasps used for labelling are those used in [12] and Figure 2. Grasp types are divided in three main categories: *Precision*, *Power* and *Intermediate*, with each category then subdivided according to the thumb position into *Thumb Abducted* and *Thumb Adducted*.

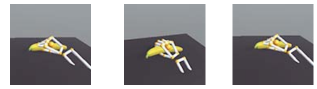
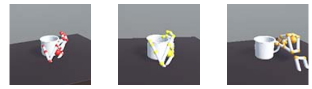
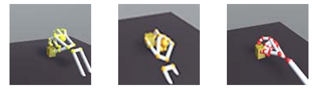
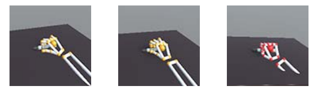
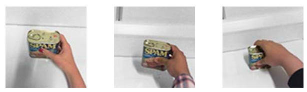
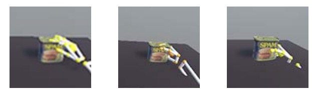
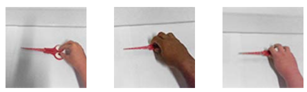
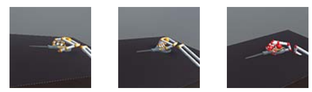
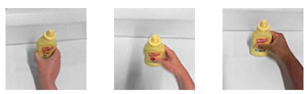
Object	Real Environment (RE)	Virtual Environment (VE)
		
		
		
		
		
		
		

Table 2: Grasp examples collected during the experiment. Column "Objects" shows the objects used in the experiment. Column "Real Environment (RE)" shows three examples of grasps collected from the RE condition, with participants' hand grasping the physical representations of the objects. Column "Virtual Environment(VE)" shows three examples of grasps collected from the VE condition, with participants' hand representation (represented using the Leap Motion Controller hand tracking data) grasping the 3D virtual representations of the objects.

Precision grasps: In these grasps the object is commonly held between the finger tips. While this allows an increased level of manipulation by movement of the fingertips, the object cannot be gripped firmly [20] (Fig. 2 (a)).

Power grasps: These grasps are linked to stability and security. These grasps are distinguished by large areas of contact between the hand and the object [10](Fig. 2 (b)).

Intermediate grasps: These grasps present elements of *Power* and *Precision* roughly in the same proportion, enabling a finer representation of grasp types [4](Fig. 2 (c)).

6 Hypothesis

Following the current literature defined in this paper, notably [12] which have found initial variations for VE approach to virtual object grasping, we propose the following hypothesis: **Grasping patterns for interacting with virtual objects are different than interacting with real objects.**

7 Results

7.1 Statistical Analysis

The Shapiro-Wilk [31] normality test found the data to be not normally distributed. Therefore, statistical significance was tested using a non parametric Mann Whitney-U test (5% alpha) comparing the two conditions overall (overall VE against overall RE) and for each object individually (i.e Banana VE against Banana RE).

7.2 Overall Findings

A total of 840 grasps were collected, labelled and analysed for this experiment. A visual example of the grasps in both VE and RE are given in Table 3. When comparing overall VE grasps against overall RE grasps we found significant statistical differences **(Z-score = -8.26, p $<$ 0.05)***, therefore accepting our hypothesis that users presented differences in grasping patters between RE and VE.

7.3 Individual Object Findings

To further explore the differences found we evaluate grasp types against each individual object. We aim to illustrate if the object attributes (i.e. the structure and form) has an influence on grasping patterns. When comparing *Banana* (Table 1 (a)) in VE against RE, no significant statistical differences were found (Z-score = -1.37, p = 0.17). When comparing *Mug* (Table 1 (b)) grasps in VE against RE, significant statistical differences were found **(Z-score = -5.05, p $<$ 0.05)***. When comparing *Lego* (Table 1 (c)) grasps in VE against RE we found significant statistical differences **(Z-score = -3.61, p $<$ 0.05)***. When comparing *Marker* (Table 1 (d)) grasps in VE against RE we found significant statistical differences **(Z-score = -5.82, p $<$ 0.05)***. When comparing *Potted meat can* (Table 1 (e)) grasps in VE against RE, we found significant statistical differences **(Z-score = -3.14, p $<$ 0.05)***. When comparing *Scissors* (Table 1 (f)) grasps in VE against RE no significant differences were found (Z-score = -0.62, p = 0.52). When comparing *Mustard* (Table 1 (g)) grasps in VE against RE no significant statistical differences were found (Z-score = -1.72, p = 0.08).

Object	Main Grasps in RE			Main Grasps in VE		
	[P3] *56.66%*	[PC4] *10%*	[P2] *8.33%*	[P3] *43.33%*	[P2] *23.33%*	[P1] *11.66%*
	[PC9] *70%*	[P6] *16.66%*	[P1] *6.66%*	[P1] *65%*	[P2] *18.33%*	[PC4] *15%*
	[PC4] *41.66%*	[PC6] *20%*	[P6] *8.33%*	[P6] *38.33%*	[PC9] *25%*	[PC1] *10%*
	[PC5] *51.66%*	[PC4] *26.66%*	[PC1] *10%*	[P2] *61.66%*	[PC6] *15%*	[PC1] *3.33%*
	[P3] *55%*	[PC5] *16.66%*	[PC4] *6.66%*	[P1] *63.33%*	[P6] *15%*	[P3] *10%*
	[PC4] *48.33%*	[P5] *26.66%*	[PC9] *11.66%*	[PC10] *66.66%*	[PC1] *18.33%*	[P6] *16.66%*
	[P3] *43.33%*	[P1] *25%*	[PC5] *15%*	[P1] *45%*	[P6] *20%*	[P2] *16.66%*

Table 3: Results showing the three most used grasps (with percentages) used in RE condition (Column “Main Grasps in RE”) and in VE condition (Column “Main Grasps” in VE) for each individual object used in the study. Each column shows the most used grasps, along with their grasp code (presented in Figure 2, colour-coded to outline their grasp category Power grasps in blue and Precision grasps in green.

8 Discussion and Conclusion

We are accepting our hypothesis that comparing grasping objects in RE against VE presents differences in terms of *grasp type* choice. We show that real objects are predominantly grasped with *Precision* grasps, while virtual objects are predominantly grasped with *Power* grasps (see Table 3). *Power* grasps are linked to stability and security while *Precision* grasps allow an increased level of manipulation by movement of the fingertips [14], showing a trend for grasp choices that allow increased manipulation for physical objects. The lack of sensory feedback in VR may have had an influence on these results, as the main feedback cue for interaction in these environments is the visual rendering [8], objects requiring less precision in manipulation as compared to real objects. Moreover, sensory feedback such as shape and mass has shown to highly influence grasping choice for real objects, while the lack of it in VR [8] allows more freedom in grasping choice without taking weight and texture into consideration. This has been shown in our results, where users often chose a grasp with a larger aperture (the distance between the thumb and the fingertips [13]) in VE than in RE. As opposed to interaction with real objects, where the shape of the hand evolves gradually to conform the contours of the object [29], in VR, users did not focus on conforming the contours of the object while grasping, performing a grasp with a larger aperture than required by the shape/size of the object. As evident in table 3, the main grasps in VE have larger spacing between the fingers which relates to this larger aperture. This is consistent with previous work looking at grasping approach in VR suggesting that users grasp virtual objects larger than real objects [12]. Additionally, the results in table 3 illustrate that in the VE condition the most common grasps for all objects were categorised as grasps that use all fingers and this was not the case with the most common grasp in RE. This is consistent with grasping real object literature, showing that number of fingers increase with size and mass of the object [14], however illustrates a further inconsistency with VE grasping. Our results also show a difference in grasp variability, with users grasping 91% of real objects using 11 grasps, while in VE, only 9 grasps account for more than 95%. This is consistent with previous work showing that a small selection of grasps (N = 8) is needed to interact with objects in VR [12].

8.1 Future work

To fully understand what influences the change in grasping approach when comparing RE and VE, future work should consider the influence of mass and object structure, building on the work of [12, 14]. Categorising these objects and correlating the grasps to representative object categories may support a richer understanding in grasping patterns and thus support more informed interaction design. Further, we suggest that designers creating VR environments that require direct interaction with virtual objects (i.e. VR training environments in construction and manufacturing [2], surgical training techniques [23] could use our results and insights to develop natural grasping interactions by triggering object interaction at a larger grasp aperture and predominantly around *Power* type grasps. Additionally, the application of our results for improved grasping experience against a benchmark grasp model could also be considered in future work, to determine the usability improvements for VR interaction. We envisage future contributions of this work to be developed around parameterizing our findings for achieving a natural and intuitive grasp model for interactions in VR.

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