Grasping objects in immersive Virtual Reality

Manuela Chessa*
University of Genoa, Italy

Guido Maiello, Lina K Klein, Vivian C Paulun
Justus Liebig University
Giessen, Germany

Fabio Solari
University of Genoa, Italy

Abstract

Grasping is one of the fundamental actions we perform to interact with objects in real environments, and in the real world we rarely experience difficulty picking up objects. Grasping plays a fundamental role for interactive virtual reality (VR) systems that are increasingly employed not only for recreational purposes, but also for training in industrial contexts, in medical tasks, and for rehabilitation protocols. To ensure the effectiveness of such VR applications, we must understand whether the same grasping behaviors and strategies employed in the real world are adopted when interacting with objects in VR. To this aim, we replicated in VR an experimental paradigm employed to investigate grasping behavior in the real world. We tracked participants' forefinger and thumb as they picked up, in a VR environment, unfamiliar objects presented at different orientations, and exhibiting the same physics behavior of their real counterparts. We compared grasping behavior within and across participants, in VR and in the corresponding real world situation. Our findings highlight the similarities and differences in grasping behavior in real and virtual environments.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Computing methodologies—Computer graphics—Graphics systems and interfaces—Virtual reality

1 Introduction

Augmented (AR) and Virtual Reality (VR) systems are designed to immerse humans into rich and compelling simulated environments by leveraging our perceptual systems (i.e. vision, touch, sound). In turn, exposure to AR/VR can reshape and alter our perceptual processing by tapping into the brain's significant ability to adapt to changes in the environment through neural plasticity. Therefore, to design successful AR/VR systems, we must first understand the functioning and limitations of our perceptual and cognitive systems. We can then tailor AR/VR technology to optimally stimulate our senses and maximize user experience. Understanding how to wield AR/VR tools to reshape how we perceive the world also has incredible potential for societal and clinical applications: in particular, for training in industrial tasks [6, 12, 28], in medical and surgical applications [8],or for rehabilitation protocols [17, 32].

Several interaction activities can be performed inside VR/AR environments. As the AR/VR interface is task dependent, it is important to first fix the purpose of interaction. Frohlich et al. [11] classify interactions in four categories: (i) *navigation* and *travel*, which consists in moving the viewport or the avatar through the environment; (ii) *selection*, which corresponds to touching or pointing at something; (iii) *manipulation*, which corresponds to modifying an object's position, orientation, scale or shape; (iv) *system control*, which corresponds to generating an event or command for functional interaction.

*e-mail: manuela.chessa@unige.it

In this paper, we focus on *manipulation* tasks, and in particular on grasping VR elements of different shape and orientation. We present the results of a pilot study that compares human grasping behaviour in VR with human grasping behaviour in the real world. The aim is to understand whether existing interaction techniques can be effectively used in VR training tasks, or if there is the need of designing new VR grasping/interaction techniques to compensate for the differences between real and virtual manipulation tasks. To this end, we replicate, in VR, the experiments presented by Klein et al. [19] that faces open questions in real grasping, showing that our brains employ a small set of heuristics to determine which locations on the object will lead to stable, comfortable grasps, so we can perform the desired action, e.g. picking something up. The novelty of this paper is to understand whether such findings could be valid also in VR, thus providing novel insights for the design of virtual environments.

In particular, we asked participants to reach, grasp and move four unfamiliar objects presented at different spatial orientations. We recorded the contact points between the object surface and participants' thumb and forefinger. We compare these data with the equivalent grasping patterns from Klein et al. [19], and we discuss the similarity and the differences between grasps executed in real and virtual environments.

2 Related work

Hand interaction with 3D virtual objects has been massively improved in recent years [3, 31, 42]. Specifically, new tracking devices have allowed the use of real-time human interaction systems: the Kinect sensor [46] and the Leap Motion [14, 43] provide reliable hand-gesture recognition and hand motion tracking, respectively. Such devices have been successfully employed to combine small finger movements with the full-body movements for intuitive object interactions in immersive virtual environments [2, 5, 44], and have also been employed for behavioural neuroscience research on eye-hand coordination [24]. These devices therefore provide reliable tracking, yet they do not yet provide naturalistic interaction modalities, not do they provide haptic feedback.

Hand-based 3D interaction modalities within virtual environments may rely on kinematic and gesture-based interfaces: predefined gestures are used to perform some actions [22, 45]. For this kind of interface a pinch gesture can be used for detecting intended grasp interactions [27]. Though such a technique is employed in several devices, e.g. the Microsoft HoloLens [1], it does not allow a natural interaction with virtual objects, since it only simulates the pinching gesture, but does not simulate a physically accurate pinching or grasping interaction with an object.

To obtain more naturalistic hand interaction in VR, physics-based hand interaction systems have been proposed that simulate the forces involved in object grasping [9, 37]. It is possible to obtain even more realistic simulations by taking into account soft fingers [10] and friction models [36], however such methods are typically computationally expensive and not well suited for real-time simulations required in immersive VR interactions (but see [16] for an example of physics-based method for interaction in VR).

By exploiting a priori information about the hand and object, it is possible to perform a set of object interactions, i.e. object grasping, by synthesizing physically plausible interactions [21, 33]. The

2019 IEEE Conference on Virtual Reality and
3D User Interfaces
23-27 March, Osaka, Japan
978-1-7281-1377-7/19/$31.00 ©2019 IEEE

main drawback of this approach is the need of prior information on hand pose and object shape that hampers its use in unconstrained environments. While this class of methods has recently been employed to develop real-time virtual grasping for manipulating complex objects [38], the authors note that automatic virtual grasping for arbitrary objects remains an unsolved problem, likely due to the complexity of human grasping behaviour and movement kinematics [7, 35, 41]. Therefore, naturalistic virtual grasping modalities are still unavailable in common practice, and the absence of such modalities is likely to influence human behaviour in VR.

The absence of haptic feedback is also potentially detrimental for grasping in VR, as no force feedback is available to the users to signal when their fingers are in contact with the surface of an object. Even in devices that allow some form of feedback (such as force, vibrational or electrotactile feedback, e.g. [18]), no haptic feedback is available as to the weight of the virtual objects being lifted and manipulated. Yet sensorimotor feedback is an important component of visually guided grasping in the real world, as it continuously recalibrates grasping forces and the perception of object weight [26, 40]. Therefore we are interested in whether the absence of naturalistic virtual grasping modalities and of haptic feedback alters grasping behavior towards virtual objects compared to real ones. Understanding how grasping behaviour is altered in VR has clear implications for the design of VR environments as well as the development of novel VR haptic interfaces (e.g. passive haptics [15]).

The study and the modelling of the human visually guided grasping in the real world is an active research field [13, 20]. Multiple factors jointly influence human visually guided grasping, even for the relatively simpler case of two-digit precision grip [19]. For instance, the surface shape of an object will determine the location of physically possible grasps with thumb and index finger in opposition to avoid that the object will slip through fingertips [29]. Moreover, the orientation and size of each grasp have to be considered in order to avoid uncomfortable configurations of our hand in 3D space and object occlusions [4, 25, 30, 34]. The location of the objects center of mass also plays a role, as for grasps far from the center of mass the object will tend to rotate under gravity [23, 29].

Here, we compare our results with those of a recent study which presents behavioral data alongside a computational model that combines the diverse aspects of human grasping to correctly predict human precision grasping [19]. This comparison is meant to shed light on the similarities and differences between human grasping behaviour in virtual and real conditions.

3 Material and methods

We present the results of a pilot study to assess the similarity in grasping patterns for a virtual manipulation task with respect to the real one presented by Klein et al. [19]. To this aim, we use a low-cost hand tracking device, the Leap Motion, which allows us to obtain a first indication of the grasp patterns, though the accuracy of this device is not comparable with the acquisition setup used by Klein et al. [19]. However, the accuracy of the Leap Motion is bounded within $0.4-0.5$ cm, as reported in [39], and allows us to discriminate the grasping modalities, and to guide future experiments by using more accurate tracking methods.

3.1 Design

We created a simple VR environment, replicating the real world setup described by Klein et al. [19]. The setup is composed of a desk, calibrated to be at the same perceived distance as the real desk the participants sat in front of, and a circular target. The users reach the object in front of them, grasp it and put it on the gray box. The users see the virtual representation of their hand, tracked by the Leap Motion, and represented with the Capsule Hand Model. See Figure 1 for a view as inside the VR Head Mounted Display (HMD) and for a schematic representation with distances and dimensions reported in cm.

Four differently shaped objects (defined as objects L, U, S and V; see Fig. 2) served as stimuli. Each object was composed of 10 cubes (each 2.5cm on a side), textured with a wood image. Two of the objects featured cubes stacked on top of each other, whereas the other two objects were composed exclusively of cubes lying flat on the ground. The objects were presented to the participants at one of two orientations. Across orientations, object L was rotated by 180 degrees, objects U and V were rotated by 90 degrees, and object S was rotated by 55 degrees. Figure 2 shows the objects positioned as if viewed by a participant.

3.2 Apparatus

The VR scene was created in Unity 3D. We used the Oculus Rift HMD to display the virtual scene to the users, and the Leap Motion sensor fixed to the front plate for finger tracking, since such a device is used for hand interaction tasks, e.g [16, 38]. In particular, we used the Orion tracking software [1], specifically developed for VR environments. The system ran on a Intel Core i7 8th Generation, equipped with a GeForce GTX 1070 graphic card.

The Leap Motion device and software are also used to track and display the virtual representation of the user hand inside the VR environment. We used the Capsule Hand model, provided by the Leap Motion Core (see Fig. 1).

3.3 Participants

Five participants (3 males and 2 females between the ages of 25 and 51, mean age: 36.8 ± 10.9 years) participated in the Experiment. Two of the participants were authors MC and FS of the paper, 2 were PhD students at the University of Genoa, 1 was an external naive participant. Except for the first two participants, the others had no previous experience with grasping and interaction in VR. None received monetary compensation for participating. All participants reported having normal or corrected to normal vision and being right handed. All participants provided written informed consent prior to participating.

3.4 Procedure

Prior to each trial, participants had to place their hand open at a starting location above over the target. One of the eight simulus objects (4 objects by 2 rotations) appeared randomly in the middle of the desk at a distance of 30 cm from the observer. Then, the subject had to reach the object and to grasp it, in order to place it onto the target. The action had to be completed in the most natural and intuitive manner as possible. The position of the thumb and forefinger tip was recorded, together with the event indicating the interaction among the fingers and the object. A new object was generated every 3 seconds. It is worth noting that the generation and the correct positioning of the target is simplified in our VR replica, with respect to the real world experiment described by Klein et al. [19].

The experiment had 8 conditions: 4 wooden textured objects of different shapes, each object presented at two orientations. Each participant repeated each condition 15 times (120 trials per participant). The total duration of the experiment is 10 minutes, not causing appreciable fatigue into participants.

3.5 Analyses

The contact point is defined as a 3D point that lies both on the hand surface and the surface of the virtual object. As the real hand can penetrate the virtual objects (see Fig. 1b), it is not trivial to define meaningful contact points. Here, we rely on the methods proposed in [16]. We start from the 3D hand pose, as estimated by

[1] https://developer.leapmotion.com/windows-vr

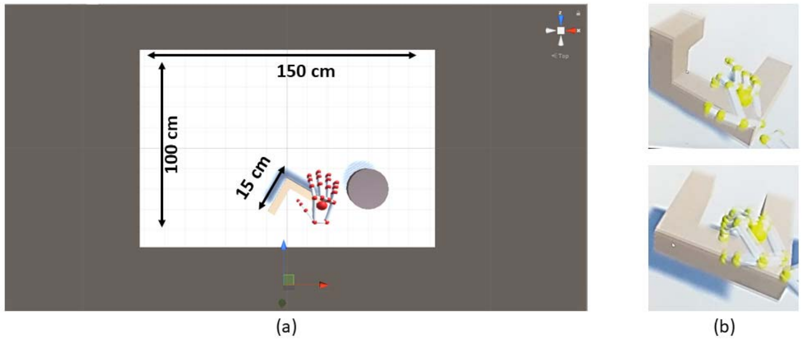

Figure 1: (a) Schematic representation of the scene, with the associated distances and dimension. (b) Enlarged view of individual grasps, from which it is possible to see both a grasp on the object surface (top) and a grasp in which the fingertips penetrate the object (bottom).

the Leap Motion device. Using a simplified 3D model of the hand, we detect the collisions between this hand and the virtual objects, by defining a small threshold distance around the virtual objects. We detect a contact when a point on the hand models surface gets closer to a virtual object than this threshold. Such an event can be detected efficiently using a physics engine. We thus obtain the 3D coordinates of the finger tips during the contact, which can be expressed as follows, as a function of the time:

$$\mathbf{G} = [TH_x, TH_y, TH_z, FF_x, FF_y, FF_z], \quad (1)$$

where $[TH_x, TH_y, TH_z]$ and $[FF_x, FF_y, FF_z]$ are the 3D coordinates of the thumb and of the forefinger, respectively.

It is worth noting that, by following such methods to detect collisions, it is possible to detect 3D coordinates not lying exactly on the objects surface. This is one of the main issues of grasping in VR, linked to the absence of haptic feedback.

From Eq. 1, we can define the amplitude of the grasp, as the distance between the thumb and the forefinger, when interacting with the object:

$$D = \sqrt{(TH_x - FF_x)^2 + (TH_y - FF_y)^2 + (TH_z - FF_z)^2}. \quad (2)$$

The distance from the contact point on the object surface to the current location of the intersecting phalanx can be used as a measure for estimating the contact force, as in [16].

Following Klein et al. [19], to compute the similarity S between two grasps $\mathbf{G_1}$ and $\mathbf{G_2}$ we first compute the Euclidean distance between the two 6D grasp vectors, $||\mathbf{G_1} - \mathbf{G_2}||$. We then divide this distance by the largest possible distance D_{max}between two points on the specific object, determined from the mesh models of the objects. Finally, similarity can be defined as as 1 minus the normalized grasp distance, times 100:

$$S = 100 * \left(1 - \frac{||\mathbf{G_1} - \mathbf{G_2}||}{D_{max}}\right). \quad (3)$$

Given the definition of grasp similarity S in Eq. 3, we can compute within-subject grasp similarity as the average similarity between grasps from the same participant to the participant's own median grasp. Between-subject grasp similarity is the similarity between the median grasp of each participant and the median grasp across all other participants.

4 Results

The positions of the thumb and forefinger during each grasp for all trials from one representative subject is plotted in Figure 2. Other subjects behaved in a comparable manner.

Figure 2 shows that contact points cover the same surface area, given a specific object and orientation (see also Fig. 3). Contact points are dependent on the orientation of the object (see L objects, top and bottom row). Moreover, if we compare the obtained results with the ones reported by Klein et al. [19], it is evident that in the VR scenario people are not able to precisely grasp the objects by placing the fingertips on opposing object surfaces. Users tend to penetrate the objects or touch them in impossible grasp configurations (see Fig. 1b). These mistakes are likely due to the absence of a naturalistic grasping modality, alongside inaccuracies in tracking by the Leap Motion device. Nevertheless, the portions of the virtual objects participants selected to grasp broadly agreed with the grasping patterns on real objects of Klein et al. [19].

Figure 3 (top) represents the heat map of the contact points, sampled as shown in Figure 3 (bottom). For each 3D position $[TH_x, TH_y, TH_z]$ and $[FF_x, FF_y, FF_z]$ of the thumb and the forefinger, we computed the distance with respect to the centroid of the discrete sampling of the object surface. Figure 3 (bottom) shows the 10 samples for the external surface of L object, orientation 2. We then computed the sample of the surface which is closer to the thumb (or forefinger) position. By repeating the procedure for all the trials we are able to build a heat map, indicating which portion of the object surface are mostly touched by the thumb (and the forefinger), and which is the most common thumb-finger configuration. By observing Figure 3 (top) it is possible to conclude that most grasping happened with the same thumb-forefinger configuration. The same pattern of results was observed for the other objects and orientations.

Table 1 shows that the average distance between the thumb and forefinger positions (see Eq. 2) is less than the ideal distance (i.e. 2.5 cm). This is due to the missing haptic feedback that prevent us to go inside the objects in the real world, but not in VR.

subject id	id00	id01	id02	id03	id04
D [cm]	0.87	1.87	1.14	0.43	0.93

Table 1: Amplitude of the grasp, as the distance between the thumb and the forefinger, when interacting with the object (see Eq. 2). Measurements for each subject are averaged across all trials.

To further quantify how these grasping patterns are clustered, Klein et al. [19] designed a simple metric of similarity between grasps (see Eq. 3). For real objects, within-subject grasp similarity was greater than between subject grasp similarity. Conversely, in VR the within-subject grasp similarity (77.56 ± 3.63) was statistically indistinguishable from the between-subject grasp similarity (75.43 ± 9.49), with $p>0.05$, paired samples t-test. This result is in line with our previous observations. Within-subject grasp similarity for virtual objects is lower than that reported for real objects by Klein et

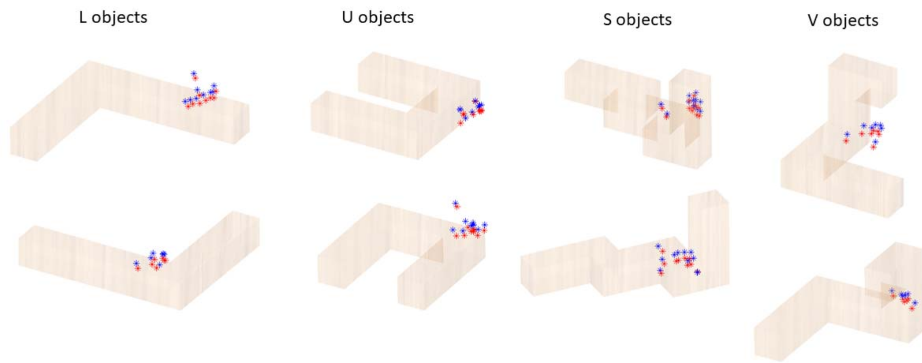

Figure 2: The four differently shaped objects employed and their rotation, as viewed by a participant. Position of the thumb (red) and of the forefinger (blue) during each grasp, for the different trials of one representative subject. The transparency of the texture has been increased to highlight the occluded contact points.

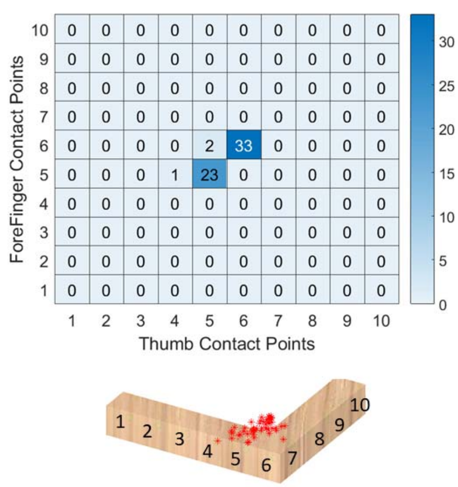

Figure 3: Top: Heat map of the contact points for the L object, orientation 2. Bottom: L object, orientation 2 and the 10 samples of the possible contact points for the thumb. Analogously for the forefinger. Same results were observed for the other objects and orientations.

al. [19], likely due to the absence of a naturalistic grasping modality and haptic feedback that hinder individual observers' idiosyncratic behaviour. Instead, between-subject grasp similarity for virtual objects is in line with that observed for real objects [19], suggesting that different participants are attempting to grasp similar portions of the objects, in VR as in real environments.

5 Discussion and Conclusion

We have conducted an initial evaluation of grasping behaviour in immersive VR, through a direct comparison with an equivalent real world experimental setup [19]. This comparison allows us to draw the following conclusions.

Grasping behaviour None of the participants explicitly attempted to grasp the objects using non-natural finger configurations (i.e. uncomfortable, unstable or impossible ones). Nevertheless, the absence of a naturalistic grasping modality and of haptic feedback resulted in impossible grasping patterns, with fingertips either within the objects or not in contact with the object surfaces.

Portion of the object to be grasped The thumb and forefinger contact positions are consistent (though different) with what Klein et al. [19] show (see Fig. 3). Moreover, our results show comparable grasp similarities both within- and between-subject analyses. This indicates that for each object and each orientation different participants choose similar grasp configurations (see Fig. 3) that were approximately maintained across trial repetitions.

Amplitude of the grasp We computed this quantity as it appeared evident, from a qualitative point of view, that the thumb and forefinger contact positions in the present study were different with respect the one measured in real world conditions. This was due to two main reasons. Firstly, the lack of a naturalistic grasp modality, coupled with the Leap Motion's inaccuracies, likely let to grasp errors and measurement noise. Secondly, the lack of haptic feedback plays a fundamental role in this experiment and in the conclusion we can draw from it. Since participants were not physically touching any objects, they exhibited the tendency to close the fingers more than the real thickness of the object they were grasping (see Table 1, and Fig. 1b). Further research should investigate whether haptic feedback is necessary to avoid this behaviour, or if feedback through different modalities (e.g. through vision or sound) could improve grasping behaviour and experience in VR. The approaches described in [16] could be also be efficiently implemented in order to conduct further experiments. This will be one of the primary aims of further analyses on grasping behaviour in immersive VR.

Detection of the 3D fingers' position The use of the Leap motion device allowed us to obtain a first indication that the grasping behaviour in immersive VR is consistent to the gasping behaviour in the real world. The Leap Motion device was chosen for this study due to its popularity as a low cost interaction device for many VR applications. Nevertheless, the problems associated with the measurements' stability and accuracy could worsen the obtained results (e.g. see contact points highlighted in Fig. 2 that in some cases are not correctly aligned with the object). Future works will test whether more accurate hand tracking devices may help reduce participants' grasp errors.

Taken together, the analyses and observations presented in this work will hopefully advance not only the design of VR systems and interaction interfaces, but also further our understanding of the human grasping behaviour.

Acknowledgments

Authors MC and FS were supported by the Interreg Alcotra Project PROSOL We-Pro. Author GM was supported by a Marie-Skodowska-Curie Actions Individual Fellowship (H2020-MSCA-IF-2017: VisualGrasping Project ID: 793660).

References

[1] L. Avila and M. Bailey. Augment your reality. *IEEE Computer Graphics and Applications*, 36(1):6–7, 2016.

[2] C. Bassano, F. Solari, and M. Chessa. Studying natural human-computer interaction in immersive virtual reality: A comparison between actions in the peripersonal and in the near-action space. In *VISIGRAPP 2018 - Proceedings of the 13th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications*, vol. 2, pp. 108–115, 2018.

[3] C. W. Borst and A. P. Indugula. Realistic virtual grasping. In *IEEE Virtual Reality 2005*, pp. 91–98, 2005.

[4] P. Cesari and K. M. Newell. The scaling of human grip configurations. *Journal of Experimental Psychology: Human Perception and Performance*, 25(4):927, 1999.

[5] M. Chessa, L. Caroggio, H. Huang, and F. Solari. Insert your own body in the Oculus Rift to improve proprioception. In *VISIGRAPP 2016 - Proceedings of the 11th Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications - Doctoral Consortium*, vol. 4, pp. 755–762, 2016.

[6] L. Chittaro and F. Buttussi. Assessing knowledge retention of an immersive serious game vs. a traditional education method in aviation safety. *IEEE Transactions on Visualization and Computer Graphics*, 21(4):529–538, 2015.

[7] V. N. Christopoulos and P. R. Schrater. Grasping objects with environmentally induced position uncertainty. *PLoS computational biology*, 5(10):e1000538, 2009.

[8] J. Egger, M. Gall, J. Wallner, P. d. A. G. Boechat, A. Hann, X. Li, X. Chen, and D. Schmalstieg. Integration of the HTC Vive into the medical platform MeVisLab. In *Medical Imaging 2017: Imaging Informatics for Healthcare, Research, and Applications*, vol. 10138, p. 1013817. International Society for Optics and Photonics, 2017.

[9] T. Erez, Y. Tassa, and E. Todorov. Simulation tools for model-based robotics: Comparison of bullet, havok, MuJoCo, ODE and PhysX. In *IEEE International Conference on Robotics and Automation (ICRA), 2015*, pp. 4397–4404. IEEE, 2015.

[10] B. Froehlich and J. Jacobs. A soft hand model for physically-based manipulation of virtual objects. In *IEEE Virtual Reality 2011*, pp. 11–18, 2011.

[11] B. Frohlich, J. Hochstrate, A. Kulik, and A. Huckauf. On 3D input devices. *IEEE Computer Graphics and Applications*, 26(2):15–19, 2006.

[12] N. Gavish, T. Gutiérrez, S. Webel, J. Rodríguez, M. Peveri, U. Bockholt, and F. Tecchia. Evaluating virtual reality and augmented reality training for industrial maintenance and assembly tasks. *Interactive Learning Environments*, 23(6):778–798, 2015.

[13] R. Gilster, C. Hesse, and H. Deubel. Contact points during multi-digit grasping of geometric objects. *Experimental brain research*, 217(1):137–151, 2012.

[14] J. Guna, G. Jakus, M. Pogačnik, S. Tomažič, and J. Sodnik. An analysis of the precision and reliability of the Leap Motion sensor and its suitability for static and dynamic tracking. *Sensors*, 14(2):3702–3720, 2014.

[15] D. T. Han, M. Suhail, and E. D. Ragan. Evaluating remapped physical reach for hand interactions with passive haptics in virtual reality. *IEEE Transactions on Visualization & Computer Graphics*, (1):1–1, 2018.

[16] M. Höll, M. Oberweger, C. Arth, and V. Lepetit. Efficient physics-based implementation for realistic hand-object interaction in virtual reality. In *IEEE Virtual Reality 2018*, pp. 175–182, 2018.

[17] M. C. Howard. A meta-analysis and systematic literature review of virtual reality rehabilitation programs. *Computers in Human Behavior*, 70:317–327, 2017.

[18] J. Hummel, J. Dodiya, G. A. Center, L. Eckardt, R. Wolff, A. Gerndt, and T. W. Kuhlen. A lightweight electrotactile feedback device for grasp improvement in immersive virtual environments. In *IEEE Virtual Reality 2016*, pp. 39–48. IEEE, 2016.

[19] L. K. Klein, G. Maiello, V. C. Paulun, and R. W. Fleming. How humans grasp three-dimensional objects. *bioRxiv*, 2018. doi: 10.1101/476176

[20] U. Kleinholdermann, V. H. Franz, and K. R. Gegenfurtner. Human grasp point selection. *Journal of vision*, 13(8):23–23, 2013.

[21] Y. Li, J. L. Fu, and N. S. Pollard. Data-driven grasp synthesis using shape matching and task-based pruning. *IEEE Transactions on Visualization and Computer Graphics*, 13(4):732–747, 2007.

[22] W. Lin, L. Du, C. Harris-Adamson, A. Barr, and D. Rempel. Design of hand gestures for manipulating objects in virtual reality. In *International Conference on Human-Computer Interaction*, pp. 584–592. Springer, 2017.

[23] J. Lukos, C. Ansuini, and M. Santello. Choice of contact points during multidigit grasping: effect of predictability of object center of mass location. *Journal of Neuroscience*, 27(14):3894–3903, 2007.

[24] G. Maiello, M. Kwon, and P. J. Bex. Three-dimensional binocular eye–hand coordination in normal vision and with simulated visual impairment. *Experimental Brain Research*, 236(3):691–709, 2018.

[25] G. Maiello, V. C. Paulun, L. K. Klein, and R. W. Fleming. Object visibility, not energy expenditure, accounts for spatial biases in human grasp selection. *bioRxiv*, 2018. doi: 10.1101/476101

[26] G. Maiello, V. C. Paulun, L. K. Klein, and R. W. Fleming. The sequential-weight illusion. *i-Perception*, 9(4):2041669518790275, 2018.

[27] M. Moehring and B. Froehlich. Effective manipulation of virtual objects within arm's reach. In *IEEE Virtual Reality 2011*, pp. 131–138. IEEE, 2011.

[28] M. Murcia-Lopez and A. Steed. A comparison of virtual and physical training transfer of bimanual assembly tasks. *IEEE Transactions on Visualization and Computer Graphics*, 24(4):1574–1583, 2018.

[29] V.-D. Nguyen. Constructing force-closure grasps. *The International Journal of Robotics Research*, 7(3):3–16, 1988.

[30] V. C. Paulun, U. Kleinholdermann, K. R. Gegenfurtner, J. B. Smeets, and E. Brenner. Center or side: biases in selecting grasp points on small bars. *Experimental brain research*, 232(7):2061–2072, 2014.

[31] V. I. Pavlovic, R. Sharma, and T. S. Huang. Visual interpretation of hand gestures for human-computer interaction: A review. *IEEE Transactions on Pattern Analysis & Machine Intelligence*, (7):677–695, 1997.

[32] D. C. Porras, P. Siemonsma, R. Inzelberg, G. Zeilig, and M. Plotnik. Advantages of virtual reality in the rehabilitation of balance and gait: Systematic review. *Neurology*, 90(22):1017–1025, 2018.

[33] M. Prachyabrued and C. W. Borst. Virtual grasp release method and evaluation. *International Journal of Human-Computer Studies*, 70(11):828–848, 2012.

[34] A. Roby-Brami, N. Bennis, M. Mokhtari, and P. Baraduc. Hand orientation for grasping depends on the direction of the reaching movement. *Brain research*, 869(1-2):121–129, 2000.

[35] J. B. Smeets and E. Brenner. A new view on grasping. *Motor control*, 3(3):237–271, 1999.

[36] A. Talvas, M. Marchal, C. Duriez, and M. A. Otaduy. Aggregate constraints for virtual manipulation with soft fingers. *IEEE Transactions on Visualization and Computer Graphics*, 21(4):452–461, 2015.

[37] J. Taylor, L. Bordeaux, T. Cashman, B. Corish, C. Keskin, T. Sharp, E. Soto, D. Sweeney, J. Valentin, B. Luff, et al. Efficient and precise interactive hand tracking through joint, continuous optimization of pose and correspondences. *ACM Transactions on Graphics (TOG)*, 35(4):143, 2016.

[38] H. Tian, C. Wana, and X. Zhana. A realtime virtual grasping system for manipulating complex objects. In *IEEE Virtual Reality 2018*, pp. 1–2. IEEE, 2018.

[39] P. P. Valentini and E. Pezzuti. Accuracy in fingertip tracking using leap motion controller for interactive virtual applications. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 11(3):641–650, 2017.

[40] V. van Polanen and M. Davare. Sensorimotor memory biases weight perception during object lifting. *Frontiers in Human Neuroscience*, 9:700, 2015.

[41] R. Volcic and F. Domini. On-line visual control of grasping movements. *Experimental brain research*, 234(8):2165–2177, 2016.

[42] C. Von Hardenberg and F. Bérard. Bare-hand human-computer interaction. In *Proceedings of the 2001 workshop on Perceptive user interfaces*, pp. 1–8. ACM, 2001.

[43] F. Weichert, D. Bachmann, B. Rudak, and D. Fisseler. Analysis of the accuracy and robustness of the leap motion controller. *Sensors*,

13(5):6380–6393, 2013.
[44] B. Wilson, M. Bounds, and A. Tavakkoli. A full-body motion calibration and retargeting for intuitive object manipulation in immersive virtual environments. In *IEEE 9th Workshop on Software Engineering and Architectures for Realtime Interactive Systems (SEARIS), 2016*, pp. 1–5. IEEE, 2016.
[45] D. Yim, G. N. Loison, F. H. Fard, E. Chan, A. McAllister, and F. Maurer. Gesture-driven interactions on a virtual hologram in mixed reality. In *Proceedings of the 2016 ACM Companion on Interactive Surfaces and Spaces*, pp. 55–61. ACM, 2016.
[46] Z. Zhang. Microsoft Kinect sensor and its effect. *IEEE multimedia*, 19(2):4–10, 2012.