The Influence of Haptic Feedback on Reaching and Grasping Movements in Virtual Reality

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Introduction

Virtual Reality (VR) has rapidly evolved from a realm of entertainment to an invaluable tool in research across a variety of disciplines. Its immersive properties allow researchers to investigate and test scenarios in controlled virtual environments. The popularity of VR is evident, with a surge in research adoption. In fields ranging from medicine to psychology, VR facilitates training, simulation, and experimentation, making it a pivotal tool for understanding and addressing complex research questions. Among many other use cases, VR is increasingly being used for motor rehabilitation because it provides a safe and highly controllable virtual environment (Rose et al., 2000; Saposnik & Levin, 2011). However, the use of VR technology for rehabilitation purposes raises an important question, namely, whether movements performed in virtual environments are kinematically equivalent to the same movements being performed in similar physical environments. As Magdalon et al. (2011) point out, this is particularly relevant for reaching and grasping movements, as these movements rely heavily on veridical sensory information about the target object (Jeannerod, 1999; Smeets & Brenner, 1999). In this essay, I will review a research article by Cuijpers et al. (2008) that addresses the importance of haptic feedback for grasping movements to cylinders in a virtual environment. I will outline the experiments conducted by Cuijpers et al. (2008), present their main findings, and comment on the implications these findings may have for the use of VR for rehabilitation purposes.

Influence of Imperfect Haptic Feedback on Grasping Movements

To grasp an object with a precision grip, we must accurately locate the target object in space (i.e., relative to our bodies) and identify its shape in order to position our fingertips appropriately. To do so, we typically rely on multiple visual cues simultaneously. Importantly, it is still an open research question how these multiple cues, which may even provide conflicting evidence, are consolidated to perform grasping movements. One hypothesis suggests that these cues are integrated into a single estimate in a statistically optimal way by assigning weights to each cue based on its reliability (Hillis et al., 2004; Landy et al., 1995). Some studies, on the other hand, indicate that "visual cues are recruited depending on the task requirements (...) and on what aspects of the movement they are needed for" (Cuijpers et al., 2008). If the latter were true, visual cues could theoretically "differentially affect the different aspects of a grasping movement, such as grip aperture and grip orientation (Cuijpers et al., 2008)". Taking this idea a step further, Cuijpers et al. (2008) investigated the extent to which imperfect *haptic* feedback influences grasping behavior by asking participants to grasp and lift (virtually rendered) cylinders while simultaneously receiving haptic feedback from real cylinders that were placed at the location of the virtual cylinders. In the following sections, I will outline the experimental methodology employed by Cuijpers et al. (2008), their hypotheses, and the obtained results.

Experimental Design. The study by Cuijpers et al. (2008) consisted of two experiments, both of which involved the grasping and lifting of cylinders. Crucially, participants did not see the real cylinders that they lifted. Instead, they viewed virtually rendered cylinders "displayed on a monitor (...) visible via a semi-transparent mirror that was placed at an angle of 45°" (Cuijpers et al., 2008). The general setup used in both experiments is illustrated in Figure 1. In both experiments, participants started from a fixed position (which varied slightly between the two conditions) and were asked to reach for and grasp a virtual cylinder as soon as it was rendered visible. A physical cylinder was placed at the location of

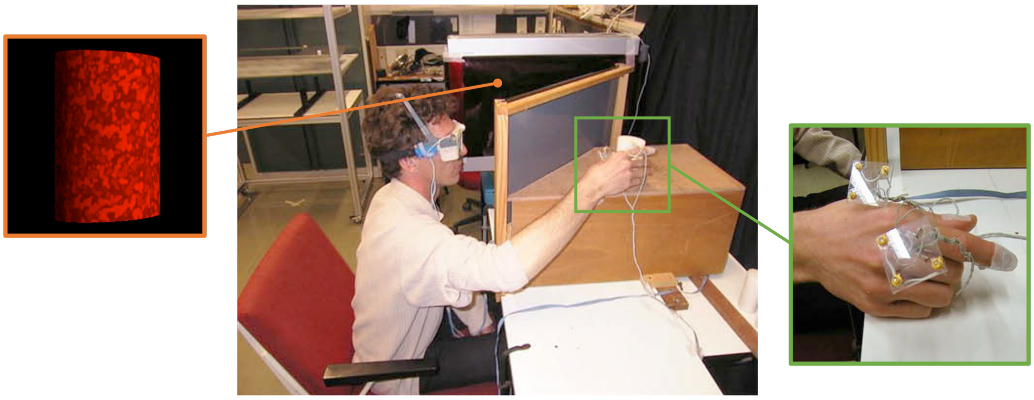

Figure 1. Setup used by Cuijpers et al. (2008). A participant is reaching for a physical cylinder obstructed by a semi-transparent mirror, simultaneously viewing a virtually rendered cylinder presented on a screen. The semi-transparent mirror prevents interference from the participant's hand with the virtual cylinder during the grasping motion. An Optotrak 3020 sensor system tracked fingertip positions.

Note. Adapted from "Consistent haptic feedback is required but it is not enough for natural reaching to virtual cylinders," by R. H. Cuijpers, E. Brenner and J. B. Smeets, 2008, *Human Movement Science, 27*(6), p. 860 (https://doi.org/10.1016/j.humov.2008.07.003). Copyright 2008 by Elsevier B.V.

the virtual cylinder to provide haptic feedback (see Fig. 1). The virtual cylinder was extinguished as soon as one of the participant's fingertips was within 1 cm or less of the physical cylinder. After briefly lifting the cylinder, participants had to set it back down and return to their starting position to complete a single trial. If, in any trial, the cylinder was not reached within 3 seconds, that trial did not count and had to be repeated immediately.

Constant feedback. The two experiments conducted by Cuijpers et al. (2008) differed in the virtual and physical cylinders being used. In their first experiment, the authors used a single circular physical cylinder with a diameter of $d = 52$ mm and a height of 100 mm. In contrast, the virtual cylinders varied in shape and orientation. For the virtual cylinders, seven different cylinders with an elliptical base were used. While the diameter d_{major} of the major axes ranged from 52 mm to 64 mm in 2 mm increments, the diameters d_{minor} of the minor axes were given by

$$d_{\text{minor}} = d^2/d_{\text{major}}, \quad d = 52 \text{ mm},$$

resulting in a constant volume for all virtual cylinders, equal to that of the circular physical cylinder. Because the same physical cylinder was paired with all seven virtual cylinders, participants received *constant* haptic feedback that was inconsistent with the virtual cylinder in all but one case. In ad-

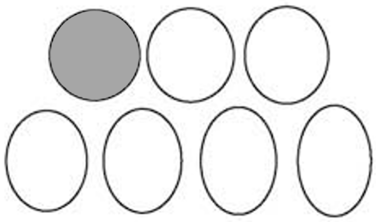

Figure 2. Outlines of the seven elliptical bases of the virtual cylinders used in the first experiment by Cuijpers et al. (2008). The filled circle represents the base of the single circular physical cylinder.

Note. Adapted from "Consistent haptic feedback is required but it is not enough for natural reaching to virtual cylinders," by R. H. Cuijpers, E. Brenner and J. B. Smeets, 2008, *Human Movement Science, 27*(6), p. 860 (https://doi.org/10.1016/j.humov.2008.07.003). Copyright 2008 by Elsevier B.V.

dition, the virtual cylinders were each presented in six different orientations, i.e., for each cylinder, the "orientation of the major axis was varied from 0° to 150° [counterclockwise] in steps of 30°" (Cuijpers et al., 2008), resulting in a total of 42 trials.

Consistent feedback. In contrast to the first experiment, Cuijpers et al. (2008) used multiple physical cylinders in their second experiment. For each physical cylinder, one principal axis remained fixed at 50 mm in diameter. The remaining principal axis varied in diameter from 20 mm to 80 mm in 10 mm increments, resulting in seven physical cylinders, all of which were also used as virtual cylinders. Eight cylinders with intermediate lengths of the second principal axis were employed as additional virtual cylinders, as shown in Figure 3. In each trial, either the identical physical cylinder or the closest matching physical cylinder was used to provide haptic feedback *consistent* with the virtual cylinder. Each combination of (physical and virtual) cylinders was presented in two orientations, either at 0° or at 45° clockwise relative to the cylinders' variable principal axes. Each stimulus condition (i.e., cylinder shape and orientation) was repeated three times, giving rise to a total of 90 trials per participant.

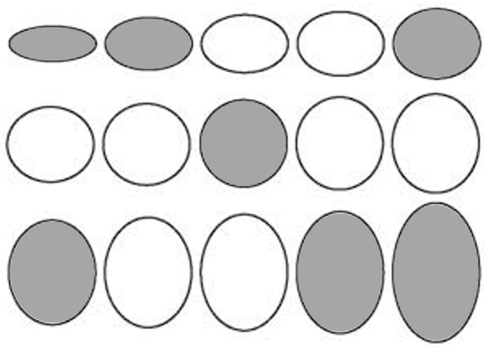

Figure 3. Outlines of the 15 elliptical bases of the virtual cylinders used in the second experiment by Cuijpers et al. (2008). Filled ellipses indicate cylinders also used to provide haptic feedback.

Note. Adapted from "Consistent haptic feedback is required but it is not enough for natural reaching to virtual cylinders," by R. H. Cuijpers, E. Brenner and J. B. Smeets, 2008, *Human Movement Science, 27*(6), p. 860 (https://doi.org/10.1016/j.humov.2008.07.003). Copyright 2008 by Elsevier B.V.

Hypotheses. In previous studies (Cuijpers et al., 2004, 2006), the authors had participants grasp real elliptical cylinders and "found that participants grasped these cylinders along one of their principal axes although their final grip orientation was systematically biased in a direction that depended on the cylinders' orientation" (Cuijpers et al., 2008). If, in the *constant feedback* condition, participants were to also grasp the virtually rendered cylinders along one of their principal axes, the surface slant felt when grasping the physical circular cylinder would match the surface slant of the virtual elliptical cylinders that participants view during the grasping movement. While the curvature of the physical cylinder will not match that of the virtual cylinders, this may not have much effect on *grip orientation* since haptic judgments of surface curvature are generally inaccurate (Pont et al., 1999). In other words, participants may not readily perceive the differences in surface curvature between the virtual and physical cylinders. Because the size of the cylinders will vary more drastically between the virtual and physical cylinders, Cuijpers et al. (2008) expect the *grip aperture* to be affected in subsequent trials so that the scaling of the grip aperture would differ from the results obtained for grasping real cylinders. Taken together, Cuijpers et al. (2008) "expect that with *constant* [emphasis added] haptic feedback the scaling of the grip aperture is reduced relative to grasps to real cylinders but not the scaling of grip orientation". Of course, the argument for grip orientation scaling being unaffected remains valid only when participants intend to grasp the virtual cylinders along one of their principal axes. If not, one would expect the scaling of grip orientation to be reduced as well relative to grasps to real cylinders, as Cuijpers et al. (2008) point out.

In the *consistent feedback* condition, Cuijpers et al. (2008) do not anticipate significant differences in the results compared to those obtained for grasping real cylinders.

Results. Cuijpers et al. (2008) restricted their analysis to the final grip orientation (defined as the orientation "just before touching the cylinder's surface") and the maximum grip aperture, as these two measures have been shown to effectively describe the grasping movement (Cuijpers et al., 2004, 2006). Further, these studies (Cuijpers et al., 2004, 2006) also indicate that the orientation of the cylinder primarily influences grip orientation, while the aspect ratio of the cylinder primarily affects maximum grip aperture. Consequently, the main quan-

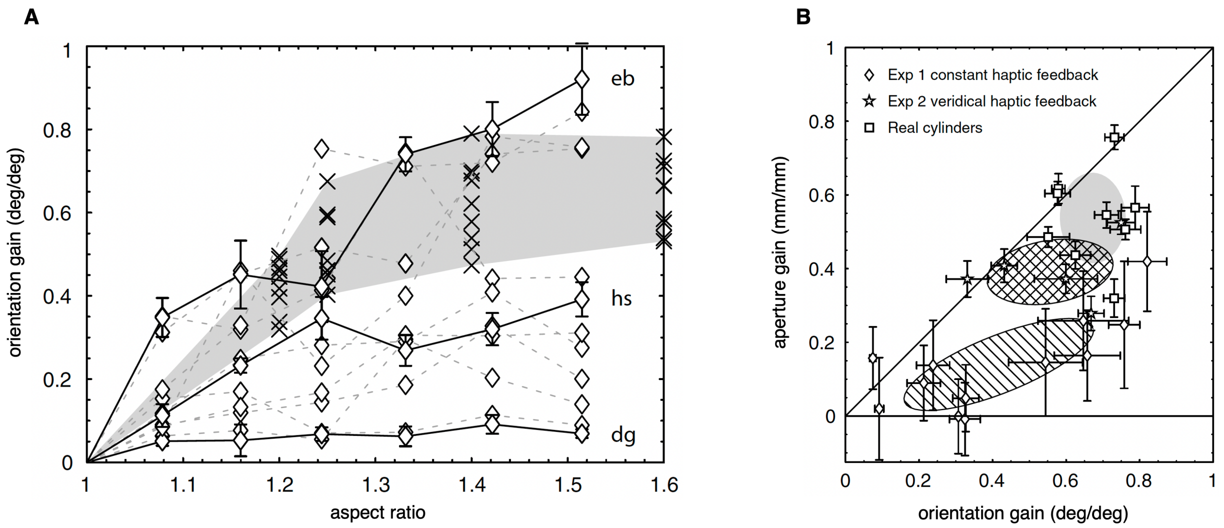

Figure 4. Results obtained by Cuijpers et al. (2008). **A** Scaling gains of grip orientation with cylinder orientation plotted against cylinder aspect ratio in the *constant feedback* condition. Diamonds represent mean values per participant, error bars indicate standard error (SE). Results from individual participants are connected by a (dashed) line. Crosses illustrate results for grasps to real cylinders (Cuijpers et al., 2006). The range of these data is highlighted by the gray area. **B** Aperture gain plotted against orientation gain for both conditions (i.e., constant and consistent feedback) as well as earlier results for grasps to real cylinders (Cuijpers et al., 2006). Diamonds: constant feedback. Stars: consistent feedback. Squares: real cylinders. Illustrated are mean values per participant, error bars indicate SE. Average results per condition (i.e., across participants) are depicted by ellipses centered on the mean of each condition. The diameter of the principal axes represents twice the standard deviation of the data in those directions.

Note. Adapted from "Consistent haptic feedback is required but it is not enough for natural reaching to virtual cylinders," by R. H. Cuijpers, E. Brenner and J. B. Smeets, 2008, *Human Movement Science, 27*(6), pp. 865, 869 (https://doi.org/10.1016/j.humov.2008.07.003). Copyright 2008 by Elsevier B.V.

tities analyzed by Cuijpers et al. (2008) were the scaling of grip orientation with cylinder orientation and the scaling of maximum grip aperture with the diameter of the nearest principal axis.

For the *constant feedback* condition, the scaling of grip orientation with cylinder orientation and the scaling of maximum grip aperture with the diameter of the nearest principal axis were determined using a fitting procedure that Cuijpers et al. (2006) had already applied to their data on grasps to real cylinders. The scaling gains of grip orientation with cylinder orientation are illustrated in Figure 4. Notably, there is large variance in the data between participants. While a few participants exhibit a grip orientation that is almost proportional to cylinder orientation (i.e., scaling gain close to 1), others hardly adjust their grip orientation at all when cylinder orientation changes (i.e., scaling gain close to 0). Most importantly, the average scaling gain of grip orientation across all participants (and aspect ratios greater than 1.3, where most participants show a saturation) was 0.42, which is significantly less than the average scaling gain of 0.67 observed for grasps to real cylinders (Cuijpers et al., 2006). Similarly, the average scaling gain of maximum grip aperture of 0.14 was well below the average scaling gain of 0.54 for real cylinders (Cuijpers et al., 2006).

While the results obtained in the *consistent feedback* condition are more closely aligned with those obtained for real cylinders, there is still a noticeable deviation. The average scaling gains of both grip orientation (0.56) and maximum grip aperture (0.39) were considerably smaller than the values reported for grasps to real cylinders (Cuijpers et al., 2008).

Not only did the mean values reported for scaling of grip orientation and maximum grip aperture fall short of those for real cylinders, but the variance of these measures across participants was much greater in the virtual environment as well, as depicted in Figure 4.

Discussion

The results proposed by Cuijpers et al. (2006, 2008) indicate that neither constant nor consistent haptic feedback is sufficient to produce natural reaching and grasping behaviors within a virtual setting. While Cuijpers et al. only investigated the precision grip for elliptical cylinders, similar findings have been proposed by Magdalon et al. (2011). In their research, Magdalon et al. compared reaching and grasping movements in "an immersive three-dimensional virtual environment with haptic feedback (...) to those made in an equivalent physical environment". In contrast to Cuijpers et al. (2008), Magdalon et al. (2011) had their participants reach for and grasp three real-world objects (can, screwdriver, and pen) requiring different grasp types (cylindrical grasp, power grasp, and precision grasp). A cyberglove/grasp system (Immersion Corp.) provided haptic feedback in the virtual environment. To eliminate the possibility that any discrepancies between the virtual and physical environments were caused solely by the use of the cyberglove/grasp system, Magdalon et al. (2011) had participants perform the identical tasks while wearing the glove in the physical environment as well. Similar to Cuijpers et al. (2008), Magdalon et al. (2011) found differences in the spatial and temporal kinematics between physical and virtual environments. For example, in the virtual environment, reaching movements were generally slower with longer deceleration times and maximum grip apertures were larger in the power and precision grip conditions (Magdalon et al., 2011).

Conclusion. In summary, the findings by Cuijpers et al. (2006, 2008) and Magdalon et al. (2011) highlight the complexity of accurately translating real-world motor actions into the virtual domain. As Magdalon et al. (2011) emphasize, this needs to be taken into account when applying VR technology for rehabilitation purposes. As VR technology continues to evolve, it is not inconceivable that the gap between the real and virtual worlds, in terms of motion kinematics, will eventually be closed. At the same time, further research is needed to critically assess any new technology to ensure that its use for rehabilitation purposes is safe and beneficial.

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