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Consistent haptic feedback is required but it is not enough for natural reaching to virtual cylinders

Raymond H. Cuijpers [a,*], Eli Brenner [b], Jeroen B.J. Smeets [b]

[a] Radboud University, P.O. Box 9104, NL-6500 HE Nijmegen, The Netherlands
[b] VU University, Van der Boechorststraat 9, NL-1081 BT Amsterdam, The Netherlands

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ABSTRACT

In virtual reality it is easy to control the visual cues that tell us about an object's shape. However, it is much harder to provide realistic virtual haptic feedback when grasping virtual objects. In this study we examined the role of haptic feedback when grasping (virtual) cylinders with an elliptical circumference. In Experiment 1 we placed the same circular cylinder at the simulated location of virtual elliptical cylinders of varying shape, so that the haptic feedback did not change when the visually specified shape changed. We found that the scaling of maximum grip aperture with the diameter of the nearest principal axis (.14 ± .04) was much weaker than when grasping real cylinders (.54 ± .04, Cuijpers, Brenner, & Smeets, 2006 Grasping reveals visual misjudgements of shape. *Experimental Brain Research*, 175, 32-44). For the scaling of grip orientation with the orientation of the cylinder we found large individual differences: the range is .07–.82 (average .42 ± .07) as compared to .55–.79 (average .67 ± .03) for grasping real cylinders. In Experiment 2 we provided consistent haptic feedback by placing real cylinders that matched the location, shape and orientation of the virtual cylinders. The scaling gains of both maximum grip aperture (.39 ± .04) and grip orientation (.56 ± .08) were substantially higher than in Experiment 1, but still lower than for grasps to real cylinders. The variability between participants for the scaling of grip orientation was also much reduced. These results showed that although haptic feedback must be consistent with visual information, it is not sufficient for natural prehension. We discuss the implications of these findings in

* Corresponding author. Tel.: +31 24 361 2608.
E-mail address: r.cuijpers@nici.ru.nl (R.H. Cuijpers).

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terms of the integration of visual information with haptic feedback.

1. Introduction

When grasping objects we typically need to position our fingertips accurately. The general view is that vision provides us with information about an object's shape and location relative to our bodies. Many visual cues may be identified (such as retinal disparity, motion parallax, eye accommodation, etc.) which could potentially provide such information. However, it is known that in isolation, different visual cues lead to different estimates of an object's shape and location (e.g., Hibbard & Bradshaw, 2003; Todd, Tittle, & Norman, 1995; Watt & Bradshaw, 2003). How these estimates are reconciled when grasping an object remains unclear. It has been suggested that the individual estimates are combined in a statistically optimal way according to their reliabilities (Hillis, Watt, Landy, & Banks, 2004; Landy, Maloney, Johnston, & Young, 1995). The resulting weighted average could then drive a motor response like reaching and grasping an object. However, other studies suggest that such a single estimate may not exist. For example, it was found that an optical illusion only affects grasping when it is directly relevant for the task at hand: a size illusion affects the lifting force but not the grip aperture (Brenner & Smeets, 1996), and an illusion of extent in the Brentano figure only affects pointing in the direction of the extent of the illusion but not perpendicular to it (de Grave, Brenner, & Smeets, 2004). One way to interpret these findings is that visual cues are recruited depending on the task requirements (Knill, 2005; Triesch, Ballard, Hayhoe, & Sullivan, 2003) and on what aspects of the movement they are needed for (Greenwald, Knill, & Saunders, 2005; Smeets, Brenner, de Grave, & Cuijpers, 2002; Watt & Bradshaw, 2003). A similar argument can be made for the integration of visual and proprioceptive information (Scheidt, Conditt, Secco, & Mussa-Ivaldi, 2005; Sober & Sabes, 2005).

This interpretation also explains why grasping resists a size illusion (Aglioti, DeSouza, & Goodale, 1995; Goodale & Westwood, 2004), and why an illusion of orientation-contrast is corrected on-line (Glover & Dixon, 2001): the estimated grip locations for the finger tips are not consistent with the associated grip aperture (estimated distance between the grip locations) or the orientation of the associated grip axis (Smeets & Brenner, 1999; Smeets et al., 2002). If it is true that visual cues are not necessarily integrated for reaching and grasping, it is conceivable that visual cues differentially affect the different aspects of a grasping movement, such as grip aperture and grip orientation. We wanted to investigate how conflicting haptic feedback influences the use of visual cues in a virtual reality environment, where we could control the visual cues individually. However, it is known that not all visual cues can be rendered realistically (Bradshaw, Glennerster, & Rogers, 1996) and that the errors that this introduces influence prehension (Hibbard & Bradshaw, 2003). It is also very hard to provide realistic haptic feedback virtually, so imperfections in the haptic feedback may also influence the way in which virtual objects are grasped. In the present study we examine whether imperfections in haptic feedback influence the way we grasp (virtual) objects.

In our earlier studies (Cuijpers, Smeets, & Brenner, 2004; Cuijpers et al., 2006) we measured how participants grasped real cylinders with an elliptical circumference. We 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. Here we investigate how participants grasp virtual renderings of such cylinders. In Experiment 1 the haptic feedback is provided by a circular cylinder that is placed at the same location as the visual information suggests. The rationale for using a circular cylinder was that the felt surface slant would always be correct if participants intend to grasp the elliptical cylinders by one of their principal axes. The cylinder's size and surface curvature will not be correct. Since we do not expect accurate haptic judgments of surface curvature (Pont, Kappers, & Koenderink, 1999), the haptic feedback may not influence judgments of shape (Bingham, Crowell, & Todd, 2004; Brenner & van Damme, 1999; Brenner, van Damme, & Smeets, 1997) and therefore grip orientation. The size is more likely to "feel" inconsistent with vision, so grip aperture may be affected in a subsequent trial (Bingham, Zaal, Robin, & Shull, 2000; Coats, Bingham, &

Mon-Williams, 2008). Therefore, we expect that with constant haptic feedback the scaling of the grip aperture is reduced relative to grasps to real cylinders but not the scaling of grip orientation. If the conflict between visual and haptic information is large enough participants may no longer consider the visual and haptic information to be from the same object. This may well occur because the haptic feedback will be altogether inconsistent if participants do not intend to grasp the elliptical cylinders by their principal axes. In that case we expect that both the scalings of grip aperture and grip orientation are reduced in a correlated way. In Experiment 1 we provide consistent haptic feedback by using cylinders whose shape is closely matched to that of the virtual cylinders. This allows us to compare the effects of consistent and inconsistent haptic feedback. With consistent haptic feedback we expect to find similar results as for grasping real cylinders (Bingham et al., 2000; Coats et al., 2008).

2. Methods

2.1. General

2.1.1. Participants

Twelve subjects participated in Experiment 1. Except for the authors (RC, JS, and EB) the participants were unaware of the purpose of the experiment. Five subjects participated in Experiment 2, four of whom had also participated in Experiment 1. All participants had normal or corrected-to-normal visual acuity. Their stereo-acuity was tested to be better than 60 arc minutes except for JS. Since the results for JS did not deviate systematically from the other participants we saw no reason to exclude his data. All participants apart from participant HS reported to be right-handed. Since all participants had to use their right hand, all participants apart from HS used their preferred hand. Again we saw no reason to exclude his data, because the data for participant HS were well within the range of those of other participants. All participants gave their informed consent and the experiments are part of an ongoing research program that has been approved by the ethics committee of the Faculty of Human Movement Sciences of VU University Amsterdam in accordance with the guidelines laid down in the Declaration of Helsinki by the World Medical Association.

2.1.2. Task

In both experiments the participant's task was to reach for and lift a visually rendered cylinder starting from a fixed starting position. A real cylinder was placed at the location of the virtual cylinder. This real cylinder was grasped and lifted. Participants moved their hand back to the starting position after placing the cylinder back at its original location.

2.1.3. Rendering of the virtual cylinders

The virtual cylinders were rendered using OpenGL on a Silicon Graphics Onyx Reality Engine at a resolution of 816×612 pixels. The screen dimensions were 385×290 mm so that the spatial resolution was 0.5×0.5 mm/pixel, which corresponds to 3×3 arc minutes for a viewing distance of about 50 cm. The screen refresh rate was 120 Hz. The shutter glasses operated at the same frequency so that the refresh rate for each eye was effectively 60 Hz. All images were drawn in red because the shutter glasses had the least cross-talk for red images. In addition, a filter was placed in front of the monitor that transmitted only red light. The cylinders were rendered in stereo and in perspective and the images were updated in real-time using measured locations of the eyes in space (spatial accuracy about 1 mm at a sampling rate of 200 Hz; eye rotations were not measured). Thus, the rendered location and shape of the cylinders was fixed in space even if participants moved their heads. The cylinders were textured by modulating their ambient and diffuse reflectance between 50% and 100% with the pattern shown in Fig. 1A. Their shape was generated by stretching the circular cylinder (Fig. 1B). The simulated lighting was 50% ambient and 50% directed lighting from an infinitely remote light source to the right, above and behind the participant (direction 1:2:1).

The rendered images were displayed on a monitor to the left of the participant and they were visible via a semi-transparent mirror that was placed at an angle of 45°. The purpose of the mirror was to make sure that the right hand did not interfere with the images when grasping the cylinder (Fig. 1C).

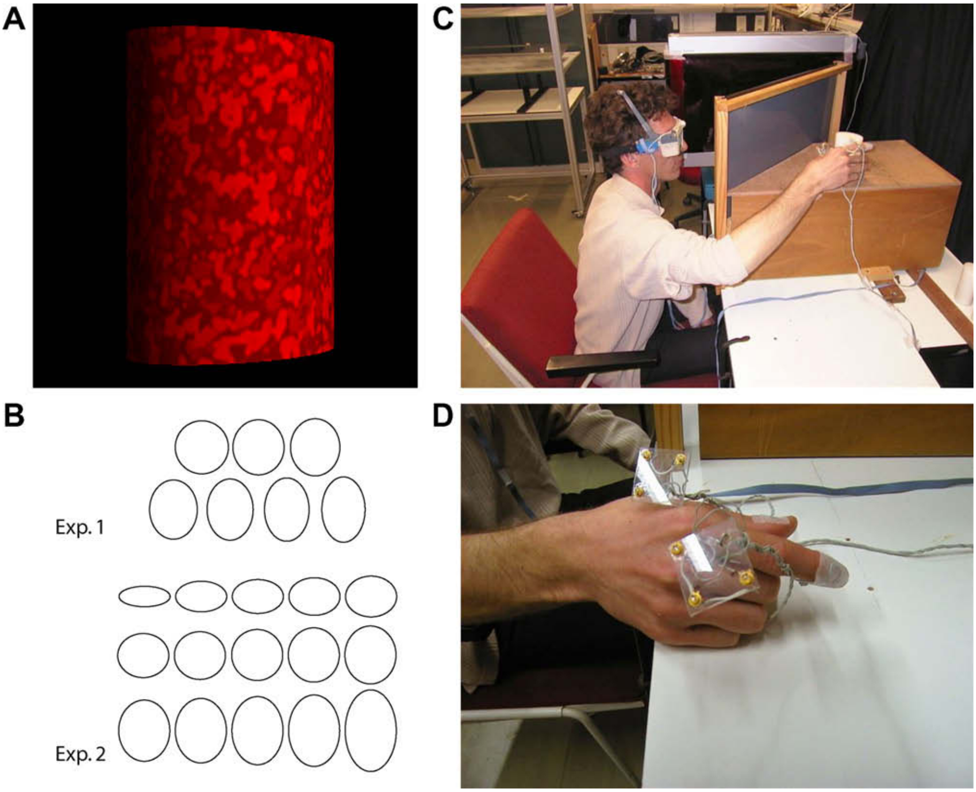

Fig. 1. (A) A rendered cylinder with aspect ratio 1.6 and orientation −45°. (B) Elliptical outlines of the virtual cylinders that were used in both experiments. (C) Picture of the experimental set-up. The virtual cylinders are displayed on a monitor that is visible via a mirror, so that monitor and mirror do not obstruct the grasping, right hand. The participant is wearing shutter glasses and his head movements are measured (IREDs attached to glasses), so that the binocular perspective exactly matches the (changing) locations of the eyes. (D) Close-up of the IREDs on stalks (three each) attached to the index finger and thumb. This allowed tracking of the fingertips even when they were occluded from the Optotrak camera system.

The height of the seat was adjusted such that the participant's eyes were at about the same height as the (virtual) cylinder's center, so that the top (and bottom) surfaces of the cylinder were invisible. This was done to maximize potential effects of perceptual distortions of shape in depth. The back side of the cylinders was never visible, but participants did not have to guess the back side's shape because they knew the cylinders were symmetrical.

2.1.4. Measuring the locations of the fingertips and the head

The positions of the fingertips and the head were tracked by measuring the locations of infrared emitting diodes (IRED) with an Optotrak 3020 sensor system. Recordings lasted 3 s and the sampling frequency was 200 Hz. To compensate for head movements we determined the locations of the eyes in space by tracking the location of three IREDs attached to the shutter glasses (see Fig. 1C). With a calibration procedure the locations of the left and right eye were determined relative to these IREDs. In this procedure participants looked with one eye sequentially through three tubes without any head movements. The intersection point of the visual lines through the tubes defines the eye's center of rotation. To measure the fingertip locations we attached three IREDs to the last phalanx of the thumb and three more to the last phalanx of the index finger. Each triplet of IREDs was mounted on a perspex square ($30 \times 30 \times 1$ mm) on a stalk so that the fingertips could be tracked even when they were occluded from the Optotrak camera system during grasping of the cylinders (see Fig. 1D). Before starting the experiment the stalks with IREDs were attached to the participant's fingertips and the shutter glasses were put on. We made sure that the target cylinder could easily be reached and that the IREDs remained visible for the Optotrak for a large range of postures by bending the antennae and repositioning the participant if necessary. We used each triplet of IREDs to define an orthonormal frame and we determined the fingertip location relative to this frame via a calibration procedure: before each session participants saw a rendered frame of a circular cylinder, which was aligned with a real cylinder. They had to grasp the cylinder at two indicated locations with thumb and index finger (the front and the back of the cylinder's top surface). The calibration was completed by measuring the IRED locations and calculating the contact positions relative to the associated frames. During this calibration procedure a light was on behind the semi-transparent mirror, so that the hand and the real cylinder were visible too. During the rest of the experiment a cover was placed directly behind the semi-transparent mirror and all lights were extinguished, so that participants could not see their hand.

2.2. Experiment 1: Constant haptic feedback

2.2.1. Stimuli

For the constant haptic feedback we always used a circular cylinder of polyvinyl chloride (PVC) with a diameter of 52 mm and a height of 100 mm. The shape and orientation of the virtual cylinders was varied: the virtual cylinders had an elliptical base and the diameter of the major axis (d_{major}) was varied from 52 mm to 64 mm in steps of 2 mm (Fig. 1B). The diameter of the minor axis (d_{minor}) was chosen such that the virtual cylinder's volume was equal to that of the real cylinder. Thus, we used seven different shapes with aspect ratios $d_{\text{minor}} = d^2/d_{\text{major}}$ where $d = 52$ mm is the circular cylinder's diameter. The orientation of the major axis was varied from 0° to 150° in steps of 30°. An angle of 0° corresponds to straight-ahead and positive angles indicate counterclockwise rotations. Note that a difference of 90° in the virtual cylinder's orientation exchanges the major and minor axes, so that we can also describe the virtual cylinders as 13 shapes having only three orientations by including aspect ratios smaller than one. The latter is more convenient for plotting the graphs of grip orientation. The virtual cylinders were rendered such that their centers were 20 cm from the edge and 20 cm above the table, so that their height and the position of their vertical axis coincided with those of the circular cylinder that provided the haptic feedback (see Fig. 1C).

2.2.2. Procedure

The starting position was indicated by the head of a small screw in the table. The participants held it between their fingertips. It was located 30 cm to the right of, 15 cm nearer than, and 20 cm below the cylinder's center. Five seconds after the participant held his fingertips at the starting position, the stimulus was automatically shown and a recording of the Optotrak was started. The participant reached for the virtual cylinder, which was extinguished as soon as the distance of one of the fingertips from the cylinder was 1 cm or less, and grasped the real cylinder that was located at the rendered position. The rationale for extinguishing the visual stimulus was to minimize potential conflicts between haptic and visual information about the cylinder's location and shape. The participant then lifted the cylinder about 1 cm vertically and put it back. In order to insure that the cylinder was placed back at the correct location, we made a small depression into which the base of the circular cylinder fit exactly. This was done by attaching a thin PVC plate to the support surface with a hole in it at the cylinder's location. The trial was completed by returning the hand to the starting position. If the participant did not reach the target within 3 s after presentation of the stimulus, or if any of the IREDs were invisible for the Optotrak during the recording, a low-pitched beep was audible and the trial was repeated immediately. If the trial was successful, a high-pitched beep sounded and the next trial was started. This was repeated until all 42 trials were completed. The order of presentation was randomized the same way for all participants.

2.3. Experiment 2: Consistent haptic feedback

2.3.1. Stimuli

In Experiment 2 we used seven cylinders made from delrin (density 1.40 g/cm^3) for the haptic feedback. The cylinders were 10 cm tall and their circumference was elliptical (Cuijpers et al., 2004; Cuijpers et al., 2006). One of the principal axes had a fixed length of 50 mm, whereas the length of the other axis varied from 20 mm to 80 mm in steps of 10 mm. We rendered virtual cylinders of the same seven shapes as well as eight intermediate shapes (Fig. 1B). For the intermediate shapes the length of one principal axis was again 50 mm and the other axis's length was either 33.2, 36.8, 43.2, 46.8, 53.2, 56.8, 63.3, or 66.8 mm. The virtual cylinders were always at the same location and had the same orientation as the real cylinders. Their shape either was the same or the nearest match was used (maximum error 3.2 mm, <10%). The cylinders were located at a distance of 40 cm from the table's edge at a height of 20 cm. The orientation of the cylinder's variable principal axis was either 0° or −45° where an angle of 0° corresponds to straight-ahead and the minus sign indicates a clockwise rotation.

2.3.2. Procedure

The procedure for Experiment 2 was very similar to that for Experiment 1 except that the experimenter needed to place one of the real cylinders in the correct position in-between trials. For that purpose a computer-controlled light switched on as soon as the participant completed a trial by returning his or her hand to the starting position. The starting position was now located 25 cm to the right of, 30 cm nearer than, and 20 cm below the cylinder's center. The PVC cover prevented participants from seeing behind the semi-transparent mirror. Marks on the support and on the cylinders helped the experimenter to accurately place the cylinders at the correct location and in the correct orientation. When the real cylinder was in place, the experimenter pressed a button and the light was extinguished. After a 5 s delay the next stimulus appeared. Again, if the Optotrak recording failed or if the participant failed to reach the target within 3 s, the trial was repeated. A high or low-pitched beep indicated whether the trial was successful or not. Each stimulus condition was measured three times yielding a total of 90 trials. The order of presentation was randomized for each participant.

3. Results

3.1. Experiment 1: Constant haptic feedback

From our earlier studies (Cuijpers et al., 2004; Cuijpers et al., 2006) we knew that manipulating the cylinder's orientation mainly affected grip orientation and that manipulating the aspect ratio mainly affected maximum grip aperture. Moreover, grasping movements were found to be very stereotypical for a given final grip orientation – just before touching the cylinder's surface – and maximum grip aperture (Cuijpers et al., 2004; Cuijpers et al., 2006). We therefore restricted our analysis to the final grip orientation and the maximum grip aperture.

Fig. 2 shows the grip orientations at the time of contact for Experiment 1. Each graph shows a single participant's final grip orientation as a function of the cylinder's aspect ratio. The diamonds, squares, and stars correspond to cylinder orientations of 0°, −30°, and −60°, respectively. For aspect ratios >1 these orientations coincide with the orientation of the cylinders' major axis and for aspect ratios <1 with those of the cylinders' minor axis. In the latter case the cylinder's major axis orientations are 90°, 60°, and 30°, respectively. The participants' responses to the virtual stimuli are very idiosyncratic. The participants shown in the top two rows of Fig. 2 hardly adjusted their grip orientation to the visible orientation of the cylinders. In contrast, the participants in the bottom two rows clearly adjusted their grip orientation to the orientation of the cylinder. The most regular patterns of such adjustments are shown in the third row of Fig. 2: for aspect ratios >1 the grip orientation was reasonably constant for each cylinder orientation, with more negative values for more negative cylinder orientations. For aspect ratios <1 only the smallest aspect ratios (the smallest for JG, the two smallest for JD, and the four smallest for RC) showed a clear effect of the simulated orientation. The participants shown in the bottom row of Fig. 2 behaved in similar ways, but they sometimes switched from grasps to the

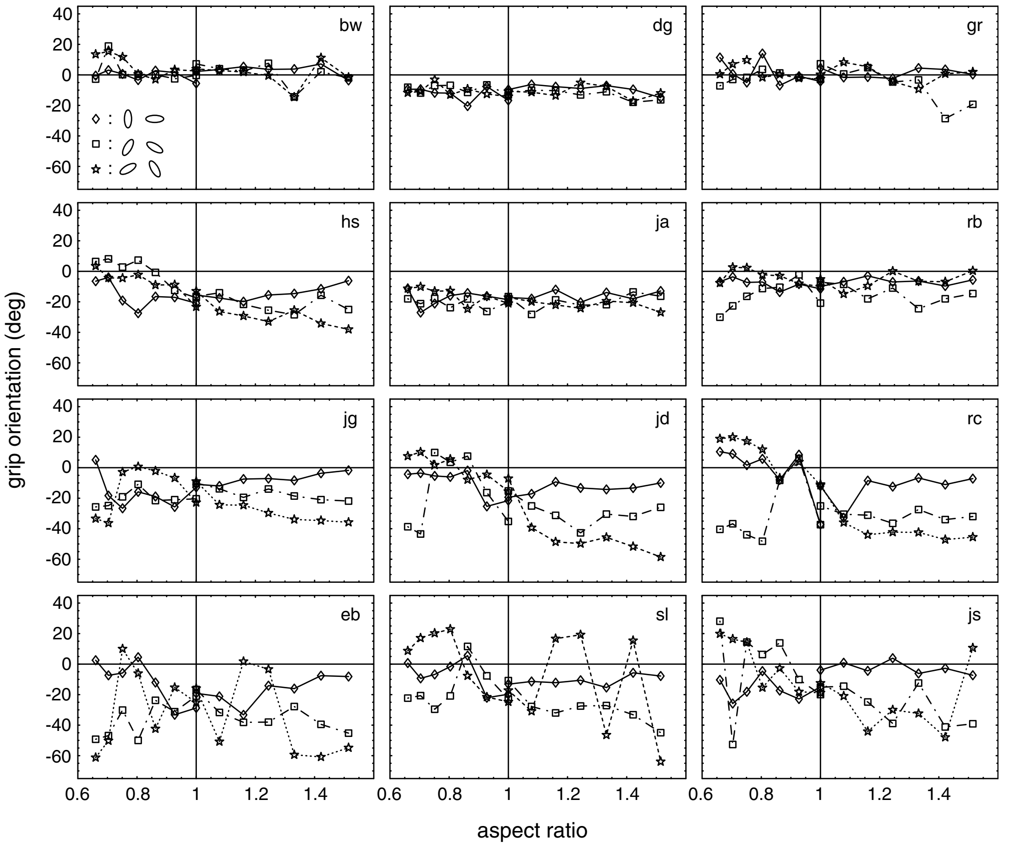

Fig. 2. Grip orientation in Experiment 1 as a function of the cylinder's aspect ratio. Diamonds, squares and stars correspond to cylinder orientations of 0°,−30°, and −60°, respectively. The cylinder orientation is defined as the orientation of the major axis for aspect ratios >1 and of the minor axis for aspect ratios <1. Each panel shows data for one participant.

major axis to grasps to the minor axis. For example, participant SL grasped the cylinders in an orientation of −60° (stars) nearest to their major axis (at −60°) for aspect ratios 1.08, 1.33, and 1.51, and nearest to their minor axis (at 30°) for aspect ratios 1.16, 1.24, and 1.42.

In order to quantitatively address how participants adjusted their grip orientations to the cylinder orientation, we used the fitting procedure developed by Cuijpers et al. (2006). We simultaneously fitted three lines given by $y = a(x - x_0) + b + y_0$, where x is the cylinder's major axis orientation, and y is the deviation of the grip orientation from the cylinder's major axis orientation. The parameters (x_0,y_0) are (90°,90°), (0°,0°), or (−90°,−90°). Thus, the slopes and offsets of the three lines were constrained, so that they corresponded to grasping the minor axis in a counterclockwise grip orientation, grasping the major axis, and grasping the minor axis in a clockwise grip orientation (see Cuijpers et al., 2006, for details). To apply the fit, we plotted the deviation of the grip orientation from the major axis orientation as a function of the major axis orientation (for each participant). Two examples are shown in Figs. 3A and B. Theoretically, if participants grasp the major axis, the deviations will be zero and the data will scatter about a horizontal line through 0°. Similarly, if participants grasp the minor axis with a counterclockwise or a clockwise grip, the data will scatter along horizontal lines through 90° and −90°, respectively. On the other hand, if participants use the same grip orientation for all cylinder orientations, the data will scatter along a line with slope −1. Fig. 3 shows the deviations of the grip orientations from the cylinder's major axis orientation for reaches to the cylinder with the largest

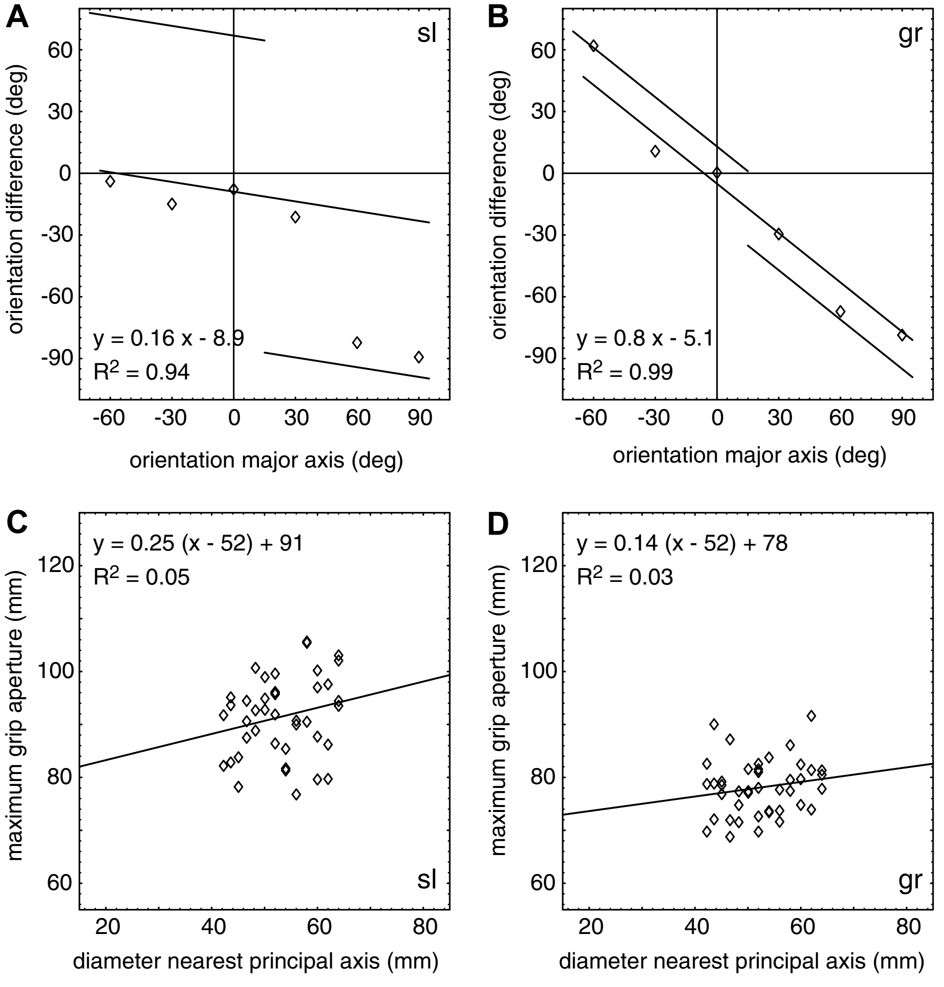

Fig. 3. (A, B) Two examples of the pseudo-linear fits of the deviation of the grip orientation from the orientation of the cylinder's major axis as a function of the orientation of the cylinder's major axis (Experiment 1). The data points reflect single trials of reaches to the cylinder with the largest aspect ratio ($64^2/52^2 = 1.51479$). The coefficient of determination and the equation of the central fitted line are indicated in the lower left corners. (C, D) Two examples of the linear fits of the maximum grip aperture as a function of the diameter of the nearest principal axis. The equation of the fitted line and the coefficient of determination are indicated in the upper left corner.

aspect ratio ($64^2/52^2 = 1.51479$) for two participants. In Fig. 3A the deviations are either close to 0° or to −90°, but with a small negative trend (slope of −16). This means that the scaling of grip orientation is 16% less than complete scaling with cylinder orientation (84%). Fig. 3B shows an example of a participant who hardly adjusted his grip orientation, resulting in fitted lines with slopes of −0.8. Thus the scaling of grip orientation was only 20%. In this case it is no longer clear whether one attempted to grasp the major or minor axis. Nonetheless, we can use the slopes of the fitted lines to estimate the gains with which participants adjust their grip orientation to the cylinder orientation.

The fitted slopes express the deviation from a perfect gain of one, so we obtain values for the scaling of grip orientation by adding 1 to the fitted slopes. Fig. 4 shows the scaling of grip orientation as a function of aspect ratio. Each line corresponds to a different participant. Clearly, the participants behaved very differently: the scaling of grip orientation covers almost the entire range from 0 (grip ori-

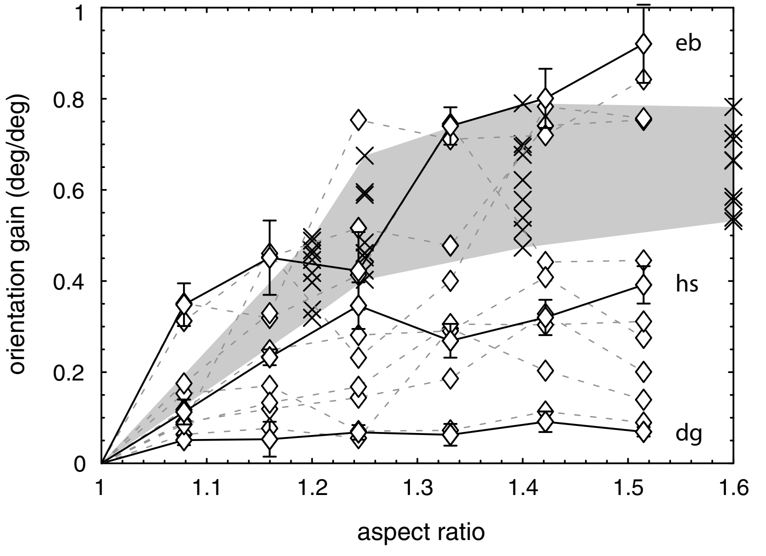

Fig. 4. Diamonds show the average scaling gains in Experiment 1 of grip orientation with cylinder orientation as a function of aspect ratio, with each line representing one participant. Solid lines highlight participants DG, HS, and EB who have small, mediocre, and high gain values, respectively. Error bars indicate SE. Crosses show the average scaling gains of grip orientation for real cylinders (from Cuijpers et al., 2006). The grey area indicates the range of values in the latter data.

entation is independent of the cylinder orientation) to 1 (grip orientation is proportional to the cylinder orientation). For most participants the gains of grip orientation adjustments gradually increased with increasing aspect ratio. Presumably, the cylinder orientation was easier to see the more elongated the cylinders were. Participants with large scaling gains usually did so for all aspect ratios, although the aspect ratio at which the scaling of grip orientation saturated was different for different participants. We also show values for the scaling of grip orientation when grasping real cylinders from our previous study (Cuijpers et al., 2006). Each cross indicates the average of one participant and the grey area shows the range. It can be seen that the scaling of grip orientation in the present experiment lies completely below the grey area for 7 out of 12 participants, and that the range is similar to that found in the previous experiment for the other 5 participants. Taking the average across aspect ratios $\geqslant 1.3$ (where most participants show a saturation), we found scaling gains ranging from .07 to .82 for grasping virtual cylinders with constant haptic feedback (average .42 ± .07, see Fig. 7). Applying the same analysis to real cylinders (Cuijpers et al., 2006), we obtained a range of scaling gains from .55 to .79 (average .67 ± .03).

We also looked at our manipulation's effect on the maximum grip aperture. Two examples are shown in Figs. 3C and D where the maximum grip aperture is plotted as a function of the diameter of the nearest principal axis (for participants SL and GR, respectively). The nearest principal axis was defined as the principal axis whose orientation differed less than 45° from the grip orientation. For these two participants the slopes, which reflect the scaling of grip aperture, were not significantly different from zero ($t(40) = 1.44$, $p = .16$ for SL and $t(40) = 1.13$, $p = .27$ for GR). The slope was only significantly different from zero for one participant. The estimated slopes were positive (range .0–.4, average .14 ± .04). Their values were much smaller than the .32–.76 (average .54 ± .04) that we obtained for grasps to real cylinders (Cuijpers et al., 2006).

It is conceivable that a cue conflict between haptic information and visual information caused participants to rely more on haptic information in late trials than in early trials. In that case one would expect the maximum grip aperture to covary more with the visual stimulus dimensions in early than in late trials because haptic feedback was constant. In other words, the variability of maximum grip aperture should decrease over trials. We also looked at the covariance directly, but this led to similar results with some artifacts as participants sometimes switched between grasps to the major and grasps to the minor axis. We performed a repeated measures ANOVA with epoch as within-subject factor, comparing 'early' (first 14 trials, one third of all trials) and 'late' (last 14 trials) values. Since the variability of the cylinder's diameter differed between early and late trials, we corrected for this difference by using the ratio between the standard deviation of the maximum grip aperture and the standard deviation of the cylinder's major principal diameter. We found a significant effect of epoch on the ratio of standard deviations, $F(1,11) = 17.55$, $p = .02$, but in the opposite direction: the SD ratio increased from 0.95 ± 0.10° in early trials to 1.43 ± 0.13° in late trials. It turned out that this difference was caused by the reduced variability of the cylinder's diameter in late trials as compared to early trials. The variability of grip orientation should have decreased over trials if participants relied more on haptic feedback in late than in early trials. Here we only included shapes with aspect ratios $\geqslant 1.3$ for which we found the scaling gain of the grip orientation to saturate (Fig. 4). Consequently, the early and late epochs comprised only six trials each. We found no significant effect for the ratio between standard deviation of the grip orientation and the standard deviation of the cylinder orientation ($F(1,11) = 1.27$, $p = .28$).

It is possible that only those participants that relied more on haptic feedback showed less variability in late trials than in early trials, and vice versa for the other participants. To test this we divided our participants into a 'haptic' group who had small scaling gains of grip orientation (top two rows of Fig. 2) and a 'visual' group who had large scaling gains of grip orientation (bottom two rows of Fig. 2). If both groups adjusted their grip formation differently over the course of trials we should find a significant interaction between epoch and group type. However, we did not find significant interaction effects for the ratio between the variability of maximum grip aperture and the cylinder's major principal diameter ($F(1,10) = 0.171$, $p = .67$), nor did we find a significant interaction for the ratio between the variability in grip orientation and cylinder orientation ($F(1,10) = 1.116$, $p = .32$).

3.2. Experiment 2: consistent haptic feedback

The poor scaling gains in Experiment 1 (for both maximum grip aperture and grip orientation) indicated that our visual simulation combined with constant haptic feedback was not sufficient to achieve natural grasping. In all likelihood, this was caused by the conflict between both information sources (Atkins, Jacobs, & Knill, 2003). In Experiment 2 we addressed this issue by providing consistent haptic feedback.

Fig. 5 shows the grip orientation as a function of aspect ratio for five participants when we provided (nearly) consistent haptic feedback (see Methods section for details). The diamonds indicate the med-

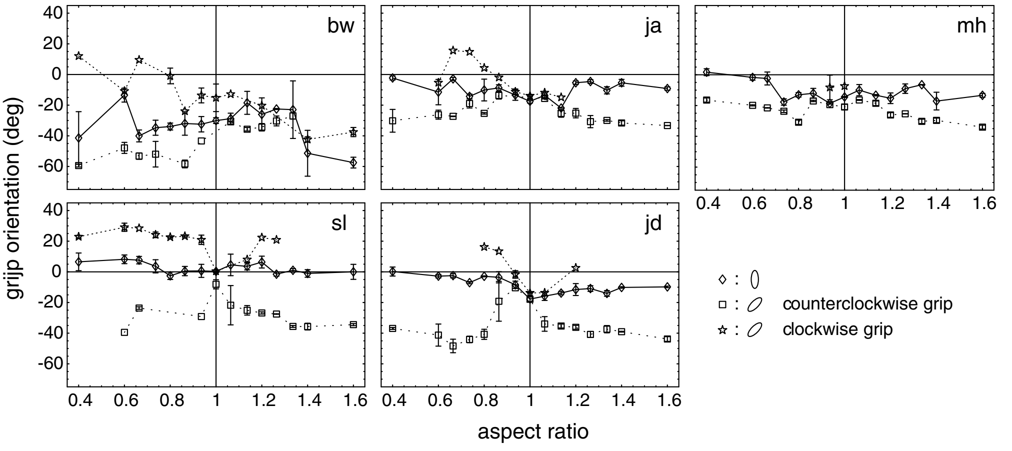

Fig. 5. Grip orientation in Experiment 2 as a function of aspect ratio. Each panel shows data for one participant. The diamonds indicate the median grip orientation for a cylinder orientation of 0°. For a cylinder orientation of −45° the data are subdivided into grip orientations more negative (squares) and more positive (stars) than the median grip orientation for a cylinder orientation of 0°. This corresponds to grasps that are more or less aligned with or perpendicular to an orientation of −45°. When sufficient data were available (at most three data points) the median deviations are indicated by error bars.

ian values when the cylinder's orientation was 0°. This corresponded to the orientation of the major axis when the aspect ratio was larger than one, and to the orientation of the minor axis when the aspect ratio was smaller than one. Participants used a similar grip orientation in both cases, showing that they switched between grasping the major axis (diamonds, aspect ratio >1) and minor axis (diamonds, aspect ratio <1) in order to keep the grip orientation constant. For a cylinder orientation of −45° the participants sometimes used two grip orientations for the same cylinder shape, one which was more negative than the median grip orientation for a cylinder orientation of 0° and one which was more positive. Thus, sometimes the participants adjusted their grip orientation in the direction of the major axis and sometimes in the direction of the minor axis. We therefore subdivided the data for a cylinder orientation of −45° into grip orientations that were more negative (squares) and grip orientations that were more positive (stars) than the median grip orientation for a cylinder orientation of 0° (diamonds). As a result, the squares represent grasps which were more closely aligned with the principal axis orientation of −45° and the stars represent grasps which were more closely aligned with the principal axis orientation of +45°.

Qualitatively, most participants behaved in a similar fashion (apart from participant BW), but quantitatively, the behavior was idiosyncratic. As the pattern was the clearest for participant SL, we discuss his results in detail and then indicate some of the differences with other participants. For a cylinder orientation of 0° his grip orientation was similar for all aspect ratios. The mean value (3.2 ± 0.9°) was close to the optimal grip orientation of 0°. It was also close to that for the circular cylinder (−2.3 ± 2.0°). For a cylinder orientation of −45° participant SL switched between two grip orientations that were similar across aspect ratios. The grip orientations were closest to the orientation of the major axis in 83% of the cases (squares with aspect ratios >1 and stars with aspect ratios <1). For aspect ratios = 1 we found mean grip orientations of −29.3 ± 2.0° (squares) and 23.1 ± 1.2° (stars).

The distribution of grasps towards the major and minor axis differed across participants. For a cylinder orientation of −45° participants MH and JD usually chose the grip orientation that was closest to the principal axis at −45° (squares) rather than that at +45° (stars). Thus, they preferred grip orientations that were perpendicular to the direction of approach irrespective of whether that meant grasping the major or minor axis. Participants JA and JD used similar grip orientations for all cylinder orientations when the aspect ratios were close to one. In addition, it is noteworthy that the gains with which participants scale their grip orientation with the simulated orientation differed between participants. Ideally, the grip orientations should be −45°, 0°, and +45°, respectively. We could not use the same method as before to determine the gain of scaling of grip orientation with cylinder orientation, because we only used two cylinder orientations. However, we could obtain an equivalent estimate by linear regression. From Fig. 4 we learned that the orientation gain was fairly constant for aspect ratios $\geqslant$1.3, so we took the mean grip orientation for each grip category (symbols in Fig. 5) across all aspect ratios $\leqslant$1/1.3 and $\geqslant$1.3 (except for participant BW, where we only took the mean across all aspect ratios $\leqslant$1/1.3 because for the larger aspect ratios the pattern of grip orientations was different from that of the other participants). We found gains of .67 ± .04, .60 ± .09, .43 ± .04, .75 ± .04, and .33 ± .06 for participants SL, BW, JA, JD, and MH, respectively (see also Fig. 7).

Fig. 6 shows the maximum grip aperture as a function of the nearest principal axis (expressed as angular deviation) for each participant. For all participants the slopes were significantly larger than zero, $t(89) \geqslant 6.01$, $p < .001$. The scaling gains varied from .28 to .52 (average .39 ± .04), that is, smaller than the scaling gain of .54 ± .04 observed for grasping real cylinders (Cuijpers et al., 2006).

3.3. *Effect of haptic feedback on grip formation*

Grip orientation and maximum grip aperture scaled more clearly with object orientation and size when consistent haptic feedback was provided than when the haptic feedback was constant. In order to study the effect of haptic feedback on grip formation in more detail, we compared the scaling gains of grip orientation and the scaling gains of maximum grip aperture within and between experiments. In Fig. 7 the scaling gains of maximum grip aperture are plotted as a function of the scaling gains of grip orientation. Each point represents the average scaling gains of one participant. The diamonds and stars indicate the results for constant haptic feedback (Experiment 1) and consistent haptic feedback (Experiment 2), respectively. The squares show the results obtained for grasps to real cylinders (Cuij-

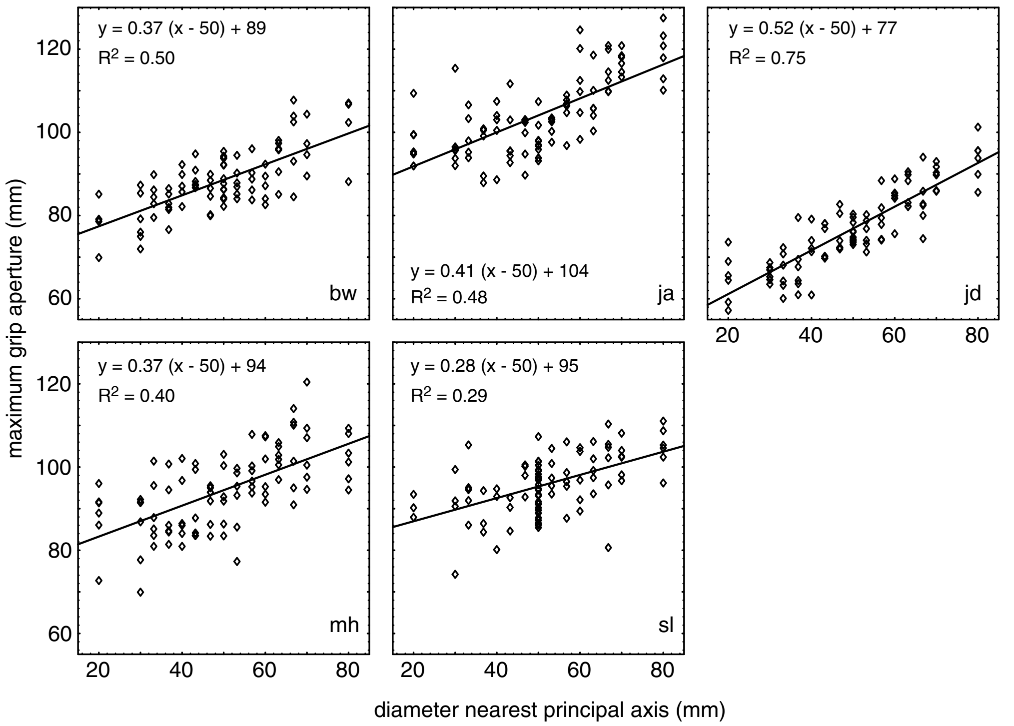

Fig. 6. Maximum grip aperture in Experiment 2 as a function of the diameter of the nearest principal axis. Each panel shows data for one participant. The equation of the fitted line and the coefficient of determination are indicated in the corner.

pers et al., 2006). The ellipses are centered on the mean of each experiment and their principle axes indicate the directions of maximal and minimal covariation. The diameter of the ellipse's principal axes is twice the SD in that direction.

With constant haptic feedback (diamonds), there was a large spread in scaling gains of grip orientation between participants (average .42 ± .07, SD .26). The spread was much smaller in the scaling gains of maximum grip aperture (average .14 ± .04, SD .12), indicating that a high scaling gain of grip orientation did not automatically imply a high scaling gain of maximum grip aperture. The slope of the major axis of the ellipse of covariation (diagonal hatch lines in Fig. 7) was much less than unity (.40). Nevertheless, the correlation between the two scaling gains was significant ($R^2 = .56$, $R = .75$, $t_R(10) = 3.54$, $p = .005$).

With consistent haptic feedback (stars), the participant averages of both the scaling of grip orientation (.56 ± .08) and maximum grip aperture (.39 ± .04) were larger than for constant haptic feedback. Only one participant had a larger scaling gain for maximum grip aperture with constant haptic feedback. The variability between participants was smaller with consistent haptic feedback than with constant haptic feedback for both the scaling of grip orientation (SD .17) and the scaling of maximum grip aperture (SD .09). The correlation between the scaling gains was negligible ($R^2 = .06$, $R = .24$, $t_R(3) = 0.43$, $p = .69$; slope of the ellipse's major axis (crossed hatch lines) was .17), suggesting that grip orientation and maximum grip aperture scaled independently.

A comparison of these findings and the results for grasps to real cylinders (squares), revealed that the average scaling gains of both grip orientation (average .67 ± .03) and maximum grip aperture (average .54 ± .04) were even larger for real cylinders. The spread of the grip orientation was smallest for real cylinders (SD .09), whereas the spread of the maximum grip aperture for real cylinders (SD .12) was similar to the spread for virtual cylinders. There was no apparent correlation between the scaling gains ($R^2 < .001$, $R = .02$, $tR(7) = .05$, $p = .96$; slope of the grey ellipse's major axis was .03).

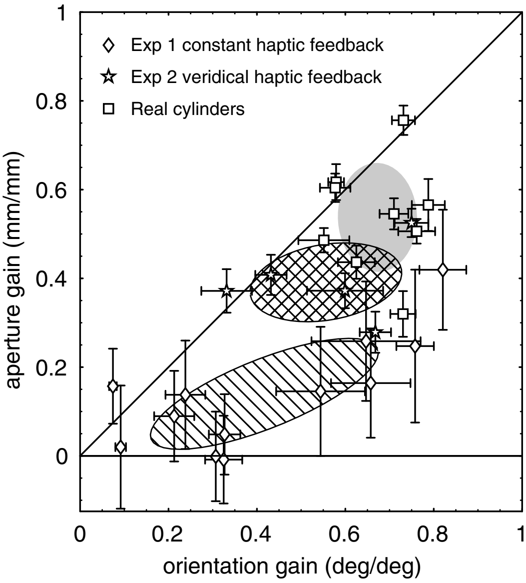

Fig. 7. Scaling of maximum grip aperture as a function of scaling of grip orientation. Each point represents the mean values for one participant. Error bars indicate SEs. Diamonds: results from Experiment 1 with constant haptic feedback. Stars: results from Experiment 2 with consistent haptic feedback. Squares: results from our previous study with real cylinders (Cuijpers et al., 2006). The ellipses are centered on the mean values of each experiment. The ellipse's principal axes indicate the eigenvectors of each data set and the diameters reflect twice the SD in those directions.

4. Discussion

We found that virtual cylinders with constant haptic feedback are grasped substantially differently from real cylinders. The scaling gains of both maximum grip aperture and grip orientation were considerably smaller. We attribute this mainly to the constant haptic feedback, as we found much larger scaling gains when the haptic feedback was made more or less consistent. Nonetheless, the scaling gains for real cylinders were larger than for virtual cylinders with consistent haptic feedback, despite the fact that the real cylinders were untextured and that the contours of the real cylinders were less salient than those of the virtual cylinders. Thus, providing accurate visual information and appropriate haptic feedback may be vital but it is not sufficient to obtain natural reaching and grasping.

It has been demonstrated that haptic and visual cues are integrated for size judgments when presented together (Ernst & Banks, 2002). In our experiments haptic and visual information were never present simultaneously: the visual stimulus was extinguished just before the fingertips touched the cylinder, whereas the haptic feedback obviously occurred after reaching the cylinder. This was done to reduce the effects of potential conflicts between visual and haptic information. However, it turned out that both visual and haptic information are important for planning reaching and grasping regardless of them not being present simultaneously. Since the haptic feedback in Experiment 1 was constant, it was possible to estimate the cylinder's size haptically from previous trials. If the grip aperture was planned as a trade-off between the visually specified size and the haptically specified size (as estimated from previous trials), then it would make sense to assume that the most weight was given to the more reliable haptic information (Atkins et al., 2003), resulting in a modest gain.

The relevant dimension of the haptic feedback for scaling grip orientation is the local surface slant. Therefore, with feedback provided by a circular cylinder, the haptically sensed surface slant would be consistent with the virtual cylinders whenever the participants tried to grasp cylinders by their principal axes. If participants did not intend to grasp one of the principal axes, the felt surface curvature may inform them about the cylinder's true shape. However, haptic judgments about surface curvature are not expected to be very accurate (Pont et al., 1999).

Another possibility is that any conflict between visual and haptic information (also for irrelevant dimensions) caused participants to rely more on haptic information than on visual information. Thus, conflicts between haptically and visually sensed diameters, may not only reduce the scaling of the maximum grip aperture but also of the grip orientation. If this occurred to different extents for different participants we would expect to find a correlation between the scaling gains of maximum grip aperture and grip orientation. We did find a significant correlation between the scaling of grip aperture and grip orientation but the gain was only .4. Thus, a weak scaling of the maximum grip aperture did not automatically imply a weak scaling of the grip orientation. Across trials one would also expect that the reliability of the haptic information improved because of repeated exposure to a constant haptic stimulus. However, we found no evidence that the variability of the maximum grip aperture and the variability of the grip orientation were smaller in late than in early trials. Nor can we explain the difference between participants with a small and a large scaling of the grip orientation as a difference in adaptation to the constant haptic stimulus. It rather seems that our participants did not change the way in which they scaled their maximum grip aperture and grip orientation in the course of the experiment.

In Experiment 2 haptic information could not be used for planning the next movement, because the different cylinder shapes and orientations were presented in random order. We therefore expected the visual information to dominate the planning of the reaching and grasping movements, whereas the haptic feedback would reinforce correctly conducted movements. We indeed found significantly higher scaling gains for both grip orientation and maximum grip aperture, but the scaling gains still fell short of the scaling gains for grasps to real cylinders despite the visual realism of the cylinders (the virtual cylinders were richly textured and binocular perspective, motion parallax, and stereopsis were rendered accurately). It appears that the visual information was considered less reliable than when grasping real objects. One reason might be that the perceived shapes and locations of real and virtual cylinders are different. This could be either due to incorrect accommodation of the eyes (Bingham, Bradley, Bailey, & Vinner, 2001) or absence of a visual background. In the study of Cuijpers et al. (2006) the cylinders stood on a table that was placed in front of a neutral background in a room with normal artificial lighting, whereas our virtual cylinders appeared to hover in the dark with no support surface and no background visible. It has been found that the support surface can help judge distances (He, Wu, Ooi, Yarbrough, & Wu, 2004; Meng & Sedgwick, 2001) but shape appears to be judged independently of distance (Bingham et al., 2004; Brenner & van Damme, 1999; Smeets et al., 2002). Haptic information may be used to calibrate judgments of distance but not necessarily judgments of shape (Brenner et al., 1997; Coats et al., 2008). Another reason might be that visual and haptic information was never present simultaneously. This may have impaired the calibration of visual judgments of shape, especially when the cylinder's shape and orientation changed every other trial. Also, the grasping hand was never visible during the experiment. This could lead to motor execution errors (Fukui & Inui, 2006) that are interpreted as signaling unreliable visual information about the cylinder's shape and location. However, in that case we would expect the scaling gains of grip orientation and maximum grip aperture to be correlated, which was not the case. Thus, it seemed that the relative effect of unreliable visual information on the scaling gains of maximum grip aperture and grip orientation differed from participant to participant.

The relative independence between the scaling of maximum grip aperture and grip orientation adds to a growing list of independent attributes of visuomotor tasks in the literature. For example, the relative contributions of binocular and monocular information differs for a motor task and a perceptual task (Knill, 2005), and for planning and on-line control (Greenwald et al., 2005). A difference was also found between the relative contributions of visual and proprioceptive information to effector position and trajectory control (Scheidt et al., 2005; Sober & Sabes, 2005). We already mentioned the relative independence of the effect of haptic information on visual judgments of distance and shape (Bingham et al., 2004; Brenner & van Damme, 1999; Brenner et al., 1997; Coats et al., 2008). Taken together, these findings suggest that reaching and grasping do not involve fixed, independent channels for the planning and control of grip and transport components (Jeannerod, 1981; Jeannerod, 1984), but rather that different aspects of visual and haptic information are recruited as needed for different aspects of reaching and grasping (Smeets & Brenner, 1999; Smeets et al., 2002; Triesch et al., 2003).

The practical implications of our results are that great care is needed when designing virtual reality environments that involve object manipulation. Even when visual information is rich enough to accurately perceive an object's shape, orientation, and location, it is not automatically used for planning and control of reaching and grasping, especially when conflicting haptic information is present. This begs the question whether research involving pantomimed grasping or grasping with artificial haptic feedback bears any relevance on grasping objects in real life. It seems that grip parameters depending on the location and size of objects in virtual environments without haptic feedback can be natural as long as proper calibration is allowed (Bingham, Coats, & Mon-Williams, 2007; Coats et al., 2008). However, when shape and orientation of virtual objects change every other trial and when grasping involves judging higher order shape parameters such as surface curvature, grasping of virtual objects need not be completely natural even with consistent haptic feedback.

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