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Distortions in Definite Distance and Shape Perception as Measured by Reaching Without and With Haptic Feedback

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Psychophysical studies reveal distortions in perception of distance and shape. Are reaches calibrated to eliminate distortions? Participants reached to the front, side, or back of a target sphere. In Experiment 1, feedforward reaches yielded distortions and outward drift. In Experiment 2, haptic feedback corrected distortions and instability. In Experiment 3, feedforward reaches with only haptic experience of targets replicated the shape distortions but drifted inward. This showed that outward drift in Experiment 1 was visually driven. In Experiment 4, visually guided reaches were accurate when participants used binocular vision but when they used monocular vision, reaches were distorted. Haptic feedback corrected inaccuracy and instability of distance but did not correct monocular shape distortions. Dynamic binocular vision is representative and accurate and merits further study.

Researchers in perception and in motor control offer a curious contrast in their assessment of visually guided actions such as reaching and grasping. For instance, in a recent paper on motor control of reaching, Ghez, Gordon, Ghilardi, and Sainburg (1995) stated that "it is generally understood that the accuracy of limb movements depends largely on precisely calibrated feedforward commands that direct the hand to the target" (p. 549). However, in the same volume, a group of noted vision researchers evaluated the role of feedforward control differently. They wrote:

> To reach forward and close a hand on a target requires matching the closure of the hand to the absolute dimensions of the shape. This could be done by continuous visual monitoring of the hand as it approaches and closes on the shape, or perhaps *less likely and certainly less accurately*, it could be done by obtaining an absolute estimate of the shape and its distance and directly matching the closure of the hand to it. (Parker, Cumming, Johnston, & Hurlbert, 1995, p. 352, italics added)

The caution evident in this evaluation of feedforward control was no doubt inspired by results of perceptual studies (e.g., Baird & Biersdorf, 1967; Beusmans, 1998; Gilinsky, 1951; Loomis, DaSilva, Fujita, & Fukusima, 1992; Norman & Todd, 1993; Philbeck & Loomis, 1997, 1998; Tittle, Todd, Perotti, & Norman, 1995; Toye, 1986; Wagner, 1985). These studies have revealed distortions in the visual perception of both egocentric distance and object shape (see Todd, Tittle, & Norman, 1995, for a review). Binocular vision, for instance, has been found to expand egocentric distances in near space and to compress them in far space (e.g., Foley, 1985; Johnston, 1991; Philbeck & Loomis, 1997, 1998). As shown in Figure 1, egocentric distance is perceived accurately at about 70–100 cm from the observer or just beyond maximum reach distance. Perceived shape has been found to be transformed accordingly by binocular vision so that, in near space, cylindrical shapes appear expanded in the depth direction relative to width, but in far space, shapes are compressed in depth relative to width (Johnston, 1991). The slope of the relation between actual and perceived egocentric distance has been found to be less than one for both binocular and monocular vision; however, as illustrated in Figure 1, monocular vision based on absolute motion parallax has been found to yield underestimation of all egocentric distances (Ferris, 1972; Gogel & Tietz, 1979). In contrast, monocular vision has been found in structure-from-motion studies to expand shape in depth by 30% relative to width (that is, in the frontoparallel direction; Todd et al., 1995). Furthermore, as found by Tittle et al. (1995), when binocular information is combined with monocular optic flow information, the results are essentially the same as those for static binocular vision.

These perceptual results leave researchers with a puzzle. If these distortions are representative, then why do they not make people clumsy? If egocentric distances are overestimated in near space with binocular vision, then why do people not find themselves regularly ramming their hands into the objects for which they reach? One can look and then reach with one's eyes closed to grasp a cup by spanning its diameter either in the frontoparallel plane or in depth. To do so, one has to evaluate both its egocentric distance and its exocentric width or depth fairly accurately. How are such visually guided actions accomplished successfully?

It may be that perceptionists have used the wrong measures. Nearly all of the perception studies have involved passive judgments rather than action measures. The exceptions are studies in which targeted locomotion was used as a measure of egocentric distance perception (e.g., Loomis et al., 1992; Rieser, Pick, Ashmead, & Garing, 1995). In these studies, performance was found to be accurate. Loomis et al. studied both targeted walking and verbal judgments. They found the former to be accurate and the latter to be distorted. In a study by Pagano and Bingham (1998), partici-

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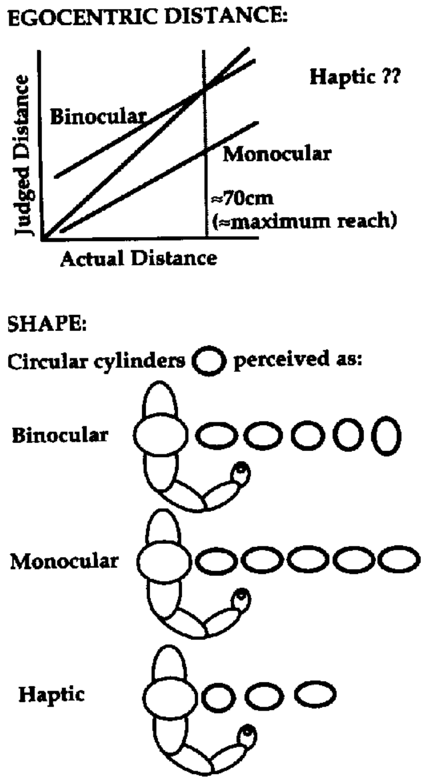

Figure 1. Illustration of typical results of previous psychophysical studies on egocentric distance and shape perception.

pants viewed targets that were within reaching distance and then, in each trial, expressed a verbal judgment of the egocentric distance and subsequently reached to the target. Correlational analysis of verbal and reaching errors revealed no relation between them. Goodale and Milner (1992) have also found perceptual judgments and visually guided actions to be dissociated (Goodale, Jakobson, & Servos, 1996; Milner & Goodale, 1995). They have suggested accordingly that the two modes are mediated by neurologically distinct channels.

However, the mere existence of separate channels for perceptual judgments and perceptually guided action would not by itself explain why there should be differences in accuracy. Why should vision be free of distortion and inaccuracy when used to guide action? Warren (1995) has suggested that it is calibration that distinguishes skilled actions from judgments. Indeed, Ferris (1972) found that verbal estimates of distance were both inaccurate and imprecise until observers were provided with verbal feedback, at which point they became both precise and accurate. Foley (1977) as well as Pagano and Bingham (1998) found verbal estimates to be much more imprecise than manual evaluations of egocentric distance. Pagano and Bingham found that both the precision and accuracy of verbal estimates improved with feedback from concurrent reaches to the target, although the precision never attained the level exhibited by the reaches themselves. Rieser et al. (1995) found that the accuracy of targeted walking depended on calibration. When they allowed participants to recalibrate their walking to artificially speeded or slowed optic flow, they found that targeted walking was correspondingly inaccurate, that is, reflecting underestimates or overestimates of egocentric distance accordingly.

Bingham and Pagano (1998) argued that targeted actions must be calibrated because optical information is inherently angular and without a spatial metric and targeted actions require perception of definite distance (Bingham, 1993b), that is, distance specified in some metric unit within measurement error. Also, calibration is important for the stability of measurements that otherwise can be subject to noise and to drift. Normally, reaching is continuously calibrated because every reach to contact a surface yields both visual and haptic feedback. Reliably accurate performance may depend on the availability of such feedback. On the other hand, the mere presence of feedback need not necessarily guarantee accurate performance. Because the feedback is provided via perception, it may itself be subject to distortions.

Bingham and Pagano (1998) investigated both monocular and binocular egocentric distance perception as evaluated by reaching. They found that feedback and calibration eliminated distortions in some viewing conditions but not in others. Reaches were accurate when guided by binocular vision with haptic feedback from contact with targets. The same feedback, however, failed to eliminate compression evident in reaches guided by monocular vision such as that shown in Figure 1. Reaches consistently undershot targets and did so more as distance increased. Reducing the size of the visual field to 48° produced additional undershooting, but in this case performance improved over trials until it matched that with normal field size. Thus, we cannot assume that feedback will eliminate distortions, although it may in some cases. This was recently confirmed by Wickelgren, McConnell, and Bingham (1997, in press), whose participants reached blindly to align a stylus below targets at five distances. Participants moved their heads either forward and back or side to side while viewing each target monocularly before reaching. In a feedback condition, participants were allowed to contact the target after aligning with it. When target distances were regressed on reach distances, slopes were less than 1 (approximately 0.80) in all conditions. Feedback reduced variable error, but it did not yield slopes of 1 as required for accurate reaching to the full range of egocentric distances.

Visual and Haptic Distortions May Cancel: A Hypothesis

When one reaches to contact a target with the hand, one obtains haptic feedback about the position of the hand and the target. This information consists of somatosensory information about the movement and position of the arm and hand and the contact of hand and target. Such somatosensory (that is, both muscle sense and cutaneous) information has been found to be intrinsic to the control of limb movements and posture (e.g., Cole, 1995; Feldman, Adamovich, Ostry, & Flanagan, 1990; Ghez et al., 1995; Hogan, 1985). Although this could provide information about distances traveled by a reach, researchers do not know enough about haptic perception of egocentric reach distances to predict what the potential effects of haptic feedback might be. On the other hand, haptic distortions in perception of exocentric distances or shape are well known to exist and have been studied extensively (Cheng, 1968; Daviddon & Cheng, 1964; Day & Wong, 1971; Deregowski & Ellis, 1972; Hogan, Kay, Fasse, & Mussa-Ivaldi, 1990; Marchetti & Lederman, 1983; Reid, 1954; von Collani, 1979; Wong, 1977). The general finding, called the "radial–tangential" illusion, is that distances in depth are expanded relative to widths. In a recent study, Kay, Hogan, and Fasse (1996) used methods very similar to those used in visual shape perception studies. Participants held a manipulandum in their right hand that allowed motion in a horizontal plane at shoulder height. The manipulandum was computer controlled to create rectangular force fields or virtual objects at specific locations within the reaching work space. Virtual objects were placed either near or far from the participant centered on his or her midsagittal plane. With their eyes closed, participants moved the manipulandum to feel and compare the lengths of the sides oriented parallel and perpendicular to the depth direction. Participants were to judge when the sides appeared equal in length, that is, when the object felt square (called the point of subjective equality, or PSE). The result was that the shape of objects near the body was judged correctly, but as distance from the body increased, objects that were perceived as square were increasingly expanded in width. The inference was that haptic perception of shape increasingly expands the depth direction with increasing distance from the body as illustrated in Figure 1.

These distortions in haptic shape perception are similar but not identical to the distortions found for vision, also shown in Figure 1. We hypothesize that the distortions should cancel when vision and haptics are used together to control reaching and the distortions are the same. If distances look larger but are also felt to be larger, then reaches should be accurate. However, this correction should occur only when actual contact with an object surface allows haptic apprehension of the distance between placement of the hand and the object surface.

Experiment 1

We investigated these possibilities using a task modeled on the fast phase of the typical reach. Reaches to grasp objects have been characterized as exhibiting two phases (Georgopoulos, 1986; Jeannerod, 1988; Jeannerod & Marteniuk, 1992; Paulignan & Jeannerod, 1996). The majority of the distance to an object is covered in a fast phase that exhibits a smooth, high-peaked, bell-shaped velocity profile and ends with the hand in close proximity to but still at some distance from the object. The object is contacted only at the end of a second slow phase of a reach. This description of reaching implies that reaches are initially targeted for a location at a small distance from the surface of an object to be grasped. Our participants reached to place a stylus at one of three distances from the surface of a target sphere, to the front, side, or back of the sphere. Blind reaches to near and far targets were performed after participants viewed the target using either one or two eyes. In Experiment 1, we investigated the importance of regular feedback. Participants performed the task without haptic feedback from contact with targets. Reaching performance was examined for distortion in both egocentric distances and object shape and for stability of performance over trials. In a subsequent experiment, participants performed the task with haptic feedback.

Method

Participants. Four adults at Indiana University participated in the experiment. They were from 23 to 42 years of age. Two were women, and 2 were men. One was an author (Geoffrey P. Bingham). One was an art student. One was a graduate student and the other a postdoctoral student, both in psychology. All had normal or corrected-to-normal vision and normal motor abilities. All were right-handed.

Apparatus. The target was a white Styrofoam sphere that was 5 cm in diameter. As shown in Figure 2 (top and bottom left), the target was held in position by a rigid framework anchored to an optical bench on the floor. One end of the optical bench was positioned directly below the right eye of the seated participant. A vertical pole attached to the bench could be telescoped to adjust the height of the target. A horizontal rod extended 22.5 cm from the top of the pole toward the observer and to his or her left at an angle of 45° with respect to the optical bench. From the end of this rod, another rod extended straight downward 10 cm, and, at its bottom, a third rod was attached to an axle that allowed the third rod to be rotated up and away from the observer. This third rod extended at 90° from the first horizontal rod and 22.5 cm toward the observer and the optical bench, at an angle of 45° to the optical bench. This third rod in the lowered position was also angled slightly downward. The third rod was inserted through the back, left, upper sector of the target sphere (relative to the participant) with the end of rod at the center of the sphere. An infrared emitting diode (IRED) was attached to the uppermost rod of the support structure.

An IRED also was glued to the side and at the end of a cylindrical plastic stylus that was 18.5 cm long and 1 cm in diameter. The participant held the stylus so that the end with the IRED extended 3 cm beyond the closed fist with the thumb on the stylus. A launch platform (a 7-cm cube) was located to the right of the seated participant's hip. Each trial began with the back end of the stylus inserted in a hole in the launch platform.

The target was illuminated with normal overhead fluorescent lighting. The framework supporting the target was wrapped in black cloth and black curtains hung behind the target from the observer's perspective.

The positions of the IREDs were sampled at 100 Hz with a resolution of 0.1 cm by a two-camera WATSMART kinematic measurement system (Northern Digital, Inc., Waterloo, Ontario, Canada) and stored on a computer hard drive. A WATSCOPE connected to the WATSMART recorded signals from the launch platform.

A gauge figure was used to check that the measurement system itself was isotropic. IREDs were placed on small wooden wedges (to orient them toward the WATSMART cameras) at each of the four corners of a 31 cm × 31 cm square piece of Plexiglas. The centers of the diodes were exactly 30 cm apart along each side of the square.

Procedure. Preceding the experimental sessions, each participant's seated eye height and maximum reach distance were measured. First, the target was positioned at eye height as follows. We used a plum bob to

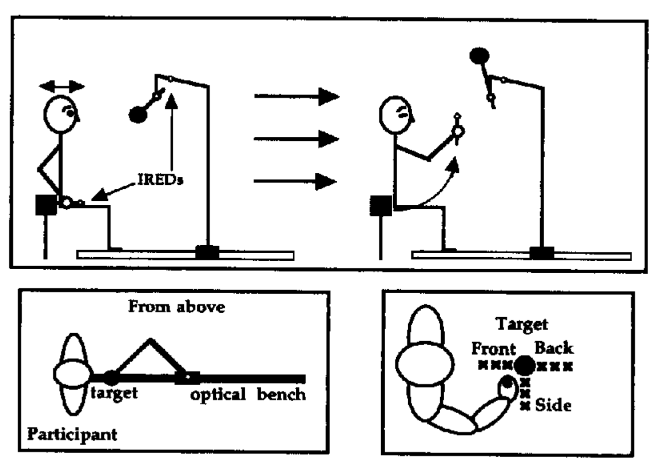

Figure 2. Apparatus and task of Experiment 1. Top: Apparatus from the side and the procedure for a single trial. Bottom left: Apparatus from above. Bottom right: Configuration of locations targeted by reaches. See text for additional details. IRED = infrared emitting diode.

position the lens of a video camera on a tripod over the end of the optical bench so that the optical axis of the camera extended horizontally along the optical bench. With the participant seated immediately to the left of the camera, the position of the chair was adjusted to place the participant's right eye in the plane of the lens (perpendicular to the direction of the optical bench). The height of the camera lens was then adjusted to match the participant's eye height. Next, the height of the target was adjusted to center its image on a video monitor. Finally, the camera was removed and the chair was moved to the right to place the participant's right eye over the optical bench.

Next, the participant's maximum reach distance was measured. While keeping his or her back firmly against the chair, the participant reached as far as possible along the direction of the bench, holding the stylus vertical in his or her fist. The end of the target support rod (without a target) was positioned at the tip of the stylus and the distance measured on the bench. Target distances were then computed as proportions of the participant's maximum reach. Two target distances were tested: .50 (near) and .80 (far) of maximum reach.

During the subsequent experimental sessions, participants reached to place the tip of the stylus at one of nine locations relative to the surface of the target sphere as shown in Figure 2 (bottom right). They reached to place the stylus at one of three distances—1 cm (close), 2 cm (middle), or 3 cm (far) from the surface—all in each of three directions from the center of the sphere (to the front, to the right side, or to the back).

At the beginning of each experimental session, the participant was shown the three distances marked on a sheet of paper. The paper was held up before the participant so that he or she could view it and then hold up the tip of the stylus against the paper and move it back and forth across each of the three distances.

The task and procedure were then explained to participants. Participants kept their eyes closed between trials. Each trial began with the participant grasping the stylus in the launch platform and the target lowered into position for viewing. The experimenter announced the reach location (e.g., "front, middle"). The participant signaled that he or she was ready. The experimenter said "Start" and began WATSMART sampling. The participant opened his or her eyes and moved his or her head through about 8 cm toward and away from the target three times at a preferred rate while viewing the target and assessing where he or she was going to reach. The participant then closed his or her eyes and reached. A second experimenter sat where he could see the participant's eyes. When the participant closed his or her eyes, this experimenter pulled a string that raised the target out of the way. Once the participant had completed the reach and placed the stylus, he or she said "OK," and WATSMART sampling was terminated. The participant then placed the stylus back into the launch platform, keeping the eyes closed until the next trial.

Reaches were tested in two viewing conditions, with binocular and monocular vision, respectively. Participants wore a patch over their left eye during monocular viewing. Trials were blocked by viewing condition and target distance. Ten reaches were performed to each of the nine locations relative to the surface in a random order. Target distances were blocked within viewing condition, with order counterbalanced across participants and viewing conditions. The 180 trials (2 target distances $\times$ 9 locations $\times$ 10 trials) for each viewing condition were performed in a single session.

Before data were collected from each participant, the gauge figure was recorded via the WATSMART with the figure horizontal, aligned with the depth and width directions, and centered alternately at the near and far target locations. The 30-cm distances between IREDs were reliably measured by the system within its measurement error in all instances. This showed that the system itself was not introducing distortions.

After the target had been placed at a given distance for a given participant, calibration trials were recorded before experimental trials were performed. The target was removed from the rod, and a diode was placed on the end of the rod. (The rod actually extended into the target sphere one diode's thickness short of the center of the sphere.) The positions of this diode (at the target center) and the diode on the uppermost (horizontal) rod were both measured. The x, y, and z distances between the two diodes were computed and used subsequently to derive target position from measurements of the IRED on the horizontal rod.

Design. All variables were within subject. The variables were viewing (binocular or monocular), target distance (near or far), direction (front, side, or back), and distance from the target surface (near, middle, or far).

Data reduction. The origin of the Cartesian coordinate system for the measurements was moved to the center of the target; the measurements of the IRED on the framework were used, together with the x, y, and z distances from the calibration trials. The x-axis of our coordinate system extended in the depth direction, whereas the y-axis (horizontal) and z-axis (vertical) determined the frontoparallel plane. We computed the final location of the tip of the stylus relative to the target as follows: Starting 25 samples back from the last sample for each trial, we used the next 50 samples back to compute a mean and standard deviation for each of the x, y, and z coordinates. We examined the maximum standard deviation value to be sure that the participant was not moving or that there were no other anomalies due to misorientation of the IRED or reflection.

Results

First, we evaluated the perception of the egocentric distance of the target by analyzing the x-coordinate (or depth coordinate) of reaches to the side of the target. For this analysis, we moved the origin to the resting eye location, that is, to the origin of the optical bench at eye height. We divided reach x distances by target x distances and performed separate analyses of variance (ANOVAs) on the data for each participant with viewing and target distance as variables. The two main effects and the interaction were significant at $p < .05$ or better in all cases, as shown in Table 1. However, in a repeated measures ANOVA performed on the combined means, only viewing was significant, $F(1, 3) = 13.2$, $p < .04$.[1] These results revealed significant individual differences. Nevertheless, egocentric reach distances were consistently smaller when participants used binocular vision. Using mean reach distance/target distance ratios for each target distance, viewing condition, and participant, we performed a one-tailed one-sample t test to test difference from 1 separately for each viewing condition. The result was significant for monocular viewing ($M = 1.11$), $t(7) = 2.62$, $p < .02$, but was only marginal for binocular viewing ($M = 1.05$), $t(7) = 1.75$, $p < .06$. Because the reach distributions were slightly rotated away from the axes, we replicated the latter analysis using the x centroids of the combined reaches to the front and back. The symmetry of these two distributions would control for the rotation. The result was again significant for monocular viewing ($M = 1.12$), $t(7) = 2.71$, $p < .02$, as well as for binocular viewing ($M = 1.06$), $t(7) = 2.04$, $p < .05$. As shown in the top two panels of Figure 3, egocentric distances were overestimated by about 12% with monocular vision. With binocular vision, distances were overestimated less, about 6% on average.

We turned next to analyses of perceived shape. For each participant and target, we used the x and y centroids of the combined reaches to the front and back to remove the egocentric overestimation and to center the entire distribution of reaches on the origin

[1] With only 4 participants, this latter test was limited in statistical power. Additional individual differences might be expected in the general population.

Table 1
Results of Analyses of Variance Performed on Egocentric Reach Distance/Target Distance Ratios: Experiment 1

Participant	Viewing	Target distance	Viewing × Target Distance		M Near	M Far
P1	83.6***	191.4***	66*	Mon:	1.32	1.15
				Bin:	1.20	1.08
P2	55.7***	6.1*	10.4**	Mon:	0.99	1.03
				Bin:	0.96	0.96
P3	4.6*[a]	79.8***[a]	18.2***[a]	Mon:	1.09	0.99
				Bin:	1.04	1.00
P4	33.3***	28.5***	40.2***	Mon:	1.07	1.20
				Bin:	1.08	1.07
Overall	13.2*[b]	0.5[b]	0.1[b]	Mon:	1.12	1.09
				Bin:	1.07	1.03

Note. $df = 1, 116$, except as noted. Mon = monocular; Bin = binocular.
[a] $df = 1, 115$. [b] $df = 1, 3$.
* $p < .05$. ** $p < .01$. *** $p < .001$.

at the center of the target. The pattern of results revealed by the subsequent analyses is illustrated in Figure 4 (see also Table 2).[2] The pattern was the same in each viewing condition at each target distance. We plotted the centroid for the reaches to each targeted location relative to the surface and fitted ellipses by eye for each distance from the surface. The targeted locations are also shown. The essential pattern was compression in depth for reaches to the locations nearest the surface and diminishing compression with increasing distance from the surface until, at the farthest distance, the pattern was circular.

We performed two ANOVAs using distances from the origin at the center of the target divided by the respective distances of the targeted locations. The targeted locations were at distances of 3.5 cm, 4.5 cm, and 5.5 cm from the origin in a given direction (front, side, or back), that is, 1 cm, 2 cm, and 3 cm from the surface of the sphere, which was itself 2.5 cm from the origin. We computed mean ratios (reach distance/actual distance) for each participant at each actual distance from the origin in each direction for each target distance and viewing condition. First, we compared reaches to the front and back (using the x-coordinates in each case). We expected no differences with direction. Second, we compared reaches to the front and side (using the y-coordinate for the side reaches). In this case, we did expect a directional difference reflecting the shape distortion shown in Figure 4.

We performed a repeated measures ANOVA[3] with viewing (monocular or binocular), target distance (near or far), direction (front or back), and distance from the surface (close, middle, or far) as variables. The only main effect was distance from the surface, $F(2, 6) = 6.6$, $p < .03$. Mean ratios increased with increasing distance from the surface (close, 0.83; medium, 1.03; far, 1.29). Reaches to the targeted location near the surface exhibited compression. They were nearly at the surface itself on average, that is, at 2.9 cm rather than at 3.5 cm. However, the mean distances between reaches to the different targeted locations were expanded so that reaches to the location far from the surface were at 7.1 cm on average relative to the targeted location at 5.5 cm. (Regression analysis revealed that the expansion was by a factor of 2.) The Viewing × Distance From the Surface interaction was significant, $F(2, 6) = 6.4$, $p < .04$, but there was no consistent trend over distances from the surface. The monocular means were 0.83, 1.00, and 1.31, respectively, whereas the binocular means were 0.79, 1.05, and 1.27. There were no differences between near and far targets or front and back directions.

Next, we performed this analysis comparing reaches to the front and to the side. Again, there was a main effect for distance from the surface, $F(2, 6) = 6.0$, $p < .04$. However, in this case, there was also a significant interaction with direction, $F(2, 6) = 7.8$, $p < .03$. To the front, the mean ratios were 0.83, 1.02, and 1.31; to the side, they were 1.10, 1.22, and 1.36. At close distance to the surface, ratios to the side were greater than those to the front. Mean reach distances were compressed to the front relative to the side. At far distance from the surface, the ratios became equal. A Tukey honestly significant difference test showed that the means were different at the close ($p < .005$) and medium ($p < .02$) distances from the surface but not at the far distance ($p > .5$). Reaches to the targeted location near the surface (at 3.5 cm) at the side were slightly expanded, that is, 3.8 cm. Reaches to the targeted location far from the surface were at 7.5 cm. This latter value was nearly

[2] A feature of the data obvious in these graphs is that the distributions of reaches were consistently rotated in a clockwise direction looking downward on the x–y horizontal plane. We measured the degree of rotation by regressing x on y-coordinates for all of the reaches to the front and back separately for each participant, target distance, and viewing condition (as well as experiment). We converted the resulting slopes to degrees of rotation away from the x-axis, that is, away from the midsagittal plane. The means computed across participants in each condition are shown in Table 2, where it can be seen that the amount of rotation was consistent across conditions. The overall mean was −8.1°. We ignored this rotation in our analyses because doing so introduced only a maximum of 1% error in some of the resulting estimates, cos(8.1) = .99.

[3] We obtained the same reported pattern of results in two multiple regression analyses performed on the combined individual data using actual distance as a continuous variable and coding the remaining factors using ±1. The two analyses accounted for 51% and 49% of the variance, respectively. The ANOVAs were easier to report.

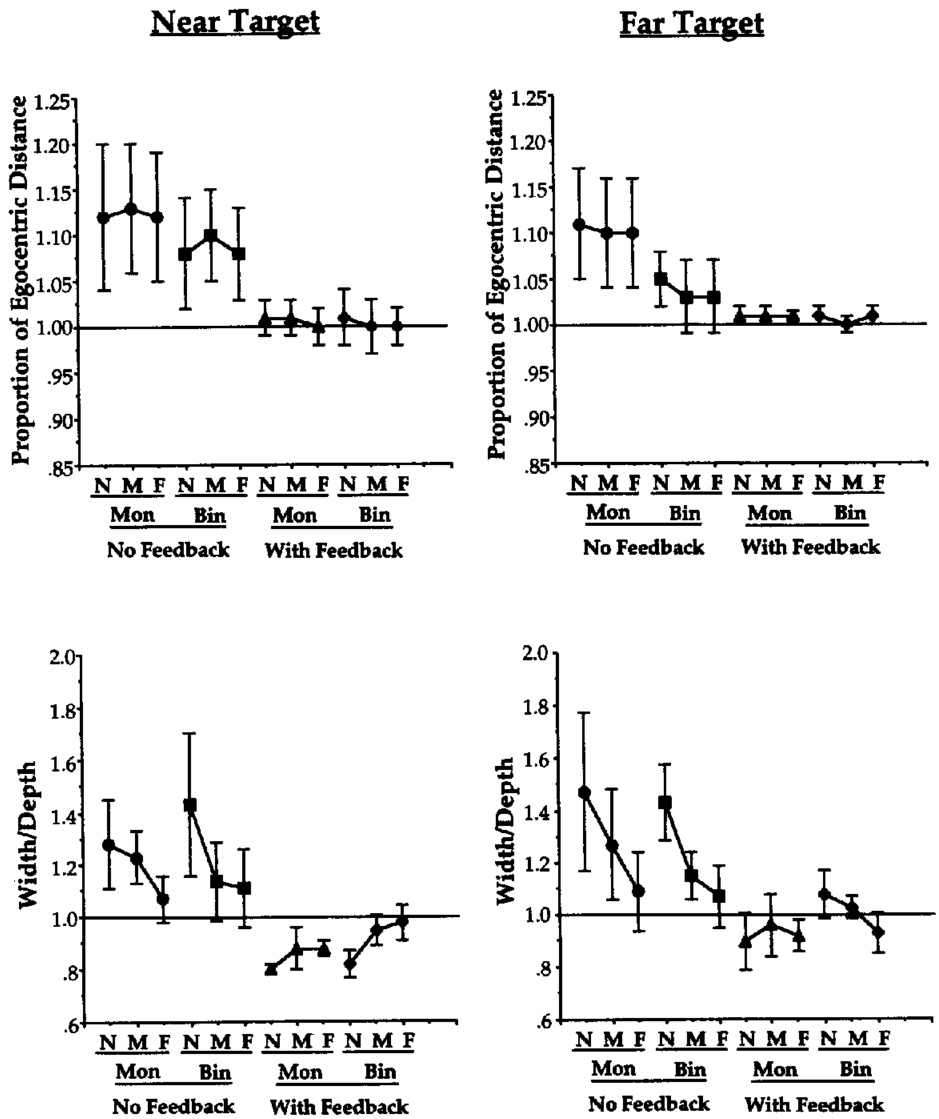

Figure 3. Mean egocentric ratios (with standard error bars; top) and mean width/depth aspect ratios (with standard error bars; bottom) plotted by target distance (near or far), viewing (monocular [Mon] or binocular [Bin]), feedback (Experiment 1, no feedback or Experiment 2, feedback), and distance from the target surface (near [N], medium [M], or far [F]). Monocular no feedback: circles; binocular no feedback: squares; monocular with feedback: triangles; binocular with feedback: diamonds.

the same to the front. (Regression analysis revealed that the distances between the mean reach locations were expanded by 1.69, a value less than that for the front, which was 2.02. This difference in slope yielded convergence to equal distances from the surface to the front and side at the far distance, as is apparent in Figure 4.) There were no differences between near and far targets or with monocular and binocular vision.

In sum, there were three effects. First, reaches close to the surface were compressed in depth (front and back) relative to width (side). Second, distances between targeted locations exhibited an overall expansion. Third, however, the rate of expansion was greater to the front and back than to the side, with the result that the relative depth to width compression was eliminated at the far distances from the surface.

Next, we computed width to depth aspect ratios using the centroids of the reaches to each location for each participant in each target distance and viewing condition. We computed an aspect ratio for each of the three distances from the surface by dividing the average front and back x distance into the side y distance. We have plotted mean aspect ratios for each viewing condition, target distance, and distance from the surface in Figure 3 (bottom left and bottom right). All means were greater than 1. We performed a one-tailed one-sample t test for each viewing condition and target distance to test difference from 1. The results were significant at $p < .05$ or better in all four cases, as shown in Table 3. Although the overall means were all 1.2 or greater, the bottom panels of Figure 3 indicate that aspect ratios were greater close to the surface and shrank to 1 with increasing

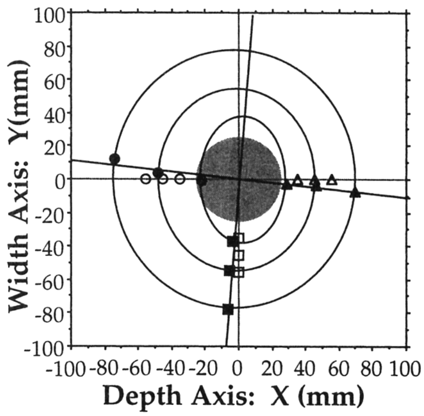

Figure 4. Constant error results of Experiment 1 illustrated by data from the binocular viewing condition at the far target distance. Open symbols: targeted locations relative to the surface of the target sphere. Filled symbols: centroids of the distribution of reaches to each targeted location. Circles: front; squares: side; triangles: back. The shaded circle represents the target sphere. See text for additional details.

distance from the surface. As shown in Table 3, we performed separate *t* tests for each distance from the surface, collapsing across viewing and target distance conditions. The aspect ratios for close and middle distances were significantly different from 1 ($p < .01$), but this was not the case at far distance from the surface ($p > .1$). This analysis confirmed the inference that reaches to locations close to the target surface yielded compression of the shape in depth, but this compression diminished with increasing distance from the surface until, at the largest distances tested, the shape was nearly round.

We next analyzed the stability of the egocentric distance and shape perception as reflected in reach performance. We had found that egocentric distances were overestimated by about 10% of maximum reach or by about 5.5 cm on average without haptic feedback. This overestimation might represent either a stable overestimate or a steady drift. To test this possibility, we performed a multiple regression analysis regressing trial number on the *x*-coordinate of reaches to the sides of the targets. We performed the analysis on data corrected for the mean egocentric overestimate. In addition to trial number, we included as independent variables target distance (coded as ± 1) and an interaction vector.

Table 2
Degrees of Rotation From the Midsagittal Plane of the Distribution of Reaches to the Front and Back of Targets: Experiment 1

Experiment and viewing condition	Near target		Far target	
	M	*SD*	*M*	*SD*
Experiment 1: Monocular	−10.2°	4.3°	−7.1°	3.3°
Experiment 1: Binocular	−8.1°	4.6°	−6.3°	3.2°
Experiment 2: Monocular	−9.1°	6.2°	−8.5°	5.9°
Experiment 2: Binocular	−9.0°	1.2°	−9.0°	3.1°

Note. Means are computed across participants for each target distance and viewing condition.

Table 3
One-Tailed One Sample t Tests of Difference From 1 of Width/Depth Ratios by Viewing Condition, Target Distance, and Distance From the Target Surface in Experiment 1

Distance	*t*	*p*	*M*
Monocular			
Near	2.7[a]	<.01	1.19
Far	2.2[a]	<.05	1.28
Binocular			
Near	2.0[a]	<.05	1.23
Far	2.8[a]	<.01	1.22
Distance from target surface			
Close	3.87[b]	<.001	1.40
Middle	2.96[b]	<.005	1.20
Far	1.40[b]	*ns*	1.08

[a] *df* = 11. [b] *df* = 15.

We performed the analysis separately on the data for each participant and viewing condition as shown in Table 4. With monocular vision, all participants exhibited a backward drift except in one case at a near target and one at a far target. With binocular vision, 2 participants exhibited backward drift, and 1 exhibited a forward drift. To determine whether this drift could account for our mean results, we next performed the analysis on the combined data adding viewing condition (coded as ± 1) and corresponding interaction vectors as independent variables.[4] The result was significant, $F(7, 426) = 8.2$, $p < .001$, $r^2 = .12$). Only trial (partial $F = 43.3, p < .001$) and the Trial × Viewing Condition interaction (partial $F = 4.0$, $p < .05$), were significant. In the monocular condition, reaches drifted farther in depth at an average rate of 0.3 mm per trial or 2.7 cm over the experimental session. In the binocular condition, they drifted at half that rate. These results account for only half of the 5.5-cm mean egocentric overestimate, so the overestimate cannot be attributed entirely to the drift that occurred after the first trial.

We also performed this analysis on the *y*-coordinate of the reaches to the front and back. In this case, the result was not significant ($p > .1$).

Next, we performed the drift analysis separately on the *x*- and *y*-coordinates at each of the targeted locations close and far from the surface in each of the three directions (front, side, and back). Of the six analyses on the *x*-coordinate, four were significant at $p < .05$ or better. These were the close locations to the front and back and both side locations. In each case, only the trial variable was significant at $p < .05$ or better. Of the six *y* analyses, only one was significant, that is, to the front, close. We used the 12 resulting linear equations to estimate the mean reach locations on Trial 1 and at the end of the session on Trial 90. The result is shown in Figure 5, where it can be seen that reaches drifted away more for locations close to the surface and without significant change in distortion of shape over time.

[4] Trials were performed in two consecutive blocks of 45 trials. In 3 instances out of 16, the second block of trials at a given target distance was not consecutive, and we excluded these data from the analyses.

Table 4
Results of Multiple Regressions Performed on X Distances of Reaches to the Side of the Target: Experiment 1

Participant	R^2	F	Trial	Target distance	Target Distance × Trial	Slope
			Monocular view			
P1	.57	17.8***[a]	36.3***	6.1*	34.1***	1.48 (Near) 0.02 (Far)
P2	.38	11.3***[b]	29.3***	*ns*	*ns*	0.42
P3	.41	12.8***[b]	37.5***	*ns*	*ns*	0.33
P4	.26	6.4***[b]	*ns*	16.4***	12.8***	0.52 (Near) ≈0 (Far)
			Binocular view			
P1	.53	15.7***[a]	3.5*	*ns*	*ns*	0.24
P2	.31	6.0**[a]	7.6*	*ns*	*ns*	−0.33
P3	.14	3.1*[b]	*ns*	6.1*	*ns*	0.10
P4	.22	5.2**[b]	11.0**	4.6*	*ns*	0.25

[a] $df = 3, 41$. [b] $df = 3, 56$.
* $p < .05$. ** $p < .01$. *** $p < .001$.

Discussion

Previous studies involving psychophysical methods and passive judgments had revealed distortions in egocentric distance and shape perception. We set out to test whether such distortions would be found with action measures. One of the previous findings had been that egocentric distances in near space are overestimated when binocular vision is used. It seems that, if this is true, people should typically hit nearby objects when they reach for them, or, at least, they should when they reach without watching their hand approach a target. Because people are generally successful in their reaching, we expected that the distortions might not be found with reaching as a measure. When visual information is used to guide a reach, the distortions could be corrected in the parameterization of the reach.

The results were surprising. Our expectations were not confirmed. First, we found overestimation or expansion of egocentric distances viewed with dynamic binocular vision. This is consistent with the previous psychophysical results. Second, we also found overestimation or expansion of egocentric distances viewed with dynamic monocular vision. The amount of expansion was twice that found for binocular vision. In this case, the more common finding has been underestimation or compression of distance (e.g., Bingham & Pagano, 1998; Ferris, 1972; Gogel & Tietz, 1979; Wickelgren et al., in press). But there have been exceptions (e.g., Philbeck & Loomis, 1997, 1998). Third, we found compression of shape in depth relative to width. This result was the same for binocular and monocular vision. The amount of compression did not vary with target distance in either case. This result is different from previous findings in two respects. In previous studies, the amount of distortion was found to vary with target distance for binocular but not monocular vision. More important, the previous finding was of expansion in depth relative to width. Our result was the opposite, that is, compression in depth. This pattern is similar to the PSE found by Tittle et al. (1995),[5] whose participants adjusted the eccentricity of a cylinder viewed in a (stereo) structure-from-motion display until the cross section of the cylinder appeared circular. The PSE to a circular cross section was an eccentricity that was compressed in depth relative to width. From this, Tittle et al. inferred that vision expanded the shape in the depth direction. In our experiment, participants were asked to place the stylus at a known distance (1 cm, 2 cm, or 3 cm) from the surface of the target sphere. That is, they were required to produce a known distance in a visually structured field. This, as in the Tittle et al. study, was a production task that might have yielded a visual PSE result. The known distances were compressed in depth relative to width as if to appear equivalent in the face of visual expansion of distances in depth. This is the result one might expect to obtain if participants were allowed to view their hand positioned with respect to the target during the production task. However, we obtained this result with blind reaching.

Finally, we found that the compression diminished with increasing distance from the target surface until, at the farthest distance tested, the distortion was absent. We considered three possible accounts. First, this might be a result of decreasing resolution in positioning with increasing distance from the target surface, especially if the resolution decreased faster in the depth than in the width direction. We examined this possibility by computing and analyzing the x and y standard deviations of the distribution of reaches at each targeted location for each participant, viewing condition, and target distance. We performed a five-variable repeated measures ANOVA on the combined standard deviations with coordinate (x or y), direction (front, side, or back), viewing (monocular or binocular), target distance (near or far), and distance from the surface (close, middle, or far) as variables. The only significant variable was coordinate, $F(1, 3) = 21.9$, $p < .02$. As can be seen in Figure 6, the mean standard deviation for x (1.7 cm) was greater than that for y (1.1 cm), but mean standard deviations close to the surface and far from it were the same, namely, 1.4 cm.

[5] Jim Todd noted this at the Psychonomics Society meeting, November 1997.

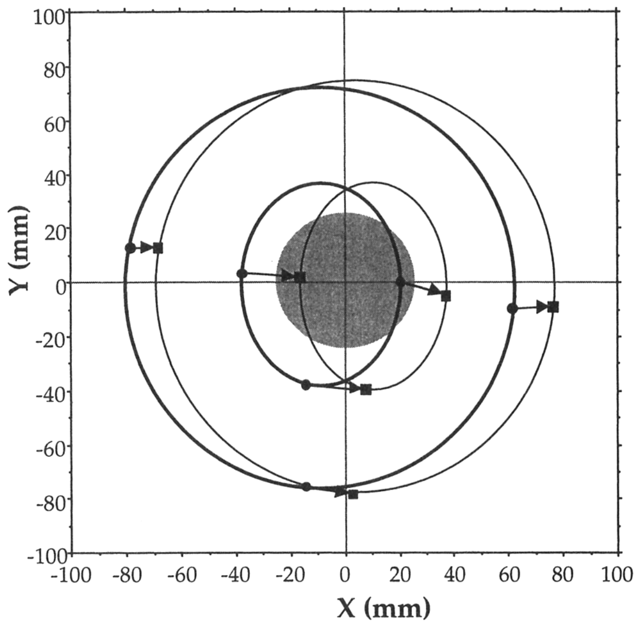

Figure 5. Mean drift that occurred over the 90 trials of the experimental session in Experiment 1: reaches without haptic feedback. Circles and thick lines: mean reach positions on Trial 1. Squares and thin lines: mean reach positions on Trial 90. Mean positions are centered to eliminate mean egocentric overshoot of 55 mm.

This result indicated that differential resolution in positioning was an unlikely source of the falloff in distortion.

A second possibility is that the diminishing distortions are specific to the perception of surface layout or shape and its effect on surrounding space. This hypothesis is that surfaces, in visually structuring the surrounding space, yield an effective field structure with diminishing strength as distance from a surface increases.

A third possibility is that the result was a haptic effect of reaching to produce shapes of increasing size. In this case, if reaches were performed to larger objects, no distortions would result. Furthermore, if this was a reflection of haptic perception, then the shape distortions obtained might also reflect a haptic PSE. We investigated this possibility in Experiment 3.

Experiment 2

We had guessed that reaches might be parameterized to eliminate the effects of distortions in the visual perception of both egocentric distance and shape. But we found that feedforward reaches exhibited both distortion and instability. Reaches in Experiment 1 were performed without the contact of hand and target that normally occurs. Such contact might provide haptic information about the location of the target that could be used to correct distortions and stabilize performance. The task, however, was to place the hand at specific distances from the target surface in different directions. Contact would indicate that the hand was at the surface. However, participants would need to apprehend and evaluate the distance between the location to which they had originally reached and the target surface. Visual apprehension of these distances would not be expected to allow correction of the visual distortions. The question was whether haptic perception would. Haptic feedback would be generated by moving the hand through the distance between the originally targeted location of the reach and the target surface.

As previously described, many studies have shown that haptic perception of distances traveled by the arm in different directions is distorted. For instance, Kay et al. (1996) found that horizontal rectangles compressed in the depth direction were haptically perceived to be squares when traced with the arm. The distortion increased with egocentric distance. There was no distortion immediately in front of the body and 30% distortion at arm's length. These haptic distortions are likely to affect performance when participants in our task are allowed to contact target surfaces. If the results of Experiment 1 reflect a visual PSE, then at far distance within reach space, the haptic distortions found by Kay et al. and the visual distortions found by Tittle et al. and revealed here are the same. When combined, the two should cancel. Distances in depth relative to width should appear larger, but they should also feel larger. That is, a distance of 1 unit should appear as 1.2 units, but when felt, a distance of 1 unit should also feel like 1.2 units, with the result that a participant should actually produce a distance of 1 unit. In contrast to far targets, no haptic distortions have been found for near targets. Therefore, the results with haptic feedback should yield visual distortions directly. Visually, distances should appear expanded in depth relative to width. Participants should reach to produce expanded distances and correctly feel themselves to be doing so.

Method

The method and participants in Experiment 2 were the same as in Experiment 1 with the following exception. In each trial, after the participant had positioned the stylus and indicated that he or she was ready so that WATSMART recording should be terminated, the target was lowered back into position, and the participant moved to touch the surface of the sphere with the tip of the stylus. If the participant had placed the stylus effectively inside the target sphere, then the stylus was gently tapped by the

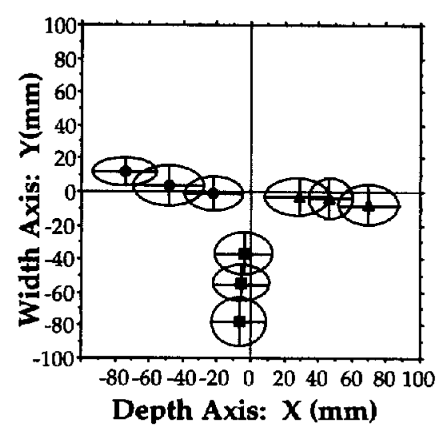

Figure 6. Variable error results of Experiment 1 illustrated by data from the binocular viewing condition at the far target distance: ellipses around the centroid of the distribution of reaches to each targeted location. Axes of the ellipsoids represent the mean standard deviation in the x and y directions. Mean standard deviations were computed across participants. Circles: front; squares: side; triangles: back.

target when it was lowered. After touching the target, the participant placed the stylus back into the launch platform, and the next trial was begun.

Results

As in Experiment 1, we first evaluated the perception of egocentric distance by analyzing the *x*-coordinate of reaches to the side of the target. We performed separate ANOVAs for each participant on the reach distance/target distance ratios using viewing and target distance as variables. As shown in Table 5, target distance was significant in all cases, and viewing was significant for 1 participant. Two participants underreached the near target by a small amount and 2 overreached, but these individual differences canceled in a repeated measures ANOVA on the combined means that yielded no significant effects. The mean ratios were all close to 1.00. As shown in Figure 3 (top left and top right), egocentric distances were accurate with both monocular and binocular vision and both near and far targets.

Using the reaches to the front and back, we divided reach distances by target distances and computed means for each target distance, viewing condition, and participant. For each viewing condition, we then performed a one-tailed one-sample *t* test to test difference from 1. The result was not significant for either monocular ($M = 1.00$), $t(7) = 0.6$, or binocular ($M = 1.00$), $t(7) = 0.4$, viewing. Egocentric distances were estimated quite accurately.

We turned next to analyses of shape. The pattern of results is illustrated in Figure 7 by viewing condition and target distance. As in Experiment 1, we performed two ANOVAs using distances from the origin at the center of the target, dividing reach distances by the distances of the targeted locations and computing mean ratios for each participant at each targeted location. As before, the targeted locations were at 3.5 cm, 4.5 cm, and 5.5 cm from the origin in a given direction (front, side, or back), and the surface of the sphere was 2.5 cm from the origin. We first performed a repeated measures ANOVA comparing reaches to the front and back using direction, distance from the surface, viewing, and target distance as variables. Only the Target Distance × Distance From the Surface interaction was significant, $F(2, 6) = 12.8$, $p < .01$. The mean ratios for close, middle, and far from the surface, respectively, were 1.29, 1.34, and 1.42 for the near target and 1.15, 1.25, and 1.45 for the far target.

Given this difference, we performed separate analyses for the near and far targets to compare front and side. In the ANOVA for the far target, distance from the surface was marginal, $F(2, 6) = 4.6$, $p < .06$, and no other variable was significant. The mean ratios to the side were 1.12, 1.25, and 1.35. These values were similar to those for the front and back. Thus, front and side were not different for the far target, and there was no distortion.

In the ANOVA for the near target, there was a main effect for direction, $F(1, 3) = 10.0$, $p < .05$. Distance from the surface was marginal, $F(2, 6) = 4.5$, $p < .06$. The mean ratios to the side were 1.05, 1.25, and 1.35. These ratios were less than the ratios in the front and back, especially close to the surface. The Viewing × Direction interaction was significant, $F(1, 3) = 15.8$, $p < .03$. The overall mean ratios for the front and side were 1.35 and 1.18, respectively, with monocular vision and 1.34 and 1.25 with binocular vision. There was expansion in depth relative to width, but less so with binocular than monocular vision.

We next computed width to depth aspect ratios for each participant, viewing condition, target distance, and distance from the surface. We have plotted mean aspect ratios for each viewing condition, target distance, and distance from the surface in Figure 3 (bottom left and bottom right). We performed one-tailed one-sample *t* tests for each viewing condition and target distance to test difference from 1. As shown in Table 6, no differences from 1 were found for far targets in either viewing condition. However, the mean ratios were significantly less than 1 for the near targets in both viewing conditions, with an overall mean of 0.89. As shown in Table 7, we tested difference from 1 at the close, middle, and far distances from the target surface separately at each target distance and found a significant difference only for the near target at the close distance, where the mean (0.81) represents a 20% expansion of depth relative to width. This was opposite to the distortion found in Experiment 1. This reproduced the visual distortions of shape found in psychophysical studies. Although

Table 5
Results of Analyses of Variance Performed on Egocentric Reach Distance/Target Distance Ratios: Experiment 2

Participant	Viewing	Target distance	Viewing × Target Distance		*M* Near	*M* Far
P1[a]	5.7*	7.3**	2.4	Mon:	1.04	1.03
				Bin:	1.03	1.00
P2[b]	1.3	40.8***	1.2	Mon:	0.94	0.99
				Bin:	0.96	0.99
P3[c]	2.2	46.2***	3.3	Mon:	1.04	0.99
				Bin:	1.02	0.99
P4[a]	2.6	78.7***	0.9	Mon:	0.91	1.01
				Bin:	0.91	0.99
Overall[d]	1.4	0.4	1.0	Mon:	0.98	1.00
				Bin:	0.98	0.99

Note. Mon = monocular; Bin = binocular.
[a] $df = 1, 116$. [b] $df = 1, 115$. [c] $df = 1, 113$. [d] $df = 1, 3$.
* $p < .05$. ** $p < .01$. *** $p < .001$.

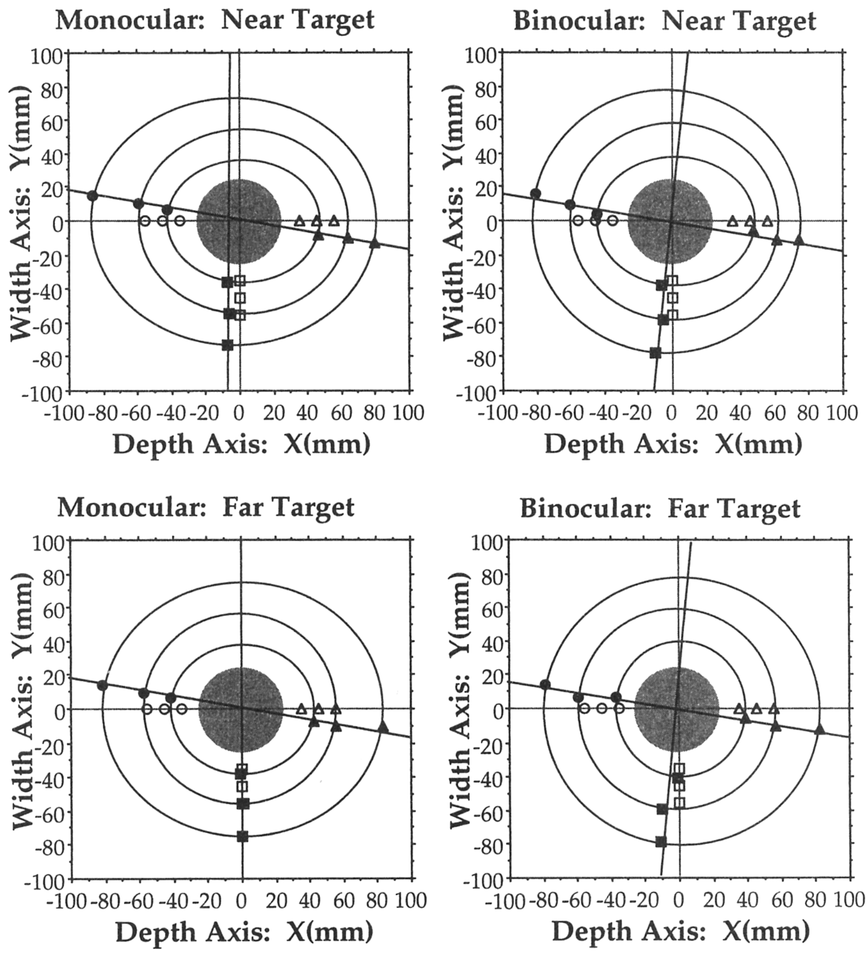

Figure 7. Constant error results of Experiment 2 plotted by viewing condition and target distance. Open symbols: targeted locations relative to the surface of the target sphere. Filled symbols: centroids of the distribution of reaches to each targeted location. Circles: front; squares: side; triangles: back. The shaded circle represents the target sphere. See text for additional details.

distortion was less at greater distance from the surface, especially for binocular viewing, there was a stronger tendency than in Experiment 1 for distortion at all distances from the surface, especially with monocular vision (see Figure 3, bottom left).

Table 6
One-Tailed One-Sample t Tests of Difference From 1 of Width/Depth Ratios by Viewing Condition and Target Distance: Experiment 2

Target	Monocular	Binocular
Near		
$t(11)$	−5.0	−2.2
p	<.001	<.03
M	0.86	0.92
Far		
$t(11)$	−1.4	0.4
p	*ns*	*ns*
M	0.92	1.02

Next, we computed the x and y standard deviations of the distribution of reaches at each targeted location for each participant, viewing condition, and target distance and performed a five-variable repeated measures ANOVA on the combined standard deviations; coordinate (x or y), direction (front, side, or back), viewing (monocular or binocular), target distance (near or far), and distance from the surface (close, middle, or far) were variables. Coordinate was significant, $F(1, 3) = 74.0$, $p < .01$. Variation in x (mean $SD = 1.58$ cm) was larger than in y (mean $SD = 0.98$ cm). The Coordinate × Distance From the Surface interaction was significant, $F(2, 6) = 9.7$, $p < .02$. As shown in Figure 8, variability increased with distance from the surface, but more so in x than in y. The Coordinate × Direction × Distance From the Surface interaction was significant, $F(4, 12) = 3.8$, $p < .05$; x variability increased with distance from the surface primarily in the front and back directions, whereas y variability increased primarily in the side direction. Thus, the pattern of variable errors became functionally specific with haptic feedback. Variability was specific to the direction and distance of the surface of the sphere relative to the targeted location of the reach. Finally, the Target Distance × Distance From the Surface interaction was significant, $F(2, 6) = 6.6, p < .05$. Variability increased with distance from the surface more for the far than the near target.

Finally, we analyzed the stability of egocentric distances and shape. We regressed trial, target distance (±1), viewing condition (±1), and interaction vectors on the side *x*-coordinates. The result was significant, $F(7, 411) = 3.7, p < .001, r^2 = .06$, but the rate of drift was only −0.07 mm per trial, that is, only 0.6 cm toward the participant over the experimental session.[6] The analysis on front and back *y*-coordinates was not significant. Of the 12 analyses on *x*- and *y*-coordinates at each targeted location, only 2 were significant at $p < .05$ or better: front, close *x* and side, far *x*. The mean reach positions computed at the beginning and end of the session are shown in Figure 9, where it can be seen that the main change was in front of and close to the target. Drift toward the participant yielded an increase in the expansion of the shape in depth. Overall, however, reaches with feedback were much more stable than those without feedback.

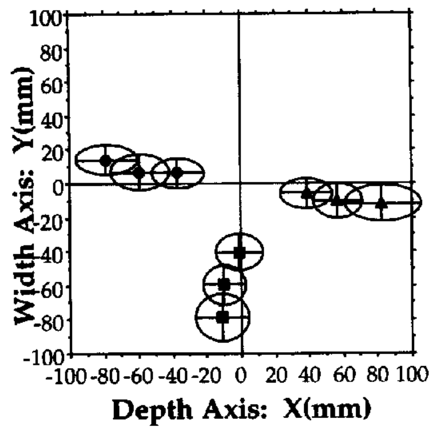

Figure 8. Variable error results of Experiment 2 illustrated by data from the binocular viewing condition at the far target distance: ellipses around the centroid of the distribution of reaches to each targeted location. Axes of the ellipsoids represent the mean standard deviation in the *x* and *y* directions. Mean standard deviations were computed across participants. Circles: front; squares: side; triangles: back.

Discussion

Performance in Experiment 2 was more accurate, more stable, and, thus, more precise. The increased precision yielded functional specificity in the pattern of variable error that had been absent in Experiment 1. Positional variability was greater in directions oriented toward the target surface. Presumably, this was produced by attempts to adjust position specifically with respect to the target surface. If this was present in Experiment 1, it was lost in the greater levels of nonspecific variability.

We found that the egocentric distances of the targets were apprehended accurately and stably over trials. In Experiment 1, egocentric distances had been overestimated without the haptic feedback, and reaches had drifted away in depth over trials. In Experiment 1, we also found distortions in perceived shape. In the current experiment, we expected visual and haptic distortions in shape perception to interact, and accordingly we predicted no distortion for far targets and expansion in depth relative to width for near targets; this is what happened. The distortion at the near target was an expansion in depth relative to width. This was opposite of the pattern in Experiment 1 and directly reflected the visual distortion of shape inferred from results of psychophysical studies. The latter result was predicted assuming that vision expands distances in depth, whereas haptic perception yields accurate assessment of these distances so that participants see the distance to be produced as larger, and the haptic experience accurately reflects this distance. We found that this distortion increased over trials as reaches to the front of the target drifted increasingly away from the surface. The fact that we found distortion in perceived shape for the near target despite accuracy in perception of egocentric distances implies that egocentric distance and shape perception are not tightly coupled. The weakness of this coupling has been noted by others (Fukusima, Loomis, & DaSilva, 1997; Gogel, 1977; Loomis et al., 1992).

Table 7
One-Tailed One-Sample t Tests of Difference From 1 of Width/Depth Ratios by Distance From the Target Surface: Experiment 2

Target	Close	Middle	Far
Near			
$t(7)$	−7.7	−1.7	−1.7
p	<.001	*ns*	*ns*
M	0.81	0.92	0.93
Far			
$t(7)$	−0.12	−0.06	−1.60
p	*ns*	*ns*	*ns*
M	0.99	1.00	0.92

Experiment 3

The reaches of Experiment 1 exhibited a compression in depth, but this compression diminished as the distance from the target surface increased until, at the largest distance, a distortion was no longer evident. This result might reflect visual organization of the space surrounding the target surface. Conversely, the result might have been produced by haptic (and here largely kinesthetic) perception of shapes and locations in reach space. To test these possibilities, we recorded reaches to targets that participants had only experienced haptically. Blindfolded participants first reached out to trace the shape of a target sphere and then performed a series of reaches to locations corresponding to the front, back, and sides of the target. We tested targets of three different sizes comparable to the sizes of the configurations targeted in Experiment 1.

We had also found in Experiment 1 that reaches drifted in depth over trials predominantly away from the participant. This instability contributed to the mean egocentric overreaching that was interpreted as a product of visual expansion of egocentric distance. The question is whether the tendency to drift outward was indeed visually driven. We examined potential drift patterns in reaches

[6] In four instances, the second block of 45 trials was not consecutive and was excluded from the analysis.

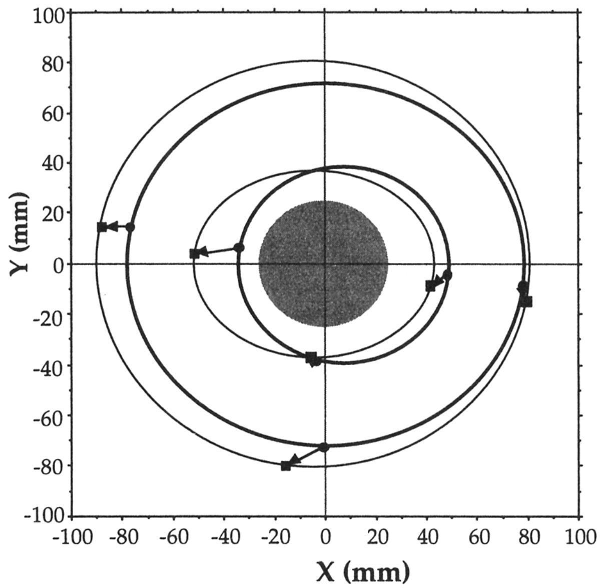

Figure 9. Mean drift that occurred over the 90 trials of the experimental session in Experiment 2: reaches with haptic feedback. Circles and thick lines: mean reach positions on Trial 1. Squares and thin lines: mean reach positions on Trial 90.

guided only by haptic experience of a target to test whether outward drift might occur as a haptic or motor effect.

Method

Participants. Five adults at Indiana University participated in the experiment. They were from 20 to 43 years of age. Two were women, and 3 were men. One was an author (Geoffrey P. Bingham). Two were graduate students, and 2 were undergraduates. All had normal or corrected-to-normal vision and normal motor abilities. All were right-handed.

Apparatus. The apparatus was the same as in Experiments 1 and 2 with the exception that three different Styrofoam spheres 5 cm, 7 cm, and 12 cm in diameter were used.

Procedure. The positioning of the participant and the target was done in the same way as in Experiments 1 and 2. Targets were tested at the same distances as in the previous experiments, that is, at .50 and .80 of maximum reach distance. Participants were blindfolded and not allowed to see the targets. Once they were seated, they gripped the stylus as in Experiments 1 and 2, and the experimenter guided their hand out to the target. They then felt the target with the stylus, repeatedly tracing the equator of the sphere in a horizontal plane. After they had done this about six times, they replaced the stylus in the launch platform (which was to their right near their hip, as in the previous experiments). The participant then performed a series of reaches to touch the sphere to the front, left, right, or back, twice each in a random order. After this, the target was removed, and the participant performed a series of reaches to the locations of the front, left, right, and back of the target. In each trial, participants were told the location to which they should reach, and then they reached. When they were satisfied that they had placed their hand and stylus in the correct location, they said "OK," and the experimenter ended WATSMART sampling. The participant replaced the stylus in the launch platform, and the next trial was begun. All four locations relative to the target surface were visited in a random order in each block of reaches. Fifteen blocks were performed for each of the three target sizes. The order in which targets were tested at a given target distance was counterbalanced across participants, as was the order of the two target distances.

Data reduction and analysis were performed as in the previous experiments with the following exceptions. The procedure was improved by including reaches to locations in four directions and by blocking trials so that all four directions were visited in each block. The four reaches in each block were then used to compute a centroid to evaluate egocentric distance and to compute an aspect ratio to evaluate shape.

Design. All variables were within subject. The variables were target distance (near or far), direction (front, left, side, or back), and target size (small, medium, or large).

Results

Egocentric distances were evaluated by computing a mean egocentric ratio for each block of reaches to the four symmetrically distributed targeted locations. We computed the egocentric ratio for each reach as before, using x-coordinates with the origin at the eye and dividing reach x distance by target x distance. We performed separate repeated measures ANOVAs on the data for each participant using target distance and target size as variables. The two main effects and the interaction were significant at $p < .05$ or better in all cases except one, as shown in Table 8. However, in a repeated measures ANOVA performed on the means computed for each participant by averaging over blocks, only target distance was significant, $F(1, 4) = 12.1$, $p < .03$. We found significant individual differences in the effect of target size but a consistent pattern of results for target distance. Egocentric ratios were smaller for the far than the near targets. Using mean reach distance/target distance ratios for each target size and distance and participant, we performed a one-tailed one-sample t test to test difference from 1 separately for each target distance. The result was significant for the far targets ($M = 0.96$), $t(14) = -1.76$, $p < .05$, but not for the near target ($M = 1.04$), $t(14) = 1.27$, *ns*. In contrast to Experiment 1, in which both near and far targets were overreached, far targets were underreached in this case, with a nonsignificant trend to overreach near targets. The extent of any overreaching in the latter case was distinctly less than in Experiment 1, as shown in the top two panels of Figure 10, which should be compared with the top two panels of Figure 3.

Next, we turned to analysis of the perceived shape. We computed a width to depth aspect ratio for each block of reaches for each participant by dividing the difference of left and right y-coordinates by the difference of front and back x-coordinates. We computed mean aspect ratios for each participant and performed a repeated measures ANOVA on them using target distance and target size as variables. Only the target size variable was significant, $F(2, 8) = 5.0$, $p < .04$. As shown in Figure 10 (bottom left and bottom right), the pattern of results was very similar to that in Experiment 1 (see Figure 3, bottom left and bottom right). Also, compare Figure 11 with Figure 4. The shape was compressed in depth, but the amount of compression decreased as the size of the target increased. We performed separate one-tailed one-sample t tests on the aspect ratios for each target distance, testing difference from 1; as shown in Table 9, the results were significant for both near and far targets. However, when we performed these t tests by target size, the results were significant for the smaller targets but not the larger targets, as shown in Table 9. This pattern of results is the same as in Experiment 1 (cf. Table 3).

We analyzed the stability of egocentric distances over blocks of trials by regressing block number on egocentric ratio. Because trials were blocked by both target size and distance, we performed

Table 8
Results of Analyses of Variance Performed on Egocentric Reach Distance/Target Distance Ratios: Experiment 3

Participant	Target distance (df = 1, 84)	Target size (df = 2, 84)	Target Distance × Target Size (df = 2, 84)		M Small	M Medium	M Large
P1	153.3***	49.5***	19.7***	Near:	1.07	1.15	1.12
				Far:	0.92	1.00	1.09
P2	1.7	46.2***	9.6**	Near:	1.01	0.78	0.80
				Far:	0.90	0.78	0.85
P3	138.7***	42.5***	9.5**	Near:	1.25	1.13	1.09
				Far:	1.08	1.03	1.02
P4	11.4***	58.4***	19.6***	Near:	1.04	0.95	1.10
				Far:	1.08	0.93	0.99
P5	386.4***	33.0***	54.0***	Near:	0.98	1.13	1.03
				Far:	0.92	0.90	0.92
Overall	12.1*[a]	0.6[b]	0.6[b]	Near:	1.07	1.03	1.03
				Far:	0.98	0.93	0.97

[a] df = 1, 4. [b] df = 2, 8.
* $p < .05$. ** $p < .01$. *** $p < .001$.

separate regressions in each case on the data for each participant. The slopes and r^2 values are shown in Table 10 where one can see that significant drift occurred in 67% of the cases, with similar proportions at near and far targets. At the near target, in 67% of those instances in which reaches drifted significantly, they drifted toward rather than away from the participant. Likewise, at the far target, 73% drifted toward the participant. Combining data for near and far targets, reaches either were stable or drifted toward the participant in 80% of the cases. Only 20% exhibited drift away in depth. Finally, we normalized the data for each participant by removing the mean egocentric deviation from the target and performed a multiple regression on the combined normalized distances with block number, target distance (±1), and an interaction vector as independent variables. The result was significant, r^2 = .10, $F(3, 449) = 15.8$, $p < .001$, but only block was significant, partial $F = 46.9$, $p < .001$. The mean rate of drift would yield about a 2-cm change over 15 blocks. This result, like that for mean egocentric distances, contrasted with that found in Experiment 1.

We analyzed definite size as follows. Within each block of four reaches, we computed the difference of x-coordinates for reaches to the front and back and of y-coordinates for reaches to the left and right. We divided these differences by the actual distances in each case, which were 5 cm, 7 cm, and 12 cm for the small, medium, and large targets, respectively. We computed means across blocks for each participant, direction (x, or depth, and y, or width), target distance, and target size. We performed a repeated measures ANOVA on these means using direction, target distance, and target size as variables. Only the Direction × Size interaction was marginally significant, $F(2, 8) = 3.3$, $p < .08$. The means in the y or width direction were 1.51, 1.27, and 1.22 for the small, medium, and large targets, respectively. The corresponding means in the x or depth direction were 1.12, 1.12, and 1.10. Widths were overestimated by 2.6 cm (0.33 × 8 cm) on average, whereas depths were overestimated by only 0.9 cm (0.11 × 8 cm). This compares with averages of 2 cm overestimation in width and 0.5 cm in depth in Experiment 1.

Discussion

We set out to investigate whether the pattern of shape distortions found in Experiment 1 should be attributed either to visual structuring of the space neighboring a perceived surface or to the haptic experience of that space. In Experiment 1, we found compression of shape in depth for reaches near the target surface but diminishing compression as the distance from the target surface increased. In the current experiment, participants never experienced the target visually but only haptically. The pattern of shape perception results was identical to that in Experiment 1. We inferred accordingly that the results in Experiment 1 reflected haptic perception of the relative locations in reach space rather than visual perception of shape. Kay et al. (1996) had found compression in depth as a haptic PSE to a square. The results of Experiments 1 and 3 also exhibit compression in depth, which we infer is a haptic PSE to a sphere or circle in the horizontal plane. We found that the amount of distortion increased as the size of the objects decreased. The mean distortion for the smallest targets was about 50%. This was much greater than the amount found by Kay et al., who only tested objects of a single size midway between the two largest sizes that we tested. The amount of distortion found for targets of that size was comparable in the two studies, about 20%. Kay et al. found greater distortion for targets far from the body. We also found a trend for this, as shown in the bottom left and right panels of Figure 10. However, this difference for the largest targets was only marginally significant ($p < .07$) in a planned comparison.

The second question investigated in Experiment 3 was whether the outward drift of egocentric distance found in Experiment 1 was a visual effect, that is, whether vision was driving these distances outward. When reaches were performed without vision in Experiment 3, we found that the predominant direction of drift was no longer outward but instead inward. Consistent with this result, we also found a difference in the pattern of mean egocentric reach distances. Egocentric distances were consistently overreached in

Experiment 1, but not in Experiment 3, in which the far target was underreached on average.

The combined results confirm our earlier inference that egocentric distance and shape perception are not tightly coupled. In Experiment 1, vision apparently played a strong role in driving the egocentric distances of reaches outward, yielding consistent overreaching and outward drift. Despite this, the shapes exhibited by the reaches reflected haptic rather than visual apprehension of relative positions and distances.

Experiment 4

The effect of vision was apparently very weak in determining the shape of the reach positions in Experiment 1. This would

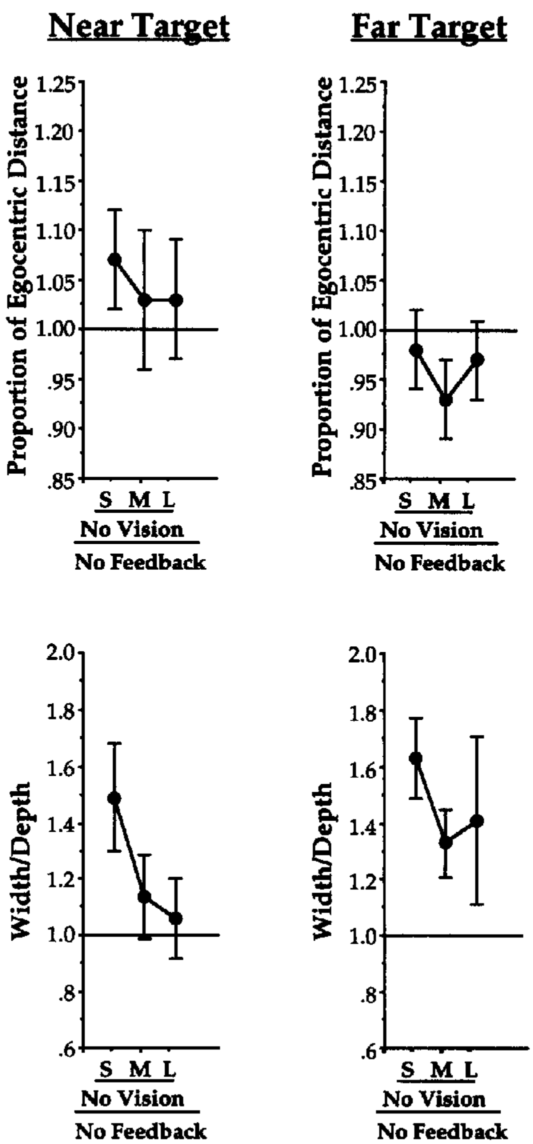

Figure 10. Data from Experiment 3: reaches with only haptic experience of the target. Values are mean egocentric ratios (with standard error bars; top) and mean width/depth aspect ratios (with standard error bars; bottom) plotted by target distance (near or far) and target size (small [S], medium [M], or large [L]).

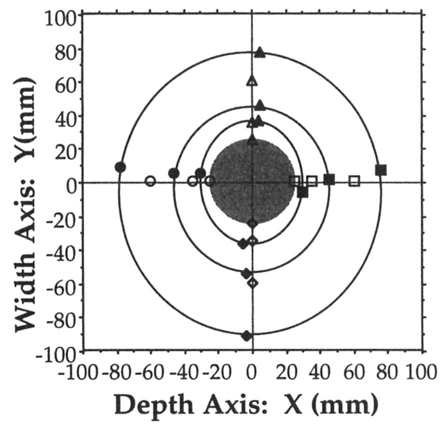

Figure 11. Constant error results of Experiment 3 illustrated by data from the near target distance. Open symbols: targeted locations on the surfaces of the target spheres of different size. Filled symbols: centroids of the distribution of reaches to each targeted location. Circles: front; squares: back; triangles: left; diamonds: right. The shaded circle represents the small target sphere. See text for additional details.

account for the lack of a significant difference in shape results with monocular versus binocular vision. If the results in both cases were determined by haptic perception,[7] then no differences would be expected as a function of viewing condition. Note that we did find differences in the egocentric distance of reaches and in egocentric drift as a function of viewing conditions. Both egocentric overreaching and egocentric drift were half as great with binocular vision as with monocular. This is a further indication of the difference between egocentric distance and shape perception.

The shape perception results in Experiments 1 and 3 make it difficult to interpret the results of Experiment 2 and to evaluate our hypothesis concerning the interaction of visual and haptic distortions. The pattern of results in Experiment 2 was consistent with our predictions, but our predictions were made on the assumption

[7] An analysis of the shape of the distributions of reaches at each targeted location in Experiment 1 provided additional evidence of the strong role of haptics. We computed the slope of the major axis of the bivariate density ellipses for each targeted distance from the surface separately for each direction, participant, target distance, and viewing condition. The slopes were converted to angular deviation in degrees from the x-axis. A repeated measures ANOVA revealed no significant differences for any of the four variables, that is, distance from the surface, direction, target distance, and viewing. The overall mean rotation was $-24.7°$ ($SD = 23.6°$). Most of the distributions at each of the targeted locations were rotated in the clockwise direction, consistent with the rotation of the entire distribution. Of the 144 ellipses that were computed, all but 17 were rotated in the clockwise direction. We performed one-tailed one-sample t tests separately on the data for each of the 4 participants to test the difference from 0. All were significant at $p < .001$, $ts(35) = -5.7, -5.7, -6.4$, and -7.1 ($Ms = -23.8°, -22.9°, -25.9°$, and $-26.2°$). These results are just the pattern of variability in positioning that would be predicted on the basis of the postural stiffness ellipses found by Mussa-Ivaldi, Hogan, and Bizzi (1985; see also Hogan, 1985). Kay et al. (1996) argued that the stiffness ellipsoids were the source of the haptic shape distortions that they found (see also Hogan et al., 1990).

Table 9
One-Tailed One Sample t Tests of Difference From 1 of Width/Depth Ratios by Target Distance and by Distance From the Target Surface in Experiment 3

Distance	*t*	*p*	*M*
Target distance			
Near	2.6[a]	<.02	1.23
Far	4.0[a]	<.001	1.46
Distance from target surface			
Small	4.87[b]	<.001	1.56
Medium	2.40[b]	<.02	1.23
Large	1.39[b]	*ns*	1.23

[a] $df = 14$. [b] $df = 9$.

that the shape distortions in Experiment 1 were visual in origin, and apparently they were not.

In Experiment 4, we used a task in which vision should play a stronger role and once again tested our hypothesis about the interaction of visual and haptic shape distortions, namely, that the two types of distortion should cancel when equal. Participants performed the same tasks as in Experiments 1 and 2, but this time they used vision while reaching as well as before reaching. The target was left in place, and participants reached to place the stylus at one of three distances to the front, back, left, or right of a 5-cm-diameter target sphere. The task was performed with either monocular or binocular vision. In the first sessions, participants were not allowed to touch the target to receive haptic feedback, similar to Experiment 1. In subsequent sessions, they moved to touch the target after the reach had been measured, similar to Experiment 2; in this case, however, they also watched while they did this. As a means of better isolating vision of the target surface and of the stylus, the task was performed in the dark. The end of the stylus was phosphorescent, and the target sphere was covered with irregular phosphorescent spots.

Method

Participants. Five adults at Indiana University participated in the experiment. They were 20 to 43 years of age. One was female, and 4 were male. One was an author (Geoffrey P. Bingham). The others were undergraduates, and none had participated in the previous experiments. All had normal or corrected-to-normal vision and normal motor abilities. All were right-handed.

Apparatus. The apparatus was the same as in Experiments 1 and 2, with the exception that the target sphere was painted black and then covered with irregular phosphorescent spots each about 3 mm in diameter and separated by about 8 mm from one another on average. The end of the stylus extending beyond the participant's hand also was phosphorescent.

Procedure. The procedure was the same as in Experiments 1 and 2 with the following exceptions. As in Experiment 3, targeted locations in four directions were tested, to the front, back, left, and right of the target sphere. Trials were blocked so that all four directions were visited in a random order in each block. Trials were next blocked by distance from the surface, then by viewing condition, and finally by target distance. Three blocks of reaches to the four directions were performed at each distance from the surface. The order of distances from the surface, of viewing conditions, and of target distances was counterbalanced across participants. A session without haptic feedback was always performed preceding a session in which participants obtained haptic feedback. The task was performed in the dark. Participants kept their eyes closed except when looking at the target immediately before reaching and then during the reach itself. Participants kept their eyes open when moving to touch the target after the reach in the session with feedback. The phosphorescence of the target and stylus was energized by shining a bright light on the surface every 12 trials or before each set of three blocks of reaches to a given distance from the surface. At this time, the participant was shown the required distance from the surface for the next set of reaches. The required distances (1 cm, 2 cm, and 3 cm) were indicated by lines drawn on paper.

Table 10
Slopes and r^2 Values From Simple Linear Regressions Regressing Block Number on the Mean Egocentric Ratio for Each Block of Reaches: Experiment 3

	Near target			Far target		
Participant	Small	Medium	Large	Small	Medium	Large
P1						
Slope	−1.60	2.40	−0.60	−4.03	−2.19	−3.00
r^2	.18	.34*	.11	.61**	.23	.80***
P2						
Slope	−3.17	−4.30	−6.20	−0.52	−1.96	−7.50
r^2	.57***	.67***	.69***	.08	.59***	.88***
P3						
Slope	−4.43	3.00	−1.70	2.11	0.10	−1.22
r^2	.67***	.68***	.44**	.72***	.00	.30*
P4						
Slope	−0.84	−2.30	3.70	1.94	3.38	0.88
r^2	.06	.43**	.69***	.42**	.49**	.12
P5						
Slope	−0.54	−0.13	−.059	−2.46	−4.38	−1.73
r^2	.05	.01	.07	.48**	.77***	.53**

Note. Regressions were performed separately for each target distance, target size, and participant. A negative slope reflects drift toward the participant.
* $p < .05$. ** $p < .01$. *** $p < .001$.

The participant was allowed to view only the relevant line, to span the line with his or her fingers, and to move the stylus over the distance tracing the line.

After the participant had been informed of the required distance from the surface, each trial proceeded as follows. The participant sat with eyes closed and hand gripping the stylus in the launch platform near his or her right hip. The experimenter announced the targeted location (front, back, left, or right). The participant said "OK," meaning that he or she heard the instruction and was ready. The experimenter said "Start" and initiated WATSMART sampling. The participant opened his or her eye(s) and moved his or her head about 10 cm sideways three times, moving from the hip. The participant was instructed to look at the targeted location while doing this. Participants were told to reach as soon as they finished the head movement; that is, they were not to pause or to "set" before reaching. Reaches were performed at a preferred rate. Once the participant had reached the targeted location, he or she said, "OK," and WATSMART sampling was stopped. In no haptic feedback trials, the participant then closed his or her eye(s) and returned the stylus to the launch platform for the next trial. In trials with haptic feedback, the participant then moved the stylus to touch the target surface while watching. After this, he or she closed his or her eye(s) and returned the stylus. Participants took a break, leaving the chair and moving around between viewing and target distance conditions.

Data reduction and analysis were performed as in Experiment 3. The reaches to the four directions in each block were used to compute a centroid to evaluate egocentric distance, to compute an aspect ratio to evaluate shape, and to compute exocentric width and depth distances to evaluate size.

Design. All variables were within subject. The variables were target distance (near or far), viewing (monocular or binocular), distance from the surface (close, medium, or far), and direction (front, left, side, or back). Three reaches were performed in each cell, for a total of 144 ($2 \times 2 \times 3 \times 4 \times 3$) trials per participant.

Results

First, we examined egocentric distances. We computed mean egocentric ratios for each participant as in Experiment 3. We performed a repeated measures ANOVA on these values using feedback (without haptic feedback or with haptic feedback), viewing (monocular or binocular), target distance (near or far), and distance from the surface (close, medium, or far) as variables. The only main effect was for viewing, $F(1, 4) = 9.5$, $p < .05$. As shown in Figure 12 (top left and top right), the target was overreached by 6% with monocular vision but by only 2% with binocular vision. Overreaching occurred at both target distances. However, the Target Distance × Viewing interaction was significant, $F(1, 4) = 7.5$, $p < .05$. With monocular vision, the near target was more strongly overreached than the far target (9% vs. 4%). Performance was the same at both targets with binocular vision. The Feedback × Distance From the Surface interaction was significant, $F(2, 8) = 8.9$, $p < .01$. Feedback reduced overreaching more for reaches farther from the surface. The reductions were by 1% close to the surface, 2% at medium distance from the surface, and 3% far from the surface. We performed one-tailed one-sample t tests to test difference of egocentric ratios from 1 (that is, the target distance). We tested each feedback and viewing condition and target distance separately. As shown in Tables 11 and 12, a significant difference was found in every case at $p < .05$ or better, but the amount of overreaching was less with binocular vision and less with haptic feedback. In general, performance was consistent across participants so that small amounts of overreaching yielded statistical significance.

To examine shape perception, we computed mean width/depth aspect ratios for each participant and performed a repeated measures ANOVA on them using feedback, viewing, target distance, and distance from the surface as variables. The only significant variable was viewing, $F(1, 4) = 9.2$, $p < .05$. The overall means were 0.81 for monocular viewing and 0.99 for binocular viewing. As shown in Figure 12 (bottom panels) and Figure 13, monocular viewing yielded expansion in depth by about 20%, whereas binocular viewing was accurate. We performed one-tailed one-sample t tests to test whether aspect ratios were different from 1. As shown in Tables 13 and 14, all aspect ratios for monocular vision were significantly less than 1, both without and with haptic feedback. Without haptic feedback, aspect ratios for binocular vision were not different from 1, but with haptic feedback, the ratios for the far target were significantly less than 1.

To examine definite size perception, we computed width and depth size ratios just as we had done in Experiment 3. To compute size ratios in depth, we divided differences in x for reaches to the front and back by actual distances between the targeted locations to the front and back, that is, 7 cm, 9 cm, and 11 cm for the near, medium, and far distances from the surface, respectively. (Each of these actual distances is the target diameter [5 cm] plus 2 times the targeted distance from the surface [1 cm, 2 cm, or 3 cm].) To compute size ratios in width, we did the same using y values for reaches to the left and right. We computed mean values across blocks for each participant. We performed a repeated measures ANOVA on the monocular viewing data using direction (depth or width), feedback, target distance, and distance from the surface as variables. Only direction was significant, $F(1, 4) = 7.6$, $p < .05$. The mean for depth (or x) was 1.48. The mean for width (or y) was 1.13. Size in depth was overestimated by 48%, whereas size in width was overestimated by only 13%.

Because of the difference in t test results for binocular viewing without and with feedback, we performed separate ANOVAs on binocular viewing data by feedback condition. No variables were significant in the ANOVA on the data from the no feedback condition. The mean x was 1.17, and the mean y was 1.16. The ANOVA in the feedback condition yielded a main effect for target distance, $F(1, 4) = 19.5$, $p < .02$, and a Direction × Target Distance interaction, $F(1, 4) = 9.2$, $p < .04$. For the near target, the x mean was 1.10 and the y mean was 1.13. For the far target, the x mean was 1.30 and the y mean was 1.17. Thus, without feedback, both width and depth were overestimated by only 16%, and with feedback, the results were essentially the same at the near target. But at the far target, whereas the width was still 17%, the distance in depth was overestimated by 30%, nearly as much as with monocular viewing.

Discussion

In this experiment, we once again tested the possibility that visual distortions of egocentric distance and shape would appear in visually guided reaching. When participants reached with vision but without haptic feedback, distortions similar to those found in psychophysical studies appeared in reaches, but primarily with monocular vision. Egocentric distances were overreached by about 6% of the target distance when monocular vision was used but

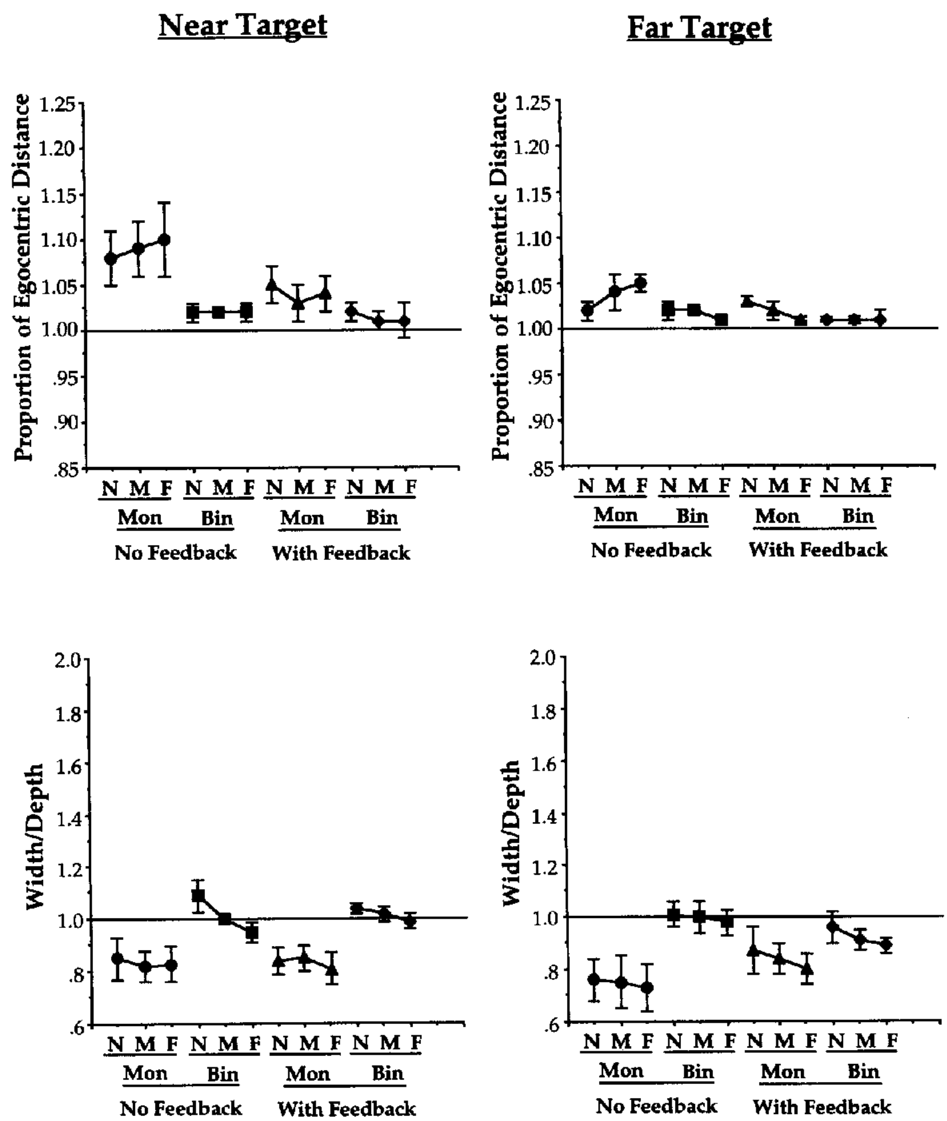

Figure 12. Data from Experiment 4: reaches performed with continuous vision. Mean egocentric ratios (with standard error bars; top) and mean width/depth aspect ratios (with standard error bars; bottom) plotted by target distance (near or far), viewing (monocular [Mon] or binocular [Bin]), feedback (no feedback or feedback), and distance from the target surface (near [N], medium [M], or far [F]). Monocular no feedback: circles; binocular no feedback: squares; monocular with feedback: triangles; binocular with feedback: diamonds.

Table 11
One-Tailed One-Sample t Tests of Difference From 1 of Egocentric Ratios by Viewing Condition and Target Distance, Without Haptic Feedback: Experiment 4

Target	Monocular	Binocular
Near		
$t(14)$	5.5	4.4
p	<.001	<.001
M	1.09	1.02
Far		
$t(14)$	5.3	5.6
p	<.001	<.001
M	1.04	1.02

only 2% when binocular vision was used. Egocentric distances became more accurate with haptic feedback, although targets were still overreached by about 3% when monocular vision was used. More to the point, monocular vision yielded strong and consistent expansion of shape in depth. This distortion was not altered by haptic feedback. The aspect ratios reflected a 20% expansion in depth at all distances from the target surface, at both target distances and in both feedback conditions. This corresponded to an average overestimation of size in depth of 48% (or 4.3 cm) versus 13% (or 1.2 cm) in width. These results disconfirm our hypothesis about the potential interaction of visual and haptic distortions in visually guided reaching with haptic feedback. Haptic and visual distortions of shape did not cancel. Haptic feedback did not calibrate reaching performed with monocular vision so as to eliminate shape distortions, although distortions of egocentric distance were reduced by half.[8]

Performance with binocular vision was different from that with monocular vision. No shape distortions were found in reaches performed without haptic feedback. Aspect ratios were not different from 1, and sizes were overestimated by only 16% (or 1.4 cm) in both depth and width. Also, the egocentric distances of reaches were accurate and precise. Targets were overreached by only 2% of their distance, and this performance was highly consistent. This task, however, would allow participants to use the relative disparities of the target and stylus to position the reach in the depth dimension, which would produce the observed accuracy and precision of egocentric distances. This alone, however, cannot explain the accuracy of perceived shape as reflected in the reaches. First, the relative amount of disparity of target surface and stylus would have to be scaled appropriately to the required distances from the surface (that is, 1, 2, or 3 cm). Second, disparity could not be used to determine the positioning to the sides of the target and so could not be used to equate distances to the side and in depth. Our finding of accuracy in perceived shape using binocular vision is not consistent with the results of psychophysical studies. On the other hand, it is reassuring to see accurate performance under conditions representative of normally good vision.

The results for binocular vision with feedback suggest that haptic shape perception may play a role after all. Haptic shape perception studies have shown that shape is perceived accurately near the body but with a 30% expansion in depth as maximum reach distance is approached. Binocular vision shape results remained accurate with haptic feedback at the near target; at the far target, however, shape was expanded in depth by about 10%. The size in depth was overestimated by 30% (or 2.7 cm) as compared with width, at 16% (or 1.4 cm). This distortion is about a half of what would be expected from haptics alone and appears to split the difference between accurate binocular performance (without haptic feedback) and the expected haptic distortion.

Finally, the results of this experiment seem to reflect visual and haptic distortions directly rather than inversely, as do PSE results. We infer that participants were simply positioning the stylus according to the perceived relation to the target surface. In contrast, the participants in Experiments 1 and 3 seem to have been trying to produce a circular pattern in the locations to which they reached, with the result that they produced distortions characteristic of a haptic PSE.

Table 12
One-Tailed One-Sample t Tests of Difference From 1 of Egocentric Ratios by Viewing Condition and Target Distance, With Haptic Feedback: Experiment 4

Target	Monocular	Binocular
Near		
t(14)	3.2	1.8
p	<.01	<.005
M	1.04	1.01
Far		
t(14)	5.8	5.2
p	<.001	<.01
M	1.02	1.01

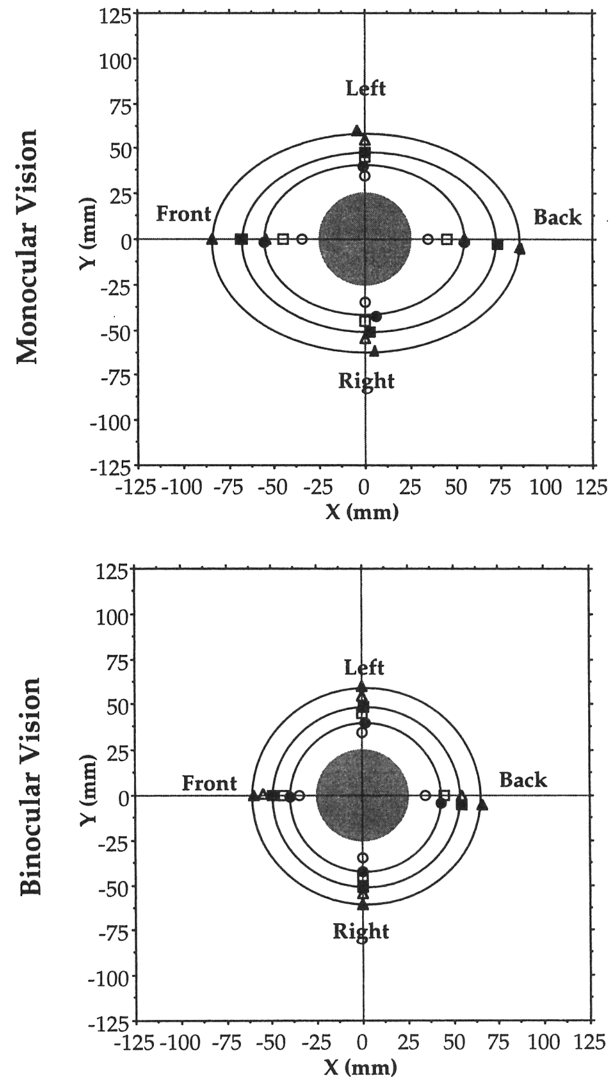

Figure 13. Constant error results of Experiment 4 illustrated by data from the monocular (top) and binocular (bottom) viewing conditions at the far target distance. Open symbols: targeted locations relative to the surface of the target sphere. Filled symbols: centroids of the distribution of reaches to each targeted location. The shaded circle represents the target sphere. See text for additional details.

Experiment 5

The PSE pattern of results in Experiment 1 might have been produced by the feedforward nature of the reaching task. The need to depend on a memory, even if for only 1 or 2 s, may have generated the "reach to produce a circle" pattern of performance. Alternatively, this might have been produced by the rather abstract

[8] We did not test the potential interaction of vision and haptics when used simultaneously; that is, our participants did not watch themselves move to touch the target and then move away to position the stylus. We did not investigate this task because our goal and intent were to study visually guided reaching, and the task is not representative of the use of vision and haptics in the guidance of reaching.

nature of the task. In Experiment 1, participants were required to reach blindly to a location at a distance from a visually perceived surface. Particularly if this is not representative of the way reaches are normally organized and performed, this production task may have induced participants to reach to produce a circle. In contrast, if participants were required only to reach to contact a visually perceived surface, then they might simply reach to a visually determined location, with the result that performance reflects visual apprehension of surface shape directly. In Experiment 5, we tested whether the feedforward or the production aspect of the task in Experiment 1 might have been responsible for the PSE pattern of results by asking participants simply to reach to locations on the target surface.

Also, we found that the distortion in Experiment 1 diminished with increasing distance from the target surface. We found in Experiment 3 that this result was haptic and a function of the effective size of the shape described by the reach locations. If reaching directly to a visually perceived surface is less abstract and allows more direct use of visual information, then we might find that this task yields the expected visual distortions at all sizes. Conversely, if the feedforward nature of the task in Experiment 1 was responsible for the results, then we should obtain the same result as in Experiment 1. We tested these possibilities in Experiment 5 by having participants reach to the surfaces of the three different spheres of increasing size. We tested reaches to the front, side, and back of the three spheres as in Experiment 1 but only at near egocentric distance viewed monocularly.[9]

Method

The method and participants were the same as in Experiment 1 with the following changes. Participants were now instructed to reach to locations on the surfaces of the target spheres, to the front, right, side, or back. Three different target spheres with diameters of 5 cm, 7 cm, and 12 cm were tested. Trials were blocked by target size, with the order of targets counterbalanced across participants. As in Experiment 1, the target was removed at reach initiation. Targets were tested only at the near target distance (.5 maximum reach) and only with monocular vision.

Results

First, we evaluated egocentric distance by computing the mean egocentric ratios for each participant and target using the x-coordinate of reaches to the front and back with the origin of the coordinate system at the resting position of the eye and dividing

Table 13
One-Tailed One-Sample t Tests of Difference From 1 of Width/Depth Ratios by Viewing Condition and Target Distance, Without Haptic Feedback: Experiment 4

Target	Monocular	Binocular
Near		
$t(14)$	−4.6	0.5
p	<.001	*ns*
M	0.83	1.01
Far		
$t(14)$	−5.1	−0.2
p	<.001	*ns*
M	0.75	0.99

Table 14
One-Tailed One-Sample t Tests of Difference From 1 of Width/Depth Ratios by Viewing Condition and Target Distance, With Haptic Feedback: Experiment 4

Target	Monocular	Binocular
Near		
$t(14)$	−6.1	1.2
p	<.001	*ns*
M	0.83	1.02
Far		
$t(14)$	−4.3	−3.3
p	<.001	<.01
M	0.84	0.92

the mean x by actual target distance. We performed a repeated measures ANOVA on these means using target size as a variable. Target size was significant, $F(2, 6) = 7.7, p < .03$. As shown in Figure 14 (left panel), the means were ordered by target size. Smaller targets were perceived at greater egocentric distance than larger targets. This pattern is consistent with an image size effect found in previous studies (Epstein, 1961; Gogel, 1977). We performed a one-tailed one-sample t test testing difference from 1. The result was not significant, $t(11) = 0.6, p > .2$, and the mean was 1.02. To compare the results of Experiments 1 and 5, we performed separate ANOVAs for each participant comparing egocentric distance ratios for reaches to the sides of the targets using the data for the monocular near target of Experiment 1. The results were significant at $p < .001$ in all four cases, $Fs(1, 58) = 93.5$, 54.5, 13.6, and 56.4 for Participants 1–4, respectively. In all cases, the mean ratios were smaller in Experiment 5 than in Experiment 1. The overall mean in Experiment 5 was 0.99, as compared with 1.12 in Experiment 1.

Nevertheless, when we performed a stability analysis on x-coordinates for reaches to the side of the target in Experiment 5, we found significant drift away from the participant, $F(1, 118) = 6.1, p < .02, r^2 = .05$, at a rate of 0.40 mm per trial. This rate of drift was comparable to that in Experiment 1, but in this case, trials were blocked by target size, so the total drift over the block of 30 trials was only 1.2 cm. This may have contributed to the greater accuracy of mean egocentric distances in Experiment 5.

Next, we evaluated shape perception by performing the same analyses as in Experiment 1. As before, we first centered the distributions for each participant and target on an origin at the center of the target by removing the mean egocentric x and y errors in each case. We combined the data for the three targets. Actual distances for this analysis were the radii of the target spheres. We computed size ratios by dividing reach distances by actual distances from the centers of the spheres.

First, we compared x size ratios for reaches to the front and back. We computed mean ratios for each participant, target size, and direction and performed a repeated measures ANOVA with target size and direction as variables. Neither of the variables nor the interaction reached significance ($p > .4$ in all cases). There was no difference between front and back or between target sizes.

[9] This experiment was performed before we had developed the revised design of Experiments 3 and 4.

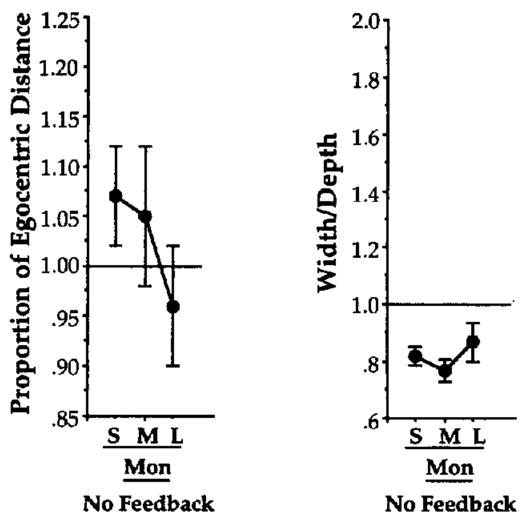

Figure 14. Data from Experiment 5: feedforward reaches to locations on the surface of a target sphere performed with monocular (Mon) vision and no haptic feedback. Values are mean egocentric ratios (with standard error bars; left panel) and mean width/depth aspect ratios (with standard error bars; right panel) plotted by target size (small [S], medium [M], or large [L]).

The overall mean ratio was 0.96. The surfaces were located accurately on average. Reaches to the small object (at 2.50 cm) were at 2.40 cm on average, whereas reaches to the medium object (at 3.50 cm) were at 3.36 cm, and reaches to the large object (at 6.00 cm) were at 5.76 cm.

We performed the same analysis comparing x distances to the front and y distances to the side. In this case, only direction was significant, $F(1, 3) = 26.8$, $p < .02$. The mean ratio to the side was 0.80. Surface locations to the side were underestimated or compressed. The mean reach distances to the side (2.0 cm, 2.8 cm, and 4.8 cm, respectively) were all inside the surfaces of the three objects.

We next computed width to depth aspect ratios for each participant and each sphere and then performed a one-tailed one-sample t test to test difference from 1. The result was significant, $t(11) = -6.5$, $p < .001$, and the mean ratio was 0.82. The mean width to depth ratios are plotted for each of the three spheres in Figure 14 (right panel). The results were comparable to the results of Experiment 4 for monocular vision of a near target (without or with haptic feedback), as shown in the bottom left panel of Figure 12. Unlike Experiments 1 and 3 and like Experiment 4, we found expansion in depth by about 20% equally for all three sizes, as illustrated in Figure 15.

Finally, we examined the x and y standard deviations for each sphere, direction, and participant, performing a repeated measures ANOVA with coordinate, direction, and target size as variables. As in Experiment 1, coordinate was significant, $F(1, 3) = 37.4$, $p < .01$. The standard deviation in x (1.32 cm) was greater than that in y (0.84 cm). Target size also was significant, $F(2, 6) = 10.2$, $p < .02$. The variability was greater for the large target (1.17 cm) than for the small target (0.93 cm). We also tested the combined standard deviation data from Experiments 1 and 5 for the monocularly viewed near target. The difference in task was marginally significant, $F(1, 3) = 7.9$, $p < .06$, and the overall means were 1.44 cm for reaches to a distance from a surface (Experiment 1) and 1.08 cm for reaches to a surface (Experiment 5). The variability was less when participants were simply reaching to the location of a surface.

Discussion

We tested first whether reaching to locations on a surface would yield visual shape distortions directly rather than the haptic PSE pattern obtained in Experiment 1. This is exactly what happened. Shape was expanded in depth by about 20%, just as we had found with monocular viewing in Experiment 4. Furthermore, we found exactly the same distortion for all three target sizes, unlike the results in Experiments 1 and 3 and like the results in Experiment 4. The results indicate that the findings of Experiment 1 should be attributed to the abstract nature of the task, namely, blind reaching to a location in space at a distance from the target surface. This and not merely the feedforward nature of the task apparently produced the tendency to reach so as to produce a circular pattern. In contrast, participants in Experiment 5 apparently used visual information to relate their reaching directly to the target surface.

Finally, we found that the precision was greater in Experiment 5 than it had been in Experiment 1, in which performance was about half again as variable. This result suggests that reaching directly to a location on a visually perceived surface is more representative of normal reaching and that people do not normally aim for a point shy of a surface; rather, they aim for the surface itself.

General Discussion

We set out to discover whether distortions of egocentric distance and shape found in psychophysical studies would be reproduced in reaches performed under visual guidance. We designed a reaching task on the basis of analyses in the motor literature. The initial and largest portion of a reach is typically described as performed under feedforward control. According to this understanding, the reach is organized before it takes place by using the available visual and

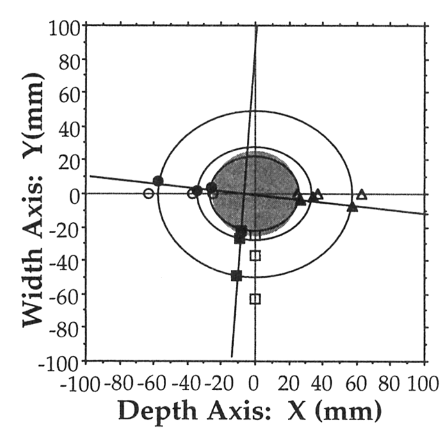

Figure 15. Constant error results of Experiment 5. Open symbols: targeted locations on the surfaces of the target spheres of different size. Filled symbols: centroids of the distribution of reaches to each targeted location. The shaded circle represents the small target sphere. Circles: front; squares: side; triangles: back. See text for additional details.

kinesthetic information about the locations of both the target and the hand. The reach is targeted to place the hand in close proximity to a target to be grasped. Subsequently, feedback control of the movement may be used to close the remaining gap and acquire the target. Whether the hand is actually aimed at a location some distance from the target surface or instead directly at the target has not been established. However, the former is often suggested for safety and stability in the face of inevitable inaccuracy and imprecision of the motor system. Given the errors found in studies of visual space perception, this might be especially advisable.

Thus, we used a feedforward reaching task and asked participants to target reaches to locations at short distances in different directions from a target surface. We gave seated participants every opportunity to obtain good visual information about the target. Before reaching, they viewed the target, looking at the location to which they would reach, while they moved their heads through a large but comfortable amplitude (approximately 10 cm) to obtain good perspective structure-from-motion information. Information from accommodation and stable object size (and, therefore, texture and image size) was also available. Finally, when the target was viewed binocularly, information from stereo could be used, namely, dynamic disparity and convergence. Immediately after looking, participants performed a reach. In Experiment 1, participants performed a series of blind reaches without actually ever contacting the target. Our first expectation was that reaching might be more or less permanently precalibrated to eliminate the visual distortions found in previous studies. If so, then reaching performance would be distortion free. This expectation was not met.

Consistent with previous findings, egocentric distances were overreached. Worse than this, egocentric distances of reaches were unstable and drifted away in depth over trials at a steady rate. With binocular vision, the rate was half as fast as with monocular vision, but there still was drift. Vindras and Viviani (1998) have also recently found instability in targeted reaching. In their experiment, participants reached rapidly to briefly lighted spots in darkness and received no feedback. The endpoint of the reaches drifted over trials away from the participant. The mean rate of drift was nearly three times that found in the current study. They found no drift in the direction of the reaches. We also found no drift in the y or frontoparallel direction.

Given the previous finding of visual expansion of egocentric distances, we surmised that this drift might be visually driven. We investigated in Experiment 3 whether backward drift would be observed without the use of vision, that is, when participants used only haptic–kinesthetic perception to guide their reaches.[10] We found in that case that egocentric distances tended to drift inward toward the participant, that is, the opposite of the previous result. We also found that reaches underestimated the egocentric distance or were accurate in Experiment 3, whereas all targets were overestimated in Experiment 1. We concluded accordingly that vision did drive egocentric distances outward in Experiment 1.

Although the shape reflected in the reaches was distorted in Experiment 1, the pattern was not the same as that found in the previous psychophysical studies. The circular shape of the target was compressed in depth, but less so with increasing distance from the target surface. Also, the result was the same at both target distances with either monocular or binocular vision. None of this was consistent with previous visual results except for a finding that the PSE for a circular cross section was compressed in depth. We investigated in Experiment 3 whether these results might be haptic rather than visual in origin. We found indeed that the entire pattern of shape results was replicated in a strictly haptic task. This indicated that perception of egocentric distance and of shape can be dissociated. In Experiment 1, the former was driven and determined by vision, whereas the latter was determined by haptics–kinesthesis.

The fact that the shape perception results in Experiment 1 did not exhibit visual effects was troubling. After all, it is generally assumed that binocular vision is organized in humans to facilitate good reaching performance. Although egocentric distance error and instability were reduced by half with binocular as opposed to monocular vision, one might still expect significant benefits in shape perception. In Experiment 4, we tested vision in a task in which it should play a stronger role. Participants continued to look while they performed each reach. The results were gratifying and reassuring. Performance with binocular vision (and without haptic feedback) was both accurate and precise. Performance with monocular vision, on the other hand, exhibited just the distortion found in the psychophysical literature. Although the accurate binocular performance in respect to egocentric distances might be attributed to disparity matching, the accuracy in shape perception could not be. The results suggest that reaches guided by binocular vision are calibrated to eliminate visual distortions. Because our participants are normally binocular, we would not expect their reaching to be calibrated for monocular vision.

We next considered whether the character of the shape perception results of Experiment 1 should be attributed to the feedforward nature of the reaching task or, instead, to the abstract and potentially unrepresentative nature of the task of aiming for a locus in empty space rather than a locus on a visually perceived surface. In Experiment 5, we tested this using a task in which participants reached to locations on a target surface. The results were comparable to those in Experiment 4. The characteristic shape distortion for monocular vision was obtained for targets of the same three sizes tested in Experiment 3. Also, the precision of the reaches was greatly improved over that found in Experiment 1. The results indicated that the task in Experiment 1 was unrepresentative of normal reaching and that the haptic PSE pattern of the results could be attributed to the abstractness of that task.

Role of Haptic Feedback

As we began our investigation, we considered the possibility that reaches might indeed exhibit the visual distortions found in

[10] *Haptics* is usually used to refer to the perception of surfaces using somatosensation (that is, including the muscle sense, cutaneous sense, and perhaps the vestibular system). *Kinesthesis* is used to refer to the somatosensory perception of positions and orientations of the limbs relative to one another and the body. Consider which is being used if one reaches blindly to a wall and then halfway to the wall or if one reaches blindly to feel a ring and then reaches to place one's hand through the ring. The point is that the second act in each case is not only performed relative to other parts of the body but performed relative to the surfaces of the wall or ring; therefore, the act is a haptic one. One might invoke memory because the acts are distributed over time, but the act of feeling the surface of an object to perceive its shape is also distributed over time, and this does not make it less haptic. The act of haptic perception requires temporally distributed structure and actions.

previous psychophysical investigations. We hypothesized that the haptic feedback normally available through contact with targets might be used to correct those distortions. The problem was that haptic shape perception was itself known to be subject to distortions. We suggested accordingly that the two visual and haptic distortions, when allowed to interact, might cancel when equal. That is, the targeted distance might be seen as expanded by half, but when that same distance was felt, it would also be felt to be expanded by half, with the result that the targeted distance would be accurately produced. This would occur when monocular and haptic distortions are combined at the distances of our far targets. A lack of haptic distortion at near targets would yield, by hypothesis, no correction. That is, participants would see a certain distance and then simply feel themselves producing it. The seen distance might or might not be different from the actual targeted distance. We tested this in two different experiments.

In Experiment 4, participants looked while they reached and while they subsequently received haptic feedback by touching the target. We predicted that performance should be the same without or with haptic feedback at the near target, and indeed it was. Binocular performance remained accurate, and the shape produced by reaching with monocular viewing remained distorted, that is, expanded in depth. We predicted that distortion produced with monocular vision at the far target should be eliminated with haptic feedback. This did not occur. The approximately 20% expansion in depth remained. Our thesis would have predicted about a 20% compression in depth with binocular viewing because binocular vision had yielded accurate performance without haptic feedback. Instead, binocular performance changed significantly in the opposite direction. Shape was expanded in depth by about 10%. If it were not for this latter result, one might conclude that concurrent vision simply overpowered any effect of haptic feedback. Indeed, concurrent vision reduced the corrective effect of haptic feedback on the egocentric distances of reaches. The amount of overestimation without haptic feedback was reduced only by half with haptic feedback. We also investigated the effect of haptic feedback in Experiment 2, in which participants performed blind reaches; in that case, the overestimation was entirely eliminated. Thus, we conclude that visual distortions are more robust with concurrent vision. In respect to shape perception, the only effect of haptic feedback in Experiment 4 was not corrective, as we predicted in the circumstance, but the distortion occurred in a direction opposite to our prediction. The haptic distortion was exhibited directly in the results but to an extent that was presumably reduced by accurate binocular vision.

We investigated the effect of haptic feedback on feedforward reaching in Experiment 2. The feedback eliminated both drift and overreaching of egocentric distances. The feedback also altered the shape results, which no longer exhibited the haptic PSE pattern found in Experiments 1 and 3. Instead, the results were similar to those in Experiments 4 and 5 (compare the bottom panels of Figure 3 [blind reaching with feedback] with the bottom panels of Figure 12 [reaching with vision without and with haptic feedback] and with the bottom panel of Figure 14 [blind reaching to the target surface without feedback]). In all cases, expansion in depth was exhibited for monocular vision and consistently so at all distances from the target surface. This was not statistically significant at the far target with feedback in Experiment 2, but the trend is evident in Figure 3 (bottom right) and in the mean aspect ratio (0.92). As in Experiment 4, in Experiment 2 no distortion was exhibited with binocular vision at the far target, although a small amount of distortion was found for the near target. In view of the results of Experiments 4 and 5, haptic feedback in the context of the feedforward reaching of Experiment 2 seems to have allowed vision to influence the shape results. That is, it seems to have made the task less abstract. This conclusion is also supported by the change in the pattern of random errors between Experiments 1 and 2. In Experiment 2, the patterns of random error reflected the functional demands of the task; that is, the errors varied relative to the target. This did not occur in Experiment 1. We cannot conclude that the results of Experiment 2 support our hypothesis about the role of haptic feedback. Haptic and visual distortions do not appear to cancel, although haptic feedback does eliminate or reduce egocentric errors and instability. In the case of feedforward reaching, haptic feedback appears to allow the more direct use of visual information about the shape of the target.

Role of Dynamic Binocular Vision

We found that binocular vision yields more accurate performance. In feedforward reaching, egocentric errors and drift were half as large with binocular vision as with monocular vision. In reaching with concurrent vision, both egocentric errors and shape distortions were near zero with binocular vision. Disparity matching might account for the accuracy of egocentric distances but not for the accuracy of shape perception. Why might our results for binocular vision be different from those of previous studies? The difference might be attributed to the representative nature of the binocular vision in the current study. Our participants used normal binocular vision, that is, dynamic binocular vision with optic flow generated by voluntary self-motion. Previous studies decoupled stereo from optic flow generated by voluntary head movement. Bingham and Pagano (1998) also found accurate reaching performance with dynamic binocular vision. These combined results suggest that the informational support for normally accurate reaching performance may reside in dynamic binocular vision, a form of vision that remains to be studied in detail.

Separate Channels Versus Different Tasks

We close with some observations concerning the notion of separate visual channels. Different results have been obtained in distance perception studies using judgment versus action measures. Action measures have often yielded more accurate or distortion-free performance. This, together with evidence from studies involving brain-lesioned patients, has been used to support the hypothesis that there are neurologically separate channels for perception of a sort used to make judgments as opposed to perception of a sort used to guide action (Goodale et al., 1996; Goodale, Meenan, et al., 1994; Goodale & Milner, 1992; Milner & Goodale, 1995). However, as demonstrated by the current results, action measures do not always yield accurate or distortion-free performance. Studies using reaching measures to evaluate monocular egocentric distance perception have consistently revealed distortion of distance (Bingham & Pagano, 1998; Pagano & Bingham, 1998; Wickelgren et al., 1997, in press). Distortions have been found in reaches with both reduced and nonreduced monocular viewing. Philbeck and Loomis (1997, 1998) found distortion of egocentric distances when participants viewed targets in reduced viewing conditions and then walked blindly to them along various routes.

Bingham and Pagano (1998) argued that the specific nature of the tasks, the nature of the available visual information about distance, and the presence or absence and form of feedback information available for calibration are the more likely determinants of the observed variations in performance. Philbeck and Loomis found that walkers undershot targets viewed in isolation in the dark. As we did in the current experiments, Bingham and Pagano (1998), Pagano and Bingham (1998), and Wickelgren et al. (1997, in press) found that haptic feedback improved performance in reaching to egocentric targets with monocular vision, but it did not eliminate distortions. Distortions were absent when distances were viewed with dynamic binocular vision. Thus, the nature of the information is important, as is the presence or absence of feedback.

On the other hand, Pagano and Bingham (1998) did find a dissociation between verbal and reaching performance. There was no correlation between the errors in the two cases. Nevertheless, it was apparent that haptic feedback was used to different effect, yielding distinct systematic errors in the two cases. The task in reaching was to avoid hitting the targets during the reach, and the persistent reaching errors reflected this; that is, the targets were underreached. The verbal performance reflected the ability to fit numbers to a presumed range of values. The tasks in the two cases were fundamentally different. Bingham and Pagano (1998) also found that the imprecision of verbal judgments was more than double that of reaching. This was also found by Foley (1977). In view of this, Bingham and Pagano noted that the skill levels are bound to be different for verbal judgment and reaching given profound differences in the amounts of practice in everyday experience.

Judgments can be expressed through actions. For instance, a grasp can be configured without contacting an object to express a judgment of the object's size or shape. Goodale, Jakobson, and Keillor (1994) studied pantomimed reaches to grasp target objects in comparison with actual reaches to grasp and found differences in kinematics. The differences were present when the actions in both cases were performed blindly after looking. Goodale et al. attributed the differences to different channels, but they failed to notice that pantomimed reaches eliminated haptic feedback from contact with the objects. We can infer from the current results that this destabilized perception of egocentric distance and altered the perception of shape, and thus it must have changed the performance of reaches and grasps.

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