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The Necessity of a Perception–Action Approach to Definite Distance Perception: Monocular Distance Perception to Guide Reaching

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In this investigation of monocular perception of egocentric distance, the authors advocate the necessity of a perception–action approach because calibration is intrinsic to definite distance perception. A helmet-mounted camera and display were used to isolate optic flow generated by participants' head movements toward a target, and participants' reaches to place a stylus either in a target hole (Experiments 1, 2, and 4) or aligned under a target surface (Experiment 3) were analyzed. Conclusions are that binocular distance perception is accurate, monocular distance perception yields compression that is not eliminated by feedback, but feedback is used to eliminate underestimation generated by restriction of the size of the visual field.

The study of definite distance perception requires a perception–action approach. As we argue, the reason is twofold. First, definite distance perception entails calibration and, therefore, a task-specific action that provides both feedback and a standard of accuracy. Calibration is complete once measurements are within a task-specific tolerance. The tolerance is determined by error variability and task requirements, and error variability is a function of both perceptual and action capabilities. Because calibration cannot be assumed to eliminate all error, task-specific actions that provide feedback must be explicitly included in any evaluation of definite distance perception.

Second, perception is a complex but coherent and functionally effective system that we can investigate only through perturbation. To be able to evaluate the effects of specific perturbations, one must compare perturbed performance with normal, unperturbed performance, and perturbations should not be confounded with one another. Visual perception necessarily entails both postural control and voluntary motor behavior. This is true because the head and eyes must be supported and moved about to sample the surrounding optical structure and because perception is expressed only through actions. The effect of a perturbation of visual information should be evaluated independently of other perturbations to motor behavior and accompanying somatosensation. Also, in the case of definite distance perception, perturbation of visual information should be evaluated in the context of the recalibrating, or stability-inducing, effect of feedback. Removal of the ability to calibrate is likely to destabilize the system and render the effects of other perceptual perturbations difficult to resolve. Because of this and because calibration tolerance is task specific, task-specific actions and associated feedback are intrinsic to definite distance perception and should be included in its study. We pursue this approach in a study of monocular distance perception and visually guided reaching.

Monocular Vision as a Perturbation of Visual Functioning

We investigated two questions that entailed different perturbations of vision. The first question was whether forward head motion enables a monocular observer to perceive the distance of a target surface well enough to guide a reach effectively. We perturbed vision by having participants wear a patch over one eye. The second question was whether monocular optic flow generated by voluntary head movement toward a target enables effective distance perception and reaching. Additional perturbations were required in this case.

Beyond its relevance to perceptual theory, the study of monocular information about egocentric distance is important because a large proportion of the general population is effectively monocular. A reasonable estimate of this proportion is 15–20%, including those with anisometropia, amblyopia, and strabismus as well as one-eyed individuals (Borish, 1970; Faye, 1984). Marotta, Perrot, Nicolle, Servos, and Goodale (1995) found that monocular observers spontaneously learn to make head movements before reaching. Presumably, these head movements are made to generate optic flow. Participants were found to make both forward head movements (i.e., toward and away from a target) and

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lateral head movements (i.e., perpendicular to the direction of a target). No clear preference for a particular direction of head movement was found. It is unknown whether one direction of head movement should be preferred over the other. As shown in Figure 1, lateral head movement generates motion parallax, whereas forward head movement generates radial flow. Motion parallax, generated by voluntary head movement, has been studied extensively and is known to provide information about definite egocentric distance[1] (Eriksson, 1974; Ferris, 1972; Foley, 1977, 1978; Foley & Held, 1972; Gogel & Tietz, 1973, 1979; Johansson, 1973; Rogers, 1993). Radial outflow generated by voluntary head movement toward a target also could provide egocentric distance information, as shown by Bingham and Stassen (1994). However, the use of distance information generated by forward head movement remains to be investigated.

Because a person's head typically moves toward a target during a reach, using forward head movement to generate information to guide the reach would be both more convenient and more natural. For instance, a seated actor will often lean forward toward an object while executing a reach to grasp it. In fact, such postural adjustments are accomplished by rotation about the base of the spine or the neck, so the resulting forward head motion entails both a vertical component that would generate parallax and a forward component that would generate radial outflow. Because forward movements generate both forms of information, they might well allow effective perception of distance. We investigated whether forward head movement provides monocular information about egocentric distance that can be used to guide reaches accurately.

Monocular vision normally includes other potential sources of distance information, including ocular parallax,[2] accommodation, and texture and luminance gradients. Our second question required isolation of optic flow generated by voluntary head movement, that is, removal of the remaining sources of visual information and thus a perturbation of monocular vision. Unfortunately, our method entailed an additional perturbation, one that might affect normal detection of optic flow. To eliminate optical structure projected from the target (including the target hole) and other surrounding surfaces and to eliminate accommodation and ocular parallax, we used a head-mounted video camera and display adjusted to produce patch-light viewing (Runeson & Frykholm, 1981). The problem was that the head-mounted display also restricted the size of the visual field to about 40°. This restriction is characteristic of computer- or video-generated displays used in vision research. We assessed its perturbing effect by having participants perform in a control condition. In this condition, they viewed the target monocularly through a head-mounted tube that restricted the visual field to 40° but did not otherwise perturb monocular vision. Previous studies suggested that a restriction of visual field size produces underestimation of distance (Bingham, 1993c; Dolezal, 1982).

As recently reviewed by Todd, Tittle, and Norman (1995), studies of monocular distance perception have revealed regular distortions in perceived distances. (See also, e.g., Baird & Biersdorf, 1967; Durgin, Proffitt, Olson, & Reinke, 1995; Gilinsky, 1951; Tittle, Todd, Perotti, & Norman, 1995; Todd & Bressan, 1990; Todd & Norman, 1991). The most common result has been that distances are systematically underestimated on the basis of monocular optical flow. When estimates are plotted against actual distances, the slope of the judgment curve is significantly less than 1, as shown in Figure 2. Different distortions have been found when estimates are based on static binocular information (e.g., Johnston, 1991). In this case, near distances tend to be overestimated and far distances underestimated. That is, as shown in Figure 2, the slope of the judgment curve is again significantly less than 1, but the curve is above a line of slope 1 and intercept 0 in near space, crosses the line at about maximum reach distance, and then extends below the line in far space. The same result has been obtained when stereopsis has been combined with optic flow. This result is especially odd because it implies that when normally sighted individuals reach for objects in near space, they should be ramming into them. However, none of these studies used reaching measures (with feedback), so the implications for visually guided reaching remain unclear.

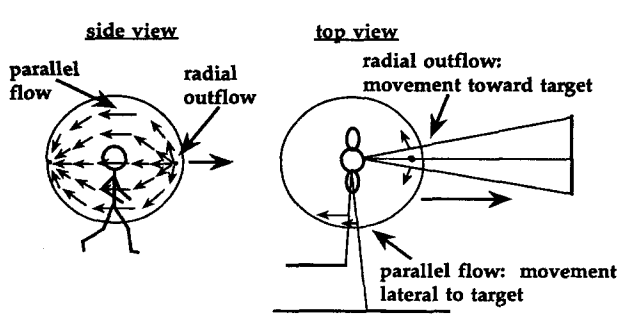

Figure 1. Optic flow generated by translation of the point of observation through rigid surroundings. In a side view, flow vectors are shown on a sphere centered about the point of observation. Radial outflow moves outward from a nodal point on the sphere in the direction of translation. Parallel flow appears in directions perpendicular to the direction of translation. Thus, as shown in a top view, lateral movement with respect to surfaces in the surround produces parallel flow. The size of the flow vectors is inversely proportional to distance. This produces motion parallax. Although motion parallax is also generated in the radial flow around the direction of heading, it has typically been studied in parallel flows lateral to the direction of heading.

[1] *Definite* means that the metric value of a distance is determined within measurement error. In contrast, *relative* means that only a ratio of a pair of distances is determined and that the metric value of any one distance in the pair is not known. See Bingham (1993c) for a discussion of the use of *definite* versus *absolute*.

[2] Eye movement generates small-amplitude (≈8 mm) translation of the point of observation and thus motion parallax. This has been shown to enable observers to distinguish separation of surfaces in depth (Bingham, 1993a, 1993b) and reveals the extreme sensitivity of human observers to depth information in optic flow. Observers have not been shown to be able to apprehend definite distances via ocular parallax.

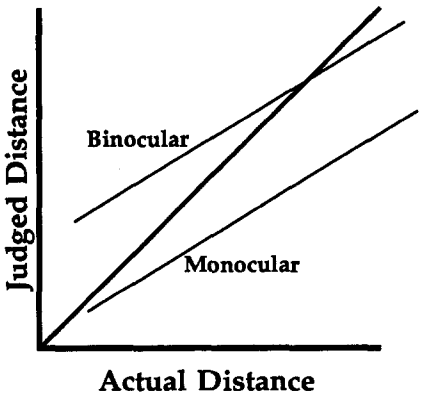

Figure 2. Illustration of characteristic results of egocentric distance perception studies using either monocular optical flow or static stereopsis.

Perception–Action Systems and the Problem of Response Measures

A number of different response measures have been used to evaluate the perception of distance. They include matching, verbal judgment, and pointing. Although widely used, matching is inappropriate for the study of definite distance perception because it measures only relative distance perception. Accordingly, the source of errors in matching is ambiguous. For instance, consider a paradigm in which distance intervals at a large distance in front of the observer are matched to nearby distance intervals to the side of the observer (e.g., Loomis, DaSilva, Fujita, & Fukusima, 1992; Wagner, 1985). This would allow evaluation of the perceived distances of intervals far away and in front only relative to those nearby and to the side, as shown by the fact that errors could not be attributed uniquely to estimates in one direction over the other. The definite length of an interval would necessarily remain unspecified. A paradigm in which the distance of a target viewed monocularly is matched to that of a target viewed binocularly would be similar (e.g., Johansson, 1973; Rogers & Graham, 1979). Judgment errors could not be attributed uniquely to either monocular or binocular vision, and again, only the perception of relative distances could be evaluated, that is, monocular relative to binocular. Ultimately, both paradigms are comparable to one in which a target viewed via motion parallax is matched to another target viewed via motion parallax. The relative amounts of parallax might be equated, but clearly no inference about the perception of definite distance would be warranted. This is especially so because motion parallax by itself is known not to provide information about definite distances. Although in the case of binocular vision, for instance, convergence has been shown in theory to provide information about definite distance (scaled by the stable distance between the eyes), the point of an experiment would be to establish this empirically. Matching cannot do so.

More suitable for the evaluation of definite distance perception are verbal magnitude estimates and targeted actions. The problem, as both Foley (1978) and Gogel (1968, 1969) noted, is that different measures have yielded different results. Foley (1977, 1978, 1985) obtained different results when egocentric distance estimates were expressed through both verbal judgments and pointing. He suggested that the problem could be averted if the two sets of estimates could be made coincident by means of a linear transform, with the implication that the differences in results would then be of no significance. There are two objections to this idea.

First, Foley applied this to constant errors but, at the same time, reported that there were differences in the distributions of variable errors. The variability of verbal estimates increased with distance, but not the variability of pointing. Similarly, Gogel and Tietz (1979) compared different measures and found that error distributions for verbal estimates were skewed, unlike those for the other measure. These differences in distributions imply that a single linear transform cannot eliminate the differences in estimates.

Second, the purpose of distance perception is not explicitly addressed in this approach. Determining the functional repercussions of these differences is paramount to an evaluation of their significance. The preeminent purpose of egocentric distance perception is the ability to scale one's actions appropriately. The question must be, if verbal judgments overestimate egocentric distances, does this mean that an observer would slam his or her hand into the target if he or she were to reach for it? Indeed, not only are results different in different tasks, but some tasks have yielded reliably accurate distance estimates. This implies that the differences in results between tasks are significant and that we cannot generalize from one task to another, at least not without additional analysis.

Investigations of targeted walking have reliably yielded accurate distance estimates (Loomis et al., 1992; Rieser, Ashmead, Taylor, & Youngquist, 1990; Rieser, Pick, Ashmead, & Garing, 1995). Loomis et al. (1992) directly compared targeted walking and matching and found that the latter produced distortions in perceived distances but the former did not. These investigators suggested that the difference in results reflected differences in egocentric versus exocentric distance perception, respectively. Perhaps more to the point, however, the targeted walking and matching tasks involved definite versus relative distance estimation, respectively.[3] Nevertheless, verbal magnitude estimation of definite egocentric distance has also yielded distorted distance estimates, so the distortions cannot be attributed uniquely to either the exocentric or relative nature of judgments (Eriksson, 1974; Ferris, 1972; Foley, 1977, 1978; Foley & Held, 1972; Gogel & Tietz, 1973, 1979; Ono & Steinbach, 1990; Rogers, 1993). See Todd et al. (1995) for a review.

[3] The distinction between definite and relative distance should not be confused with that between egocentric and exocentric distance. Definite exocentric distance perception would be required, for instance, to size the preshape of a grasp. Relative distance perception is strictly insufficient for any (ballistic) targeted action.

The difference in results between targeted walking and magnitude estimation might be interpreted to suggest that action measures and explicit judgments reflect different perceptual systems. Goodale and Milner (1992), in fact, hypothesized that separate visual pathways exist for perception used to identify objects and perception used to guide actions. Although the suggested distinction is a bit unclear (because object recognition is relevant to the guidance of actions),[4] one possible interpretation is that one kind of perception can produce discrete verbal judgments, whereas another kind is continuously integrated with ongoing actions. The latter would entail continuous gearing of perception and action, whereas the former would allow discrete identification of object types, distances, orientations, locations, and the like. The extant distance perception results might be explained if perception used in (discrete) identification is error prone and perception used for (continuous) guidance of action is accurate.

The question is, why should discrete judgments be more inaccurate? A recent study of catching by Peper, Bootsma, Mestre, and Bakker (1994) revealed that errors in performance were introduced when the continuous gearing of perception and action was interrupted and participants were forced to make discrete anticipatory estimates of the distance at which a projectile would pass by them. However, if discrete judgments merely interrupt continuously geared perceptual processes, then only a single perceptual channel would be entailed. Adopting this hypothesis to account for judgment errors would obviate Goodale and Milner's (1992) two-channel hypothesis, but it would also entail the assumption that all discrete perceptual evaluations merely interrupt continuously geared perception. This assumption seems inappropriate for object or event recognition. It also implies incorrectly that ballistic targeted actions like throwing cannot be accurate. In fact, the accurate performance in the targeted walking studies was produced by blind walking. Vision was interrupted before targeted walking was begun. Thus, although the question remains for Goodale and Milner's two-channel hypothesis (i.e., Why should discrete judgments be error prone?), the question is moot. If we have interpreted Goodale and Milner's hypothesis correctly, then the hypothesis cannot be used to address the difference in results between targeted walking and other judgment measures because perception was not geared continuously to a targeted action in any of the tasks.

A more relevant hypothesis is that of Rieser et al. (1995). They suggested that a number of distinct perception–action systems exist, as shown by individuals' ability to recalibrate each system independently. Rieser et al. investigated both targeted walking and targeted throwing and showed that each action could be recalibrated without affecting the other. In their experiments, participants first performed targeted walking accurately by viewing targets and then walking to them without vision. Then participants walked on a treadmill while the treadmill was pulled on a cart around a parking lot. The cart was pulled at speeds faster or slower than the treadmill speed. In this way, participants were exposed to optic flows that were faster or slower than appropriate to their walking. When the participants subsequently performed the targeted walking task again, they under- or overshot the target distances. When participants were asked to throw beanbags to the targets, however, their performance was unaffected and remained accurate. Next, participants rode on the cart and threw beanbags to approaching or retreating targets until they could hit the targets reliably. Standing again on the ground, participants under- or overshot the targets with the beanbags, but targeted walking remained unaffected.

These results suggest that the distortions that have been found in egocentric distance perception studies are a function of the specific response measures. Poor performance should be expected when response measures entail unusual actions that are infrequently performed and thus poorly calibrated. This would be consistent with the results of Ferris (1972), for instance, who found that verbal judgments of egocentric distance initially underestimated actual distances but became accurate when observers were given feedback and allowed to calibrate their judgments.

Definite Distance Perception and Calibration

Calibration is essential to definite distance perception because the evaluation of a scaling constant is required to relate perceptual information to an expressed distance. Without some form of calibration, only a relative measure can be obtained because an arbitrary value for the scaling constant yields no information about definite distance. Visual perception of definite distance requires scaling constants for two reasons. First, optical measurements are angular. The visual perception of distance requires that optical measures (e.g., angular displacements or velocities) be scaled by some spatial unit. Second, a measure of definite distance must be expressed or exhibited in some unit that is particular to the means of expression.

For example, given a surface that projects an image into the optical pattern detected by an eye, a translation of the eye will generate an optical angular displacement, that is, a change in the image size, as shown in Figure 3. The change in image size scales to the distance of the surface as follows:

$$D_S = SD_A = AI_1/[I_2 - I_1], \quad (1)$$

where I_i are image sizes before (1) and after (2) eye translation, A is the amplitude of eye translation, D_A is distance in eye translation units, and S is a scalar that transforms D_A into the required distance measure, D_S. The S transformation is required because a measurement must be scaled in the units of expression.[5] The appropriate value of S

[4] This was dramatically demonstrated some years ago by Bill Warren, who, while speaking at a conference, lifted a large rock out of a box and tossed it at an unsuspecting member of the audience. As the audience gasped, the person initially recoiled and then recognized from the trajectory that the rock was styrofoam and smoothly caught it.

[5] Distance, D_S, could be expressed verbally in head-movement units, H (i.e., "It's twice as far as I have moved my head"). But $H \neq A$ (that is, $S \neq 1$), because A is a unit of action and H is a

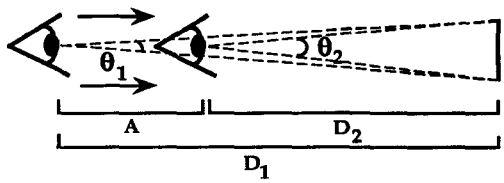

Figure 3. Distance information obtained from approach of a monocular observer to a surface. The viewing distance changes from D_1 to D_2 as the observer translates through amplitude $A = D_1 - D_2$, and the corresponding visual angles subtended by the surface change from θ_1 to θ_2. Image sizes used in Equation 1 are $I_i = 2\tan(\theta_i/2)$.

depends on the required unit of distance. One value will be required if distance is to be expressed verbally in feet, another if distance is to be expressed verbally in arm-length units, and yet another if distance is to be expressed by walking in units appropriate to the control parameter for walking. If distance is to be expressed by reaching, then presumably the unit must be appropriate to the control parameter for reaching. The general problem is to find, for a given unit, the appropriate value of S.

One could begin by setting S to any arbitrary value. At this point, without any further information (i.e., feedback), the measurement remains relative and is not definite. The reason is that the relation between the resulting measure and the required measure would remain unknown. Note that discussions of ratio measure usually involve the use of a graph with actual distance on the abscissa, judged distance on the ordinate, and accurate measure in the required units represented as a slope of 1. An arbitrary scaling coefficient then yields a slope of definite value other than 1. The definite value of that slope inappropriately implies a known relation between the arbitrary scaling coefficient and the required unit of measure. If the coefficient is arbitrary, then so is the result, and no information is gained.

There are two possible ways that a relation might be established. First, a direct relation could be established between A and D_S, that is, $S = 1$. If the head movement (of Figure 3 and Equation 1) was produced by walking (from D_1 to D_2), and if the perception of distance was to be expressed by walking to the target surface (from D_2), then a direct relation would obtain between A and $D_S = D_2$. Note, however, that continuous calibration is built into this solution because walking and image size covary continuously. Furthermore, this direct scaling solution cannot be general. The reason is that the source and use of information cannot always be identified in this way. For instance, to apply this solution to reaching, the hand would have to be attached to the eye (or head) and be moved by moving the head to the target surface—an awkward proposition at best. This means that for reaching, head-movement units have to be related to reaching units through the appropriate value of S. In this case, head-movement and hand-movement units are similarly constrained in scale and thus are related. The maximum amplitude of head movements that can be made by a seated observer is roughly comparable to the amplitude of the maximum reaches (and presumably there is information about this). The action units in the two cases may also be closely related, but this remains to be shown. In any case, the constraints should place an initial measurement within a nonarbitrary ballpark. This would make the measure definite, although still fairly inaccurate.

A second more general way that a measure of definite distance could be established is through the use of feedback to calibrate the measure. Calibration could take different forms. For instance, the measure resulting from an arbitrary value of S could be compared with an independent assessment of the distance in terms of the required measure. So, if one is judging distance verbally in feet, then one could measure the distance with a ruler and evaluate the accuracy of the judgment. In reaching, an error would mean missing the target surface by a given distance. In this alternative, a visual estimate followed by a reach and a visual estimate of the resulting error distance could be used to adjust S as follows: $S = S_i/[1 - D_1/D_2]$, where S_i is the initial value of S and the D_i are the first and second distance estimates, respectively. This assumes an accurate reach to the perceived distance. Another potential alternative would be to use continuous gearing of an ordinally scaled perceptual variable (e.g., Bingham, 1995; Bootsma & Peper, 1992) to guide a reach to the target and then to compare information from reaching to a distance estimate. Additional possibilities remain.

Calibration is required not only to evaluate a scaling constant but also to ensure stability of measurement. All measurements involve imprecision (i.e., noise or random error) as well as drift in systematic error. Stability is an issue for all measurement systems, and it is an intrinsically functional affair. A tolerance is used to determine accuracy (and thus stability). (Tolerance limits are inherent to the measurement of stability; e.g., Glendinning, 1994, pp. 27–51.) The tolerance limit depends on the way the measurement is to be used (Bingham, 1985; Tarasevich & Yavoish, 1969). For instance, the tolerance required to pass a stylus through a large ring at a given distance is larger than that required to place the stylus a centimeter in front of a surface at the same distance. This is important because calibration will tend to bring expressed measurements only within a tolerance determined by the task-specific actions used to express the measure. Thus, the very notion of definite distance is inalienably linked to actions that are used to express perceived distances. Because calibration is intrinsic to the perception of definite distance and because calibration depends, in turn, on criteria for accuracy, the functional criteria for tolerance must be well specified as part of an investigation of distance perception. Otherwise, it is impossible to evaluate the accuracy of distance perception. This is the problem with the results of so many studies that have purported to reveal significant distortions (i.e., inaccuracies) in distance perception. Criteria for accuracy

verbally expressed unit. It is unknown how these two types of units might be related. We assume, therefore, that determining the scaling between H and A units is equivalent to the general problem of scaling perceived distance by finding a value for S (e.g., $H = SA$).

have not been defined explicitly as part of the task performed by participants, and participants have not been allowed feedback despite the fact that they have been required to perform in perturbed conditions. On the basis of the extant evidence, it is difficult to determine what these results really mean.[6]

In retrospect, Foley's (1977, 1978, 1985) suggestion that he could use a linear transform to normalize experimental results may have been made under the assumption that the transform simulates calibration that would normally occur. The problem with this approach (in addition to those problems already described) is that calibration may not be able to eliminate inaccuracies or distortions. First, although the distortions found in so many studies do seem odd, it is not clear that they are all strictly afunctional. Overestimation of near distances based on static stereopsis would be afunctional, at least in the context of blind reaching, because it would mean smashing one's hand into a target. But the underestimation of distances found with monocular parallax need not be afunctional if the hand can be haptically guided over the remaining error distance to the target. The only cost might be the extra time required to guide the (uninjured) hand to the target. If this is acceptable given the performance criteria, then calibration might not eliminate the error because the reaches would fall within tolerance.

Second, distributions of random errors might combine with performance criteria in a way that prevents calibration from eliminating systematic errors. For instance, if the ability to resolve distances decreases with increasing distance in some viewing conditions, and performance criteria require that distance not be overestimated (e.g., do not hit the target), then calibration is not likely to eliminate systematic underestimation (that is, it would not raise judgment curves to a slope of 1). Thus, differences in error distributions can be important.

Our question is whether reaches performed with monocular vision will underestimate target distances and, if so, whether they will continue to do so with normal feedback from contact with target surfaces. Servos, Goodale, and Jakobson (1992) found that reaches were slower and that the preshaping of grasps was smaller when guided by monocular as opposed to binocular vision. On the basis of this indirect evidence, these authors inferred that distances were being underestimated. We investigated this using a more direct measure in the context of forward head movements. We also compared performance with normal monocular vision to performance with only monocular optic flow to see if forward head movements generate optic flow containing usable distance information and, if so, whether performance based on that information alone would be comparable. Finally, we controlled for an accessory restriction in the size of the visual field by examining its unique effect on performance. The latter results should be relevant to the issue of display generation in vision research with potential application to visual measurement (Smith & Snowden, 1994) and clinical understanding of the effects of low vision (Faye, 1984).

Experiment 1

Using a helmet, we fixed a miniature display to the observer's head to allow unimpeded reaching to targets. The display was fed signals from one of two cameras. The lens of the first camera (the "headcam") was attached to the helmet next to the observer's eye. The second camera (the "static camera") was on a tripod next to the observer's head and at eye level. Each seated participant was asked to remove a hand-held stylus from a hole in a launch platform located near the hip and to place the stylus into a target hole. The target was located at eye level some distance directly in front of the participant. Participants were instructed to bring the stylus up in front of the target as rapidly as possible, with the restriction that they not collide with the target at high speed. Thus, optimal performance required the participants to use as short a path as possible, to bring the hand up to eye height directly in front of the target, and then to move the stylus directly forward into the target hole. We measured the distance from the eye at which the hand took the corner to move toward the target.

Participants were tested in a number of different viewing conditions. We tested normal monocular viewing with forward head movements to determine the normal level of accuracy. This also allowed us to evaluate the effect of the headcam on distance perception and reaching. We tested headcam viewing throughout a reach for comparison with normal monocular viewing. We tested static-camera viewing throughout a reach to evaluate the effect of optic flow generated by head motion in headcam viewing. In this condition, lack of vision during the reach would have made it extremely difficult for participants to find and get to the target in a reasonable time. We used headcam viewing only before a reach to provide a strong test of distance apprehension. Reaches in this condition were blind. Finally, we tested monocular viewing through a tube to evaluate the effect of the restricted field of view entailed by the headcam.

Method

Participants. Four participants associated with Indiana University, ranging in age from 29 to 39 years, participated in the experiment on a voluntary basis. One participant was female and the remaining 3 were male. All 4 were right-handed. We were 2 of the participants (Participants 1 and 4), and the remaining 2 were a graduate student and a computer programmer in the psychology department.

Apparatus. Figure 4 depicts the apparatus used. Participants were seated. The shoulders were strapped firmly to the back of a chair so as to allow freedom of movement of the head and arm while motions of the shoulders and trunk were restricted. Participants reached with a cylindrical plastic stylus that was 18.5 cm long

[6] This understanding of definite distance also implies that results obtained from judgments of relative distance cannot be generalized to definite distance perception without further study. Todd and co-investigators have shown that observers are not very good at comparing relative distances along different directions (Todd & Reichel, 1989). However, if the perception of definite distance in each direction is independently calibrated, then relatively accurate comparisons might be possible.

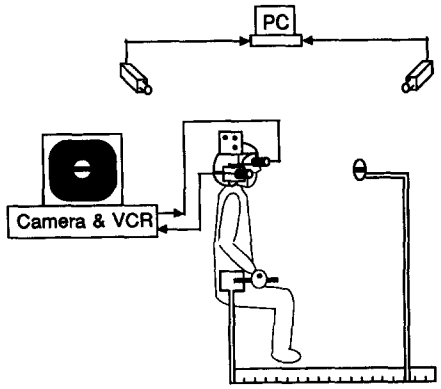

Figure 4. The participant viewed a disk-shaped target that was positioned at eye level with the use of an optical bench. The participant removed a stylus from a launchpad at the hip and inserted the stylus in a hole in the center of the target. The target was viewed on a miniature video monitor that was attached to a helmet and positioned over the right eye. This monitor was fed a signal from one of two cameras. Only the camera attached to the helmet next to the right eye is shown in the figure. The lens was level with the eye. The experimenter observed the display on another monitor. A two-camera WATSMART system was controlled with a PC and was used to measure the motions of an infrared emitting diode (IRED) attached to the hand and three IREDs attached to the head. The three IREDS on the head were used to track the position and orientation of the point of observation in the helmet-mounted camera.

and 1.0 cm in diameter and that weighed 23.2 g. The participant held the stylus firmly in the right hand so that 4.0 cm extended in front of, and 3.2 cm extended behind, the closed fist. Each trial began with the back end of the stylus inserted in a hole in the launch platform, which was located next to the participant's hip, approximately 15 cm to the right, and 5 cm behind, the right iliac crest (hip bone). The stylus interrupted a beam in both the launch platform and target that triggered a signal at the beginning and end of each reach. The Cartesian coordinates of three infrared emitting diodes (IREDs) placed on a helmet, along with one IRED placed on the right index finger, 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 the signals from the launch platform and target.

A patch was placed over the participant's left eye. An eyepiece attached to the helmet and positioned over the right eye allowed participants to view a monochrome video display. A camera lens (the headcam) was attached to the right side of the helmet 9.0 cm to the right of the right eye, pointing forward. The total weight of the helmet with viewer, lens, IREDs, and supporting hardware was 1.8 kg. A second camera was mounted on a tripod (the static camera) and could be swung in place at eye level 15.0 cm to the right of the participant's right eye. Control switches allowed the experimenter to determine which image, originating from the headcam or the static camera, was fed to the head-mounted display. Switches also allowed the experimenter to control when the head-mounted display was switched on or off. The display was switched on manually by the experimenter at the beginning of each trial and was automatically switched off at the end of each trial by a signal from the target. Thus, the display was blank between trials. In addition, the display could be set to automatically switch off (with a delay of less than 10 ms) when the stylus left the launch platform at the initiation of a reach.

The target set consisted of 18 flat, round disks covered with uniform (i.e., smooth, textureless) white retroreflective tape. Each target had a 1.2-cm hole at its center. A black stripe of a width corresponding to 0.25 of the target diameter was affixed across the center of the target to mask the relative size of the hole. The targets were constructed of Plexiglas with great care so that there were no features that would allow a given target to be distinguished. Three targets of each size were constructed so that each could be placed at two orientations to the vertical (both orientations with the black stripe horizontal). In effect, any of six targets could be used to produce a given image size at a given distance. Also, each target was used at more than one distance. Altogether, 78 different target configurations were used (2 distances × 2 image sizes × 3 targets × 2 orientations + 3 distances × 3 image sizes × 3 targets × 2 orientations). The targets were illuminated by two fluorescent lights with parabolic reflectors mounted above and behind the participant's head. When brightly illuminated, the target appeared in the head-mounted display as an isolated shape in a dark field. We adjusted the brightness and contrast of the head-mounted display to produce "patch-light" images. The field was dark, structureless, and continuous with the black stripe through the center of the target. The visible structure of the target was devoid of internal texture. Before each trial, the experimenter placed one target from the set at eye level at a given distance along a line extending from the camera lens, parallel to the sagittal plane of the observer. We covaried target size with distance from the camera lens to produce a constant image size (without head movements). Because target size covaried with distance, image brightness did not vary with distance. We controlled target position using mounts attached to an optical bench. To mask the sound of the target being positioned by the experimenter, we had the participant wear earphones through which loud music was played between trials.

Procedure. We tested each participant's reaching performance under five viewing conditions, which were preceded by a set of trials in which the participant performed verbal judgments.

Condition 0, verbal judgment: The participant viewed the target through the headcam while actively moving his or her head toward and away from the target and then expressed distance estimates in units of his or her own arm length.

Condition 1, headcam reach: As in the previous condition, each participant looked at the target while actively moving the head toward and away from the target through 2–4 oscillations. The participant was instructed to reach when he or she had apprehended target distance. The participant reached to place the front end of the stylus into the target hole as rapidly as possible, with the restriction that he or she not collide with the target face at high speed.

Condition 2, static-camera reach: Participants viewed the target through the camera mounted on the tripod (the static camera). The participant reached as in Condition 1 shortly after the display was turned on.

Condition 3, headcam-ballistic reach: In Conditions 1 and 2, the participant was able to use visual information about the movements of the hand once the hand was brought into view during the later part of a reach. In Condition 3, participants were not able to do this. The procedure was the same as in Condition 1 with the exception that the camera was automatically switched off (the participant's view became completely occluded) when the stylus was removed from the launch platform. If participants had difficulty finding the target hole once the target had been contacted, then the experimenter verbally guided the participant to the hole. (This procedure was used in all subsequent blind reaching conditions.)

Condition 4, restricted-field monocular reach: The procedure

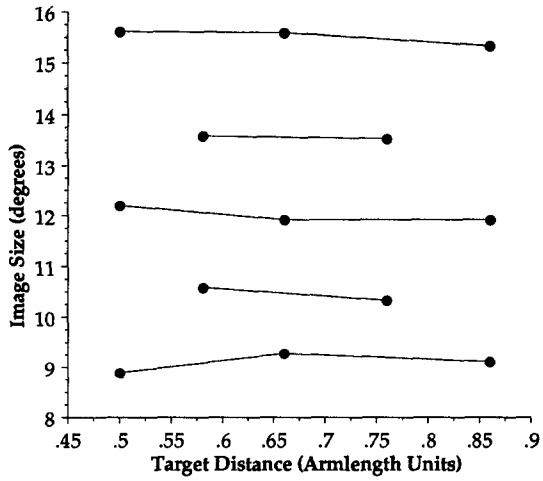

Figure 5. Image sizes and target distances were selected that were not correlated with one another.

was the same as in Condition 1 with the exception that participants viewed the target without the video display screen. The participant wore the helmet with the viewing screen removed. Instead of the viewing screen, a black tube was attached to a pair of swimming goggles so that the field of view was restricted to approximately 40°. The tube was 4.0 cm in diameter and extended 6.5 cm from the eye.

Condition 5, monocular reach: The procedure was the same as in Condition 4 with the exception that participants viewed the target normally with the right eye. That is, participants viewed the target without the video display screen or the field-restricting tube over the right eye.

In all conditions, the camera was turned off (or the participants' eyes were closed) and the headphones were turned on between trials while the experimenter adjusted the size and distance of the target. The occluding patch remained over the left eye in all conditions. Five target distances were presented in random order for each condition. A different random sampling of targets and orientations was used in each condition for each participant. Several days before the experiment, each participant sat in the apparatus with his or her shoulders strapped to the chair, and the distance of maximum reach was measured. These distances were 697, 657, 547, and 547 mm for Participants 1–4, respectively. The target distances presented to the participant during the experiment are expressed as a proportion of this maximum reach, where the maximum reach is equal to 1.0. During the verbal judgments (Condition 0), three target distances were within reach (corresponding to .70, .81, and .92 of maximum reach), one was just outside the limit of reach (1.06), and 1 was out of reach (1.20). In the reaching conditions, all target distances were within reach at .50, .58, .66, .76, and .86 of the participant's maximum reach. Figure 5 shows the mean image sizes used at each of the five distances. We chose the sizes so that image size could not be used by the participants to predict distance ($r^2 < .01$).

The experiment was performed in two different sessions. In the first session, participants performed 25 verbal judgments (Condition 0), followed by 25 headcam reaches (Condition 1) and then 25 static-camera reaches (Condition 2). In the second session, participants performed 25 headcam-ballistic reaches (Condition 3), followed by 25 restricted-field monocular reaches (Condition 4), and finally 25 monocular reaches (Condition 5). Participants were allowed to remove the helmet and to rest briefly after every 12 trials. Each session took 1.5–2 hr. Participants 1 and 2 performed the second session 1 day after the first session, and Participants 3 and 4 performed the second session 2 days after the first session. Data recorded from Conditions 1 through 5 are reported in this article.

Data reduction. When the participant moved the stylus toward the target, immediately after removing it from the launch platform, there was a large vertical (z) component to the hand trajectory. This was because the target was located at eye level, whereas the launch platform was located next to the hip. Participants brought the hand up into the field of view at various distances from the lens and then moved the hand horizontally along the line of sight (that is, along the x direction) to place the end of the stylus into the target hole. As shown in Figure 6, the x location at which a participant raised his or her hand before turning the corner toward the target was treated as the reach distance. This locus was determined as the point at which hand velocity in the x direction (V_x) exceeded 90% of the hand tangential velocity (V). Specifically, reach distance was identified as the first point at which $V_x/V \geq .90$. The degree to which the x location of the reach distance corresponded to the x location of the target was used as an index of accuracy in perceived target distance. Because the task required that the hand be brought up in front of the target in order to place the stylus in the hole, we expected that the x location of the reach distance would underestimate the x location of the target by at least the 4.0-cm length that the stylus extended beyond the diode on the hand.

Hand tangential velocity (V), component velocities (V_x, V_y, V_z), distance from the target (D), and component distances (D_x, D_y, D_z) were computed. Before we computed velocities, we filtered the sampled positions (x, y, z) of the single hand-mounted IRED using forward and backward passes of a second-order Butterworth filter with a resulting cutoff at 5 Hz. (We had determined that no significant spectral components existed in the data above this cutoff.) Mean hand trajectory data and *SD*s were computed as follows. Sampled values for each trajectory were indexed in terms of the distance from the target. Values from a set of trajectories were collected in bins, one for each x, y, and z coordinate at each 0.01-cm distance from the target. The bin size ensured that no two points from a single trajectory were placed in a common bin. Bins intervening between points from a given trajectory were filled by means of linear interpolation. Means and standard deviations were then computed for each bin.

We used the three IREDs mounted on the helmet to determine

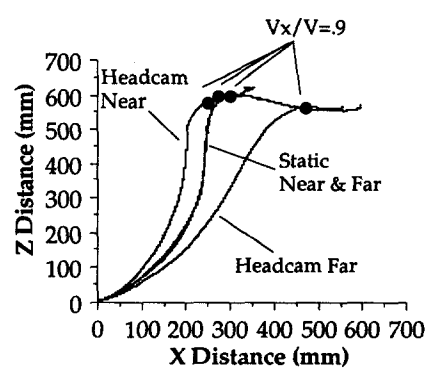

Figure 6. Mean reach paths projected in a vertical x–z plane viewed from the side of the participant. Mean paths to the nearest and farthest targets are shown for headcam and static-camera reaches for a representative participant. The mean locus of the $V_x/V = .9$ point is shown for each mean path.

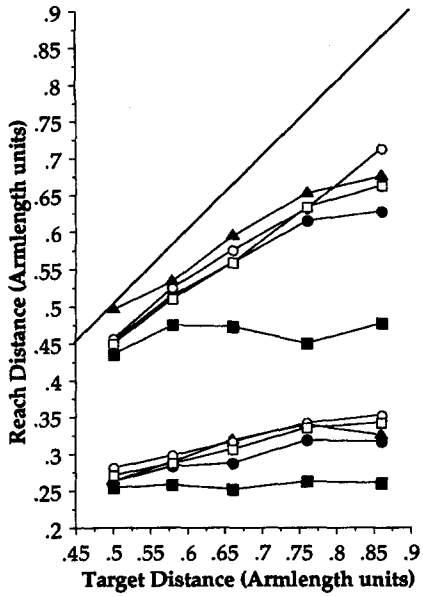

Figure 7. The mean x distance of the $V_x/V = .9$ points is shown for each of the five distances for each viewing condition plotted against target x distance. Also shown in the lower set of curves are mean x distances of the peak tangential velocity of the hand. Distances are shown in arm-length units. Headcam reaches = open squares; static-camera reaches = filled squares; headcam-ballistic reaches = filled triangles; restricted-field reaches = filled circles; monocular reaches = open circles. A line with a slope of 1 and an intercept of 0 is also shown.

the position and orientation of the headcam lens. The field of view for the headcam relative to the IREDs was determined as follows. An experimenter traced the field of view with an IRED mounted on his index finger while viewing the IRED through the headcam. For instance, with the IRED kept just visible at a corner of the display, the finger was moved outward to successive positions that were measured. By fitting lines to the measured positions, we found the field of view to be pyramid-shaped, as expected, with the apex fixed at the nodal point of the camera lens. The vertices of this pyramid-shaped field of view were separated by 48° horizontally and 39° vertically (with these angles measured about the nodal point in the lens). Using this information, we calculated the position of the nodal point in the lens and the orientation of the viewing pyramid with respect to the location of the three IREDs mounted on the helmet at each sample point in time. We used these to determine the time and position of the hand when it entered the field of view, that is, the point at which the hand trajectory crossed the surface of the viewing pyramid.

Results

A plot of the mean distances of $V_x/V = .9$ and of the peak V versus target distances is shown in Figure 7 for each of the viewing conditions. The distances described are along the x axis, which extended from the eye to the target. We performed a multiple regression predicting the distance of $V_x/V = .9$ using the distance of the target, the image size of the target (in degrees), and the participant's arm length for reaches of all participants in the headcam condition (*n*s are less than 100 because occasional trials were lost owing to failures in WATSMART collection.) The result was significant, $F(3, 90) = 63.5, p < .001, r^2 = .68$. The contributions of target distance, $\beta = .76$, partial $F = 125.7, p < .001$, and image size, $\beta = -.14$, partial $F = 4.6$, $p < .05$, were significant. The partial Fs and βs indicated that target distance was the dominant factor predicting the distance of $V_x/V = .9$. Results of the multiple regressions for the headcam-ballistic, restricted-field, and monocular viewing conditions were similar to those for the headcam condition (see Table 1). In the multiple regression for the static-camera condition, however, none of the three factors reached significance. We obtained similar results in multiple regressions predicting the distance of the hand's peak velocity using the distance of the target, the image size of the target, and the participant's arm length (see Table 2).

To determine if the regressions for distance of $V_x/V = .9$ differed as a function of viewing condition, we conducted multiple regressions using the continuous independent variables of target distance and participant arm length, the categorical variable of viewing condition (coded orthogonally), and a viewing condition by target distance interaction variable to predict distance of $V_x/V = .9$. If the interaction variable failed to reach significance, we performed the analysis again without the interaction variable to test the viewing condition main effect (Pedhazur, 1982). We conducted separate multiple regressions to compare the headcam viewing condition with the static-camera, headcam-

Table 1
Values of r^2, Partial F, and Coefficient (Coef., or Slope) for Multiple Regressions Predicting Distance of $V_x/V = .90$ From Target Distance, Target Image Size, and Participant Arm Length, as a Function of Viewing Condition for the Combined Data of the Participants

Viewing condition	r^2	n	Target distance		Image size		Arm length	
			Partial F	Coef.	Partial F	Coef.	Partial F	Coef.
Headcam	.68	94	125.7***	.72	4.6*	−4.0	.2	.04
Static camera	.09	95	2.6	.09	<1	0	2.4	.14
Headcam ballistic	.75	95	119.6***	.66	12.6***	−6.1	1.5	.11
Restricted field	.77	93	166.0***	.72	1.4	−2.0	2.5	.14
Monocular	.90	93	507.3***	.80	4.0*	−2.1	<1	.02

*$p < .05$. ***$p < .001$.

Table 2
Values of r^2, Partial F, and Coefficient (Coef., or Slope) for Multiple Regressions Predicting Distance of Peak V From Target Distance, Target Image Size, and Participant Arm Length, as a Function of Viewing Condition for the Combined Data of the Participants

Viewing condition	r^2	n	Target distance		Image size		Arm length	
			Partial F	Coef.	Partial F	Coef.	Partial F	Coef.
Headcam	.56	94	49.7***	.27	6.0*	−2.7	4.9*	.12
Static camera	.47	95	3.8	.07	<1	.9	36.9***	.33
Headcam ballistic	.55	95	33.8***	.23	5.3*	−2.6	5.7*	.14
Restricted field	.46	93	53.9***	.30	<1	−.3	0	0
Monocular	.43	93	48.2***	.28	<1	−.1	0	0

*$p < .05$. ***$p < .001$.

ballistic, restricted-field, and monocular viewing conditions, respectively, and to compare the headcam-ballistic and restricted-field viewing conditions with the monocular viewing condition (see Table 3). For the headcam and static-camera comparison, a significant interaction indicated that the slopes of the regression lines differed as a function of viewing condition. For the remaining comparisons, nonsignificant interactions indicated that the slopes of the regression lines were the same. However, the intercepts were found to be significantly different in three of the five comparisons. On average, headcam reaches were 1.2 cm farther from the target than were monocular reaches. Similarly, restricted-field reaches were 0.9 cm farther from the target than were monocular reaches. Headcam and restricted-field reaches were not different from one another. Headcam-ballistic reaches were not different from monocular reaches and were 1.2 cm beyond headcam reaches.

These results showed that the participants performed similarly in the headcam, headcam-ballistic, restricted-field, and monocular conditions and performed differently in the static-camera condition. (We obtained essentially the same pattern of results by analyzing distances of peak velocities.) In the static-camera condition, the reaches did not vary with target distance, whereas the reaches in the remaining conditions indicated that participants were detecting and using egocentric distance information to guide the hand. We had anticipated that the restriction of the size of the visual field by the headcam might produce relative underestimation of distance, and the results confirmed this. Modest although significant relative underestimation was obtained in both the headcam and restricted-field viewing conditions. The headcam-ballistic reaches, however, did not exhibit this effect. Apparently, blind reaching eliminated the relative underreaching that was otherwise produced by restricted viewing. Abrams has found that blind reaches are longer than reaches performed with concurrent vision (Abrams & Pratt, 1993; Pratt & Abrams, 1996).

We performed simple regressions predicting the distance of $V_x/V = .9$ from the distance of the targets separately for each viewing condition and for each of the four participants, and then, for each viewing condition, we computed the mean and standard deviation of the slopes and r^2s. We also computed the mean and standard deviation of the coefficients of variation for each viewing condition by first

Table 3
Values of r^2, n, and Partial F for Multiple Regressions Predicting Mean Distance of $V_x/V = .90$ From Target Distance, Viewing Condition, the Target Distance × Viewing Condition Interaction, and Participant Arm Length for the Combined Data of the Participants

Viewing conditions compared	r^2	n	Independent-variable partial F			
			Target distance	Viewing condition	Interaction	Arm length
Headcam vs. static camera	.62	189	84.4***	40.2***	70.0***	6.3*
Headcam vs. headcam ballistic	.69	189	227.3***	<1	<1	9.1**
	.69		228.3***	11.6***		9.0**
Headcam vs. restricted field	.72	187	274.7***	<1	<1	8.3**
	.68		232.6***	<1		6.7*
Headcam vs. monocular	.77	187	399.0***	<1	<1	5.0*
	.77		399.5***	14.9***		5.0*
Headcam ballistic vs. monocular	.79	188	405.1***	1.7	1.6	7.3**
	.79		403.1***	<1		7.1**
Restricted field vs. monocular	.82	186	515.7***	<1	<1	6.8**
	.82		517.3***	10.8**		6.8**

*$p < .05$. **$p < .01$. ***$p < .001$.

Table 4
Means and Standard Deviations of Slope, r^2, and Coefficient of Variation for Each Viewing Condition

Condition	Slope		r^2		Coefficient of variation	
	M	*SD*	*M*	*SD*	*M*	*SD*
Headcam	.60	.32	.53	.30	.11	.05
Static camera	.07	.05	.03	.02	.10	.04
Headcam ballistic	.60	.23	.56	.23	.09	.04
Restricted field	.67	.15	.70	.22	.08	.05
Monocular	.76	.08	.86	.06	.06	.04

computing the coefficient for each distance and participant. The results are shown in Table 4. The slopes were flat and nonsignificant in the static-camera condition. Mean slopes were less than 1 in all remaining conditions, ranging from .6 in headcam conditions to .76 in the monocular condition. The differences in coefficients of variation were tested with a two-tailed, paired *t* test. The only significant differences were between the monocular condition and each of the remaining conditions: headcam versus monocular, $t(19) = 3.67, p < .01$; static camera versus monocular, $t(19) = 3.42$, $p < .01$; headcam ballistic versus monocular, $t(19) = 2.83$, $p < .01$; and restricted field versus monocular, $t(19) = 2.42$, $p < .03$. The pattern of results with a one-tailed test was the same, with the addition that the difference between the restricted-field and headcam conditions was marginally significant, $t(19) = 1.52$, $p < .07$. The coefficient of variation for monocular viewing (6%) was about half that for headcam viewing (10%).

Additional evidence that perception of distance was metric rather than merely categorical or ordinal was provided by an examination of the scatter of reach distances for each of the five target distances in each viewing condition. There was a small amount of variability in target positioning (≈2 cm). We tested whether reach distances covaried with these small variations in target distance by regressing target distance on reach distance separately for each distance level and viewing condition using the combined data of the 4 participants in arm-length units. We computed means (and standard deviations) of slope, r^2, and the standard deviation of target distance across the five distances in each viewing condition. These are shown in Table 5 together with the number of regressions out of a possible five that were significant at $p < .05$ or better. Given the small variations in target distance, relatively strong relations were found in the monocular, restricted-field, and headcam conditions. The relation was noisier in the headcam-ballistic condition. The significance of one of the two significant regressions in the static-camera condition depended on a single outlying point, and that of the other depended on two outlying points. These results indicate that participants perceived metric distance, a result supported by metric variations in reach distances in the restricted-field versus monocular conditions and by similar variations in subsequent experiments.

Double-step targeting experiments have shown that even rapid reaches can be continuously guided by vision (e.g., Georgopoulos, 1986; Georgopoulos, Kalaska, & Massey, 1981; Jeannerod & Marteniuk, 1992). Such continuous guidance may involve the use of visual information other than distance (Bingham, 1995; Bootsma & Peper, 1992). We intended to assess distance perception via reaching and thus required that reaches be controlled using perceived distance. The results in the headcam-ballistic condition (where vision was occluded during the reach) provided assurance that the results did not reflect continuous visual guidance. Similar assurance was provided in the headcam and restricted-field conditions by properties of reaching trajectories. Figure 6 shows mean reach paths to the nearest and farthest targets for a representative participant in the headcam and static-camera conditions. In all but the static-camera condition, the reaches to near and far targets diverged at the beginning of the reaches. This divergence revealed the use of distance information, especially for the headcam and restricted-field conditions, because early portions of the reaches were occluded from vision. Early portions of reaches were also occluded in the static-camera condition, but these reaches did not reflect the perception of target distance. Static-camera reaches to near and far targets followed the same path to the line of sight. Only when the hand had entered the field of view did the reach to the far target diverge to travel along the line of sight to the target (presumably under continuous guidance).

Similarly, analysis of the velocity profiles in all but the static-camera condition revealed early divergence in hand velocities as a function of target distance. The mean hand tangential velocity profiles for a representative participant are shown in the left panel of Figure 8 for reaches to near and far targets in the headcam viewing condition. We normalized

Table 5
Means and Standard Deviations of Slope, r^2, and Standard Deviation of Target Distances (in Arm-Length Units) and Number of Distance Levels (of a Possible 5) Yielding Significant Regressions for Each Viewing Condition

Condition	Slope		r^2		*SD* of target distance		No. $p < .05$ or better
	M	*SD*	*M*	*SD*	*M*	*SD*	
Monocular	1.16	.31	.44	.16	.03	.005	5/5
Restricted field	1.25	.54	.34	.18	.04	.008	4/5
Headcam	1.31	.40	.31	.10	.04	.02	5/5
Headcam ballistic	.91	1.00	.24	.26	.04	.005	3/5
Static camera	.61	.61	.11	.13	.03	.01	2/5

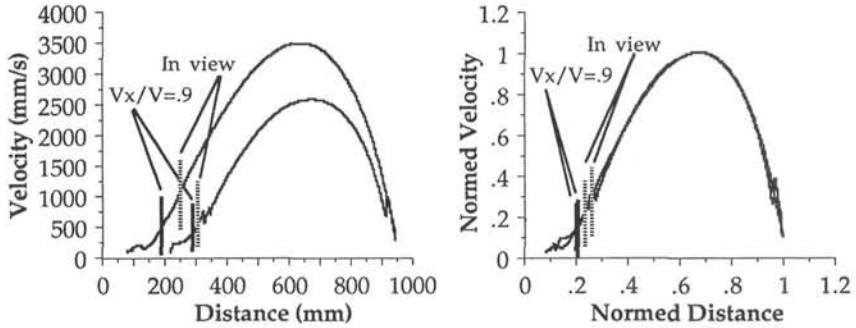

Figure 8. Left: Mean tangential velocity of the hand for reaches to the nearest and farthest targets in the headcam reach condition for a representative participant. Velocities are plotted against the distance to the target. Also shown are the locations of the mean $V_x/V = .9$ points (solid lines) and the mean distances at which the hand came into view (stippled lines). Right: Same as left panel but the distances have been divided by the target distance and the velocities have been divided by the peak velocity.

the mean velocity profiles by dividing all distances in a trajectory by the initial distance to the target and by dividing all velocities in a trajectory by the peak velocity. The results, as illustrated in the right panel of Figure 8, revealed that the form of the reaching movements up to $V_x/V = .9$ was the same whether to near or far targets and thus that this portion of the movement was scaled in proportion to the total distance.

To evaluate the possibility that the hand trajectory in the headcam condition might have been modified after the hand had come into the field of view and before it had reached $V_x/V = .9$, we measured the location of the hand at the point when it penetrated the surface of the viewing pyramid. The size of the mean visual angle subtended by the hand and target (24.2°) relative to the vertical angle of the viewing pyramid (39°) indicated that participants kept the target centered within the visual field. Using the data for all 4 participants in the headcam condition, we regressed the distance to the target when the hand appeared in view on the distance to the target at $V_x/V = .9$. The regression yielded a slope of .95, an intercept of 68.8, and an r^2 of .92. In contrast, the difference of these two measures failed to correlate significantly with target distance. Furthermore, the overall mean movement time between the hand's coming into view and its reaching $V_x/V = .9$ was 100 ms. This is too short a time when compared with the 130 ms estimated by Carlton (1992) for change of hand trajectories from visual stimuli. Thus, reaches up to the $V_x/V = .9$ point in either of the headcam conditions were not contaminated by continuous guidance. Presumably, the same might be assumed of the restricted-field reaches. However, it remains possible that the superior performance in the monocular condition might be attributed in part to continuous visual guidance.

Although mean reaching performance in the headcam, headcam-ballistic, and restricted-field viewing conditions was comparable to that in normal monocular viewing, the reaches in the two headcam and restricted-field conditions were more variable, as indicated by the lower mean r^2s (i.e., .53, .56, and .70, respectively, as opposed to .86) and the significantly larger coefficient of variation. These results show that headcam and restricted-field viewing did indeed perturb vision.

If the headcam and the restricted field perturbed distance perception and reaching, then how did participants respond to the perturbation over trials in which reaching provided feedback about actual target distances? There are (at least) two ways in which viewing conditions might have perturbed distance perception, and both would result in an increased overall coefficient of variation. First, experimental viewing conditions might have rendered distance more difficult to resolve so that participants might not have been able to discriminate among target distances as well. In this case, recalibration would not be expected to eliminate the effect of the perturbation. Second, viewing conditions might have altered the magnitudes yielded by the optical variable (without affecting resolution of distances) so that recalibration would be required and would correct for the change. We examined the pattern of errors over successive trials in each condition to see if errors were locally consistent (i.e., consistent in size on neighboring trials) and exhibited a trend to decrease over trials.

Because regression analysis indicated that reach errors were proportional to target distance, we computed proportional errors to eliminate variation in error with target distance. We computed the proportional error by subtracting the distance of $V_x/V = .9$ from target distance and then dividing by target distance. Mean proportional errors are plotted in Figure 9 against trial number for each of the viewing conditions in the order that they were performed. As is apparent in this graph, there were no trends in proportional errors in the headcam, static-camera, headcam-ballistic, or monocular viewing conditions. We performed a repeated measures analysis of variance on proportional errors with viewing condition and trial as factors. Viewing condition was significant, $F(4, 12) = 14.6$, $p < .001$, as were trial, $F(24, 72) = 1.88$, $p < .03$, and the interaction, $F(96, 288) = 1.44$, $p < .02$. In pairwise comparisons among viewing conditions in which we used either a t test or Tukey's

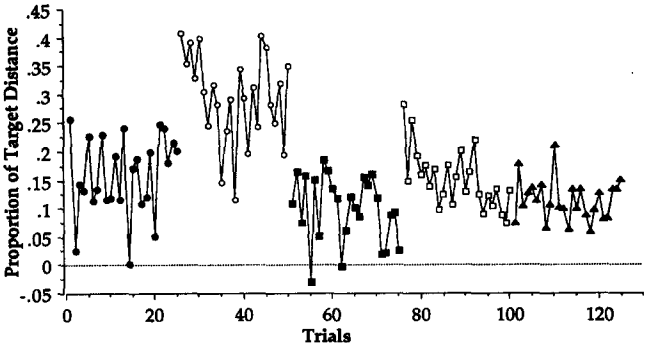

Figure 9. The mean proportional error for each trial is shown plotted by trial in each of the successive viewing conditions in the order in which they occurred. The proportional error is the x distance from the target of the hand at the $V_x/V = .9$ point divided by the target x distance. Headcam reaches = filled circles; static-camera reaches = open circles; headcam-ballistic reaches = filled squares; restricted-field reaches = open squares; monocular reaches = filled triangles.

honestly significant difference test, the only differences were significant at the $p < .01$ level. The static-camera condition ($M = .29$, $SD = .14$) was different from the headcam ($M = .16, SD = .12$), headcam-ballistic ($M = .10, SD = .12$), restricted-field ($M = .15$, $SD = .09$), and monocular ($M = .11, SD = .06$) conditions.[7] In simple effects tests, trial was significant only for headcam, $F(24, 72) = 1.79, p < .03$, and restricted-field viewing, $F(24, 72) = 1.73$, $p < .04$. However, no regression analysis (whether linear or second- or third-order polynomial) of proportional errors versus trial number, either for the data of each individual participant or for the collected data, was close to statistical significance except for the restricted-field condition. The linear regression on the collected data in the restricted-field condition was significant, $F(1, 91) = 8.8$, $p < .001$, $r^2 = .09$, $y = -.004x + .21$. Similarly, regressions performed on the data of Participants 1 and 4 in this condition were significant, with r^2s of .31 and .39, respectively. Initially, in this condition, the mean proportional error was double that in the previous condition, as shown in Figure 9. Errors then fell progressively to the level in the subsequent monocular viewing condition.

To evaluate this pattern of results, we had to analyze movement times to be sure that decreases in errors were not simply being produced by concurrent increases in movement times, that is, by the speed–accuracy trade-off (Fitts, 1954; Schmidt, Zelaznik, & Frank, 1978; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). (For an extended discussion of origins of the relation in motor control variables, see, e.g., Agarwal, Logsdon, Corcos, & Gottlieb, 1993; Latash & Gutman, 1993; and Zelaznik, 1993). We analyzed movement times from reach initiation up to $V_x/V = .9$. In a repeated measures analysis of variance on movement time, viewing condition was not significant ($p > .1$), but trial, $F(24, 72) = 1.68$, $p < .05$, and the interaction, $F(96, 288) = 1.43$, $p < .02$, were significant. In pairwise comparisons among viewing conditions in which we used a t test, the only differences were significant at the $p < .05$ level. Static-camera viewing was different from restricted-field and monocular viewing. The mean times were as follows: headcam, 438 ms ($SD = 86$ ms); static camera, 593 ms ($SD = 257$ ms); headcam ballistic, 454 ms ($SD = 124$ ms); restricted field, 404 ms ($SD = 60$ ms); and monocular, 392 ms ($SD = 87$ ms). In simple effects tests, trial was significant only for restricted-field, $F(24, 72) = 1.77$, $p < .04$, and monocular, $F(24, 72) = 2.00$, $p < .02$, viewing. However, regression analysis (linear or second- or third-order polynomial) of movement times versus trial number, either for the data of each individual participant or for the collected data, was significant only for the restricted-field condition. The linear regression on the collected data in the restricted-field condition was significant, $F(1, 91) = 10.2$, $p < .002$, $r^2 = .10$, $y = -.003x + .44$. Regressions performed on the data of Participants 2 and 3 in this condition were significant, with r^2s of .32 and .30, respectively. Thus, the pattern of results for movement times was essentially the same as that for proportional errors. They did not trade off; that is, a reduction in errors was not produced by increases in movement time. Rather, movement times decreased and improved as errors did. A trend for improvement over trials was evident only in the restricted-field viewing condition, not in the two headcam viewing conditions. In the restricted-field condition, 2 of the participants showed progressive improvement primarily in errors (Participants 1 and 4), whereas the remaining 2 showed improvement primarily in movement times (Participants 2 and 3).

Finally, not only were reaches more variable in headcam viewing conditions, but the pattern of variability was different. We computed means and standard deviations of errors for each participant at each target distance in each viewing condition. Simple linear regressions of means on standard deviations were significant in both the restricted-field and monocular conditions, with nearly identical positive slopes in the two cases. For the restricted-field condition, $y = .24x + 14.7$, $r^2 = .36$, $p < .01$. For the monocular condition, $y = .23x + 10.2$, $r^2 = .20$, $p < .05$. However, the same regressions were not significant ($r^2 < .01$, $p > .5$) in either of the headcam conditions. The slopes were flat and the intercepts were each equal to about 35 mm. Thus, variable errors were proportional to systematic errors in the restricted-field and monocular conditions but not in the headcam viewing conditions, where variable errors were larger overall.

The perturbing effects of the viewing conditions may be

[7] When we performed this analysis including only the data for the four viewing conditions and excluding static-camera viewing, viewing condition remained significant, $F(3, 9) = 5.16$, $p < .03$, as did the interaction, $F(72, 216) = 1.59$, $p < .01$. In pairwise comparisons using t tests, differences between the headcam and monocular, headcam and headcam-ballistic, and headcam-ballistic and restricted-field viewing conditions were all significant ($p < .05$). This replicated the pattern of results we obtained using multiple regressions with the exception that monocular viewing was not significantly different from restricted-field viewing in the analysis of variance on proportional errors.

summarized as follows. Static-camera viewing eliminated perception of distance and allowed reaches to the targets only with continuous guidance once the hand was brought within the visual field. Moving headcam viewing allowed perception of distance, but the ability to resolve distances was reduced. Although the concurrent reduction in the size of the visual field may have changed the values of the optical measurements (yielding underestimation), no recalibration occurred over trials, presumably because of the low resolution. Movement times for reaches provided an effective confidence score for distance estimates. (The results of analysis of movement times were confirmed by analysis of reaching velocities.[8]) Reaches were significantly slower in headcam and static-camera conditions than in restricted-field and monocular conditions. This suggests reduced confidence in reaching as a result of inferior distance perception. We concluded that the absence of relative underreaching in the headcam-ballistic condition was an effect of the blind nature of the reaches rather than of progressive recalibration, because no recalibration was exhibited. When reaching without vision, participants apparently aimed to make contact with the target earlier, that is, at or just after the end of the initial phase of the reach. Anecdotally, we noted that the longer a blind participant wandered about in search of the target hole, the farther afield he or she tended to go and the more he or she would require verbal direction from the experimenter. Generally, if the participant found the hole without help, he or she did it immediately.

Initially, relative underestimation of perceived distance was produced by restricted-field viewing but without a change in the ability to resolve distances. Perceived distances were recalibrated over trials in this condition, eventually attaining the accuracy of monocular reaches. Because restricted-field performance finally reproduced monocular performance, we concluded that the superior performance in the monocular condition was not dependent on continuous guidance during early portions of reaches. Finally, monocular viewing produced a slope ($\approx$.75) that was significantly lower than 1. The results reflected compression of perceived distance, just as have results in so many previous judgment studies. Notably, this compression was not reduced or eliminated by recalibration over trials despite the availability of both haptic and visual feedback! The evident recalibration in the preceding restricted-field condition showed that feedback was indeed available and could be used by the participants to calibrate the reaches in some conditions.

Experiment 2

We found, as expected, that restricting the size of the monocular visual field to 45° yielded underestimation of distance. However, the effect was fairly modest. Because restricted-field viewing was common to the preceding headcam conditions, the restricted-field effect may have been partially reduced by adaptation. In Experiment 2, we tested the restricted-field effect without preceding headcam viewing. We also found evidence of recalibration over trials with restricted-field viewing. We did not find recalibration with normal monocular viewing despite compression in the distances of monocular reaches. In Experiment 2, we retested these conditions with an additional 4 participants. Because the respective presence and absence of recalibration with restricted-field and monocular viewing is an especially important result, we tested whether it would be replicated.

Method

Only restricted-field and monocular viewing were tested, in that order. In all other respects, the method was the same as in Experiment 1 except that only three distances (.50, .66, and .86 of maximum reach) and three image sizes were tested, with six trials at each distance.

Four undergraduates at Indiana University, ranging in age from 18 to 21 years, participated in the experiment on a volunteer basis. All were unaware of the purpose of the study. Participants were paid $4.25 per hr. Two participants were female, and 2 were male. One participant of each gender was African American and the other was Caucasian. All 4 were right-handed.

Results

A scatter plot of V_x/V = .9 distances versus target distances for both viewing conditions appears in Figure 10 for each participant, together with a plot of the overall means. These plots show clearly that restricted-field reaches were significantly shorter than monocular reaches. We performed a multiple regression predicting the distance of V_x/V = .9 from the distance of the target and the participant's arm length in each condition. As shown in Table 6, the results for Experiment 2 were comparable to those for the same conditions in Experiment 1 (shown in Table 1) with the exception that the slope for restricted-field reaches was lower (.54) than previously (.72). This difference in slope reflects a stronger restricted-field underestimation effect. We performed a multiple regression using target distance, participant arm length, viewing condition (coded orthogonally), and a viewing condition by target distance interaction to predict the distance of V_x/V = .9. As shown in Table 7, the slope difference between the monocular and restricted-field conditions was significant. We performed simple regressions

[8] A regression of target distance on mean velocity (from reach initiation up to V_x/V = .9) for the combined headcam conditions was significant ($p < .001$, $r^2 = .29$), with a positive slope (1.25) equal to about half that (2.05) for the combined restricted-field and monocular conditions ($p < .001$, $r^2 = .46$). So for headcam reaches, mean velocity increased less rapidly with target distance. A multiple regression predicting mean velocities that used target distance, a categorical variable representing combined headcam versus combined restricted-field and monocular viewing (with orthogonal coding), an interaction vector, and participant arm length was significant, $F(4, 370) = 69.1$, $p < .001$, $r^2 = .43$. The target distance factor was significant, $F = 128.0$, $p < .001$. Mean velocity increased with target distance. The slope difference was significant, partial $F = 13.9$, $p < .001$. The slope for headcam reaches was less steep. The intercept difference was significant, partial $F = 6.4$, $p < .02$. Headcam reaches were slower. Finally, arm length was significant, partial $F = 7.3$, $p < .01$. The larger participants produced larger mean velocities.

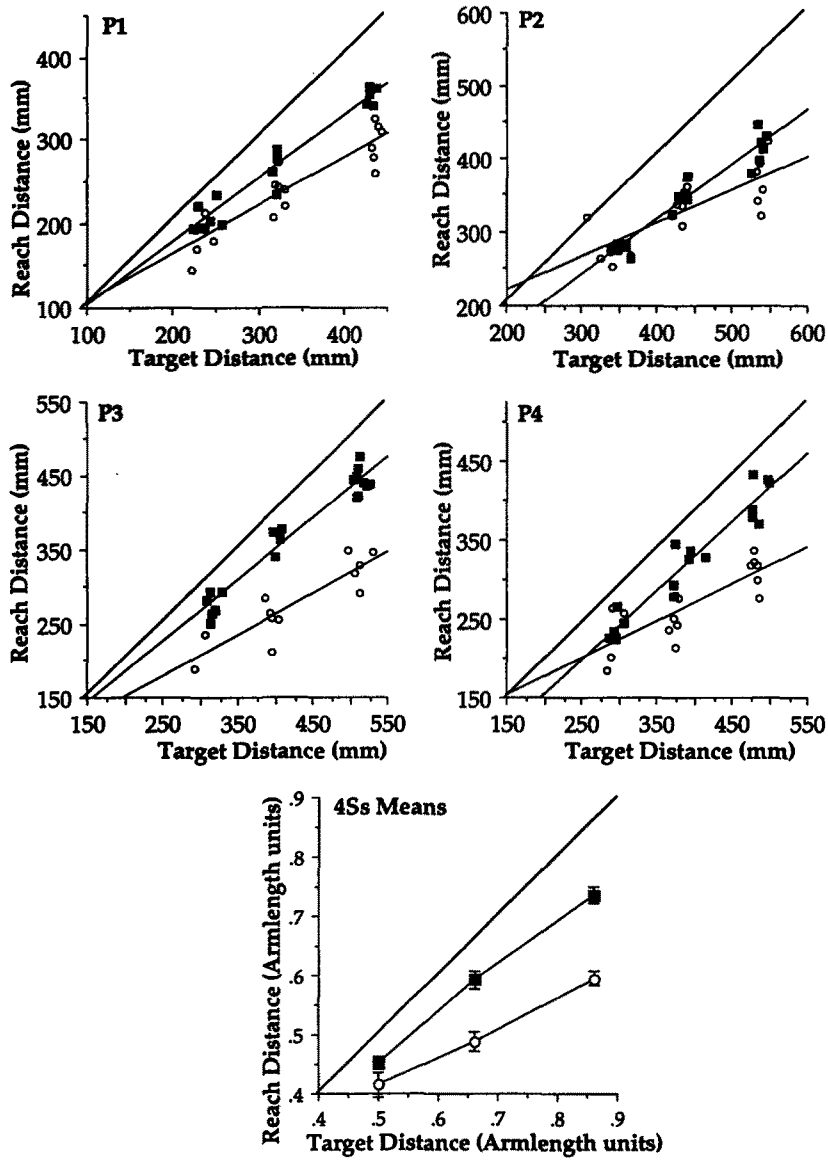

Figure 10. For each participant (P1 through P4), the distances of the $V_x/V = .9$ points in each of the two viewing conditions are shown plotted against target distances. Also shown are overall means (with standard error bars) for each of the three target distances in each viewing condition plotted in arm-length units. Monocular reaches = filled squares; restricted-field reaches = open circles. A line with a slope of 1 and an intercept of 0 is shown in each panel. Ss = subjects.

of target distance on the distance of $V_x/V = .9$ for each participant and condition and computed the mean and standard deviation of the slopes and r^2s, as shown in Table 8, together with the mean and standard deviation of the coefficients of variation. All values were comparable to those of Experiment 1 except that the mean slope for the restricted-field condition was lower.

Next we examined trends in proportional errors over trials within each condition. In Figure 11, proportional errors in each condition are plotted against trial number for each participant. Also shown are mean proportional errors. Linear regression of trial number on the combined proportional errors of the 4 participants was not significant for monocular reaches, $y = -.0002x + .17$, $r^2 < .01$, $p > .5$, but was significant for restricted-field reaches, $y = -.006x + .35$, $r^2 = .16$, $p < .001$. Proportional errors were initially greater in the restricted-field condition (.35 vs. .17) but decreased over trials. The level of proportional errors in the monocular condition did not change over trials.

The results thus confirmed the restricted-field effect. Distances were relatively underestimated with restricted-field viewing, but reaching errors diminished over trials, which reflected participants' recalibration and elimination of the effect using feedback from reaching. Monocular errors

Table 6
Values of r^2, Partial F, and Coefficient (Coef., or Slope) for Multiple Regressions Predicting Distance of $V_x/V = .9$ From Target Distance and Participant Arm Length, as a Function of Viewing Condition for the Combined Data of the Participants

Viewing condition	r^2	n	Target distance Partial F	Target distance Coef.	Arm length Partial F	Arm length Coef.
			Experiment 2			
Restricted field	.74	66	175.0***	.54	<1	.09
Monocular	.92	71	726.8***	.78	3.2	.12
			Experiment 3			
Headcam ballistic under	.66	48	85.6***	.53	3.0	.46
Monocular ballistic under	.85	50	253.5***	.72	12.5***	.69
			Experiment 4			
Monocular	.91	94	573.4***	.76	38.2***	.36
Binocular	.95	100	1437.4***	.96	3.8	.09

***$p < .001$.

did not diminish over trials despite the availability of feedback. The low monocular slope (≈.80) was stable.

Experiment 3

Did the low slope in the monocular condition reflect compression of perceived distances? The low slope may have been produced by a functional adaptation to the pattern of variable error. In Experiment 1, we found in the monocular condition that variable errors increased with distance. Given the instruction not to hit the target and this pattern of variable error, participants may have aimed increasingly farther in front of the target with increasing target distances so as to avoid collision with the target. Worringham (1991, 1993) showed that in such tasks systematic errors are directly proportional to variable errors. The next two experiments were intended to test these possibilities. In Experiment 3, we changed the task. In Experiment 4, we changed the information.

In Experiment 3, participants reached below the target to align the stylus with the target surface. Participants reached without vision during the reach. The task eliminated the need to avoid hitting the target. On the other hand, the task also made the criteria for accuracy less clear. After holding the stylus aligned at the perceived target distance, the participants reached around in front of the target to place the stylus into the target hole. Thus, they continued to have haptic feedback about actual target distance.

Method

Only headcam and monocular viewing were tested, in that order. Participants reached underneath the target to align the stylus with the target surface. After holding the stylus aligned at the perceived

Table 7
Values of r^2, n, and Partial F for Multiple Regressions Predicting Mean Distance of $V_x/V = .9$ From Target Distance, Viewing Condition, the Target Distance × Viewing Condition Interaction, and Participant Arm Length for the Combined Data of the Participants

Viewing conditions compared	r^2	n	Independent variable partial F: Target distance	Viewing condition	Interaction	Arm length
Restricted field vs. monocular	.88	137	787.7***	4.0*	22.4***	3.0
Headcam ballistic under vs. monocular ballistic under	.76	98	259.7***	2.6	6.9*	<1
Monocular vs. monocular ballistic under	.86	95	384.9***	4.3*	<1	<1
Monocular vs. binocular	.93	194	1,743.4***	7.6**	14.5***	32.3***

*$p < .05$. **$p < .01$. ***$p < .001$.

Table 8
Means and Standard Deviations of Slope, r^2, and Coefficient of Variation for Each Viewing Condition

Condition	Slope		r^2		Coefficient of variation	
	M	*SD*	*M*	*SD*	*M*	*SD*
			Experiment 2			
Restricted field	.51	.06	.74	.09	.10	.03
Monocular	.80	.06	.94	.01	.06	.02
			Experiment 3			
Headcam ballistic under	.51	.08	.52	.11	.09	.04
Monocular ballistic under	.72	.02	.84	.05	.05	.02
			Experiment 4			
Monocular	.75	.06	.88	.04	.05	.02
Binocular	.96	.01	.94	.03	.04	.03

distance, participants placed the stylus in the target hole. Participants reached without vision during the reach. In the headcam condition, the display was blanked upon removal of the stylus from the launch platform, just as in the headcam-ballistic condition of Experiment 1. In the monocular condition, the participant closed his eye before initiating a reach. In all other respects, the method was the same as in Experiment 1.

The first two participants from Experiment 1 performed in Experiment 3. The second participant had left the psychology department to take a job with the university computing service. He was paid $5.00 per hr.

Results

A scatter plot of $V_x/V = .9$ distances versus target distances for both viewing conditions appears in Figure 12 for each participant, together with a plot of the overall means. The means for these 2 participants in the comparable conditions of Experiment 1 are also shown. Blind reaches under the target overshot near targets and undershot far targets. Although the participants complained of uncertainty in placing their hands, they both were nevertheless surprised at the results, especially the overshooting of closer targets. We performed a multiple regression predicting the distance of $V_x/V = .9$ from the distance of the target and the participant's arm length in each condition. As shown in Table 6, the r^2s and slopes in Experiment 3 were somewhat less than those in the same conditions in Experiment 1.

We first compared monocular and headcam performance in Experiment 3. We performed a multiple regression using target distance, participant arm length, viewing condition (coded orthogonally), and a viewing condition by target distance interaction to predict the distance of $V_x/V = .9$. As shown in Table 7, the slope difference was significant. We performed simple regressions of target distance on the distance of $V_x/V = .9$ for each participant and condition and computed the mean and standard deviation of the slopes and r^2s, as shown in Table 8, together with the mean and standard deviation of the coefficients of variation. The r^2s and coefficients of variation were comparable to those in Experiment 1. The mean slope of the headcam condition (.51) was less than the slope in the monocular (.72) condition in Experiment 3 and lower than the slope in the headcam and headcam-ballistic conditions (.60) of Experiment 1. We interpreted this as a stronger restricted-field effect produced by participants' inability to use the haptic feedback to improve performance as a result of the ill-defined requirements for accuracy. We found no trends in proportional errors over trials. How alignment to the surface should relate to stylus position once the stylus was in the hole was rather unclear (and perhaps difficult to resolve haptically).

Next, we performed a multiple regression to compare the monocular reaches in Experiments 1 and 3 and to test both the significance of the intercept difference apparent in Figure 12 as well as the apparent lack of difference in slope. As shown in Table 7, the slopes were not different, but the intercepts were. The lack of a difference in slope implied that the compression of distance estimates as found in Experiments 1 and 2 reflected monocular perception of distance rather than a task-specific adaptation to the increasing variability of reaches. The intercept difference was presumably a simple result of the change in task from bringing the stylus up in front of the target to placing it in the plane of the target. There was no reason to attribute the relative position of the curves in Figure 12 to feedback given the lack of trends in errors over trials. The main result was that the task changed the position of the entire curve, but not its slope.

Experiment 4

We found that the compression of monocular reaches was preserved despite change to a task that eliminated the need to avoid hitting the target. The question remained whether the compression was specific to monocular as opposed to binocular distance perception. As illustrated in Figure 2, the difference between binocular and monocular distance perception found in previous judgment studies was essentially a difference in intercept, not a difference in slope. Both have yielded low slopes, but monocular judgments tend to consistently underestimate all distances, whereas binocular judgments overestimate near distances and underestimate far distances. In Experiment 4, we compared monocular and binocular reaching.

Method

Only monocular and binocular viewing were tested, in that order. Participants reached to place the stylus into the target hole without hitting the target at high speed. Participants reached without vision during the reach. In both conditions, the participant closed his or her eyes before initiating a reach. Monocular and binocular viewing were tested on different days. In all other respects, the method was the same as in Experiment 1, including the use of head movement toward and away from the target before each reach.

The first 2 participants from Experiment 1 performed in Experiment 4 together with 2 additional participants who had not been in any of the previous experiments. Both of the new participants were graduate students in the psychology department. One was male,

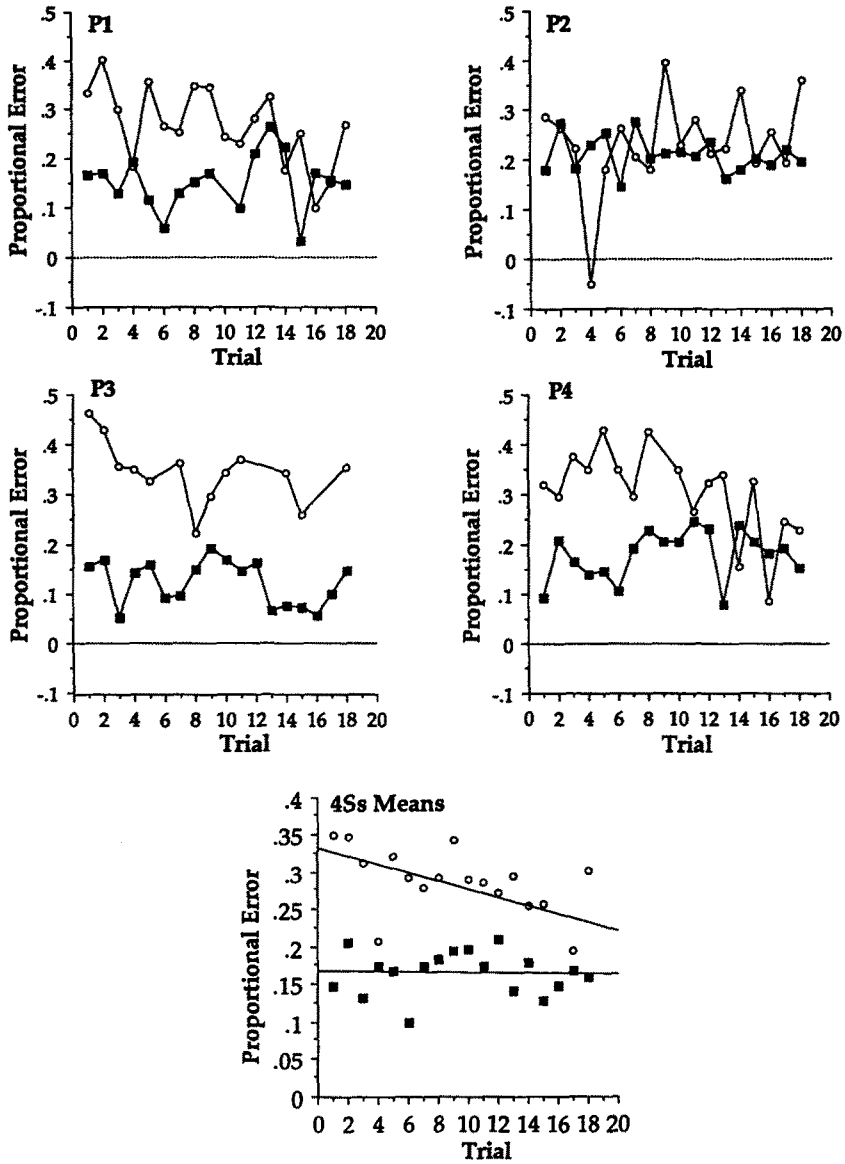

Figure 11. For each participant (P1 through P4), proportional error is plotted by trial in each of two viewing conditions. Also shown are mean proportional errors with least-squares best fit regression lines for each condition. Monocular reaches = filled square; restricted-field reaches = open circles. Ss = subjects.

and 1 was female. Both were right-handed and were naive concerning the purpose of the study. Three of the participants were paid $5.00 per hr.

Results

A scatter plot of V_x/V = .9 distances versus target distances for both viewing conditions appears in Figure 13 for each participant, together with a plot of the overall means. Binocular reaches were consistently closer to the target than monocular reaches and overall were remarkably accurate. We performed a multiple regression predicting the distance of V_x/V = .9 from the distance of the target and the participant's arm length in each condition. As shown in Table 6, the monocular r^2 and slope in Experiment 4 were essentially the same as those in the previous experiments (about .90 and .75, respectively). However, the binocular slope (.96) was greater and very nearly equal to 1 (as was the r^2).

We compared monocular and binocular performance by performing a multiple regression using target distance, participant arm length, viewing condition (coded orthogonally), and a viewing condition by target distance interaction to predict the distance of V_x/V = .9. As shown in Table 7, the slope difference was significant. We performed simple

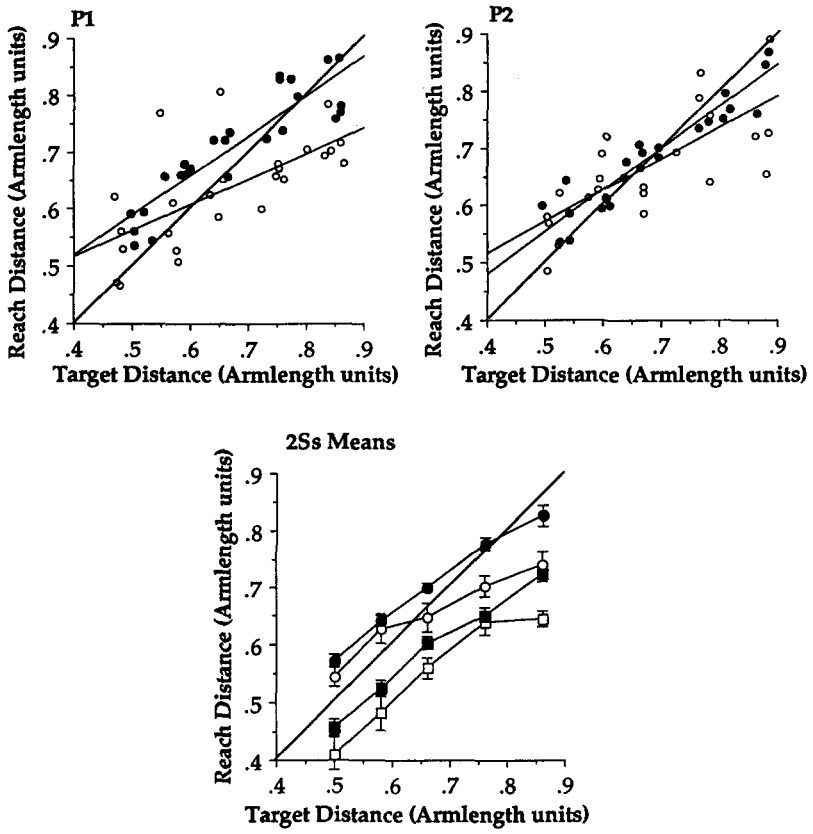

Figure 12. For each participant (P1 and P2), the distances of the $V_x/V = .9$ points in each of the two viewing conditions are shown plotted against target distances. Also shown are overall means (with standard error bars) for each of the five target distances in each viewing condition and the comparable means from Experiment 1. Monocular reaches = filled circles; headcam reaches = open circles; monocular reaches in Experiment 1 = filled squares; headcam reaches in Experiment 1 = open squares. A line with a slope of 1 and an intercept of 0 is shown in each panel. Ss = subjects.

regressions of target distance on the distance of $V_x/V = .9$ for each participant and condition and computed the mean and standard deviation of the slopes and r^2s, as shown in Table 8, together with the mean and standard deviation of the coefficients of variation. The mean slope and r^2 for the monocular condition (.75 and .88, respectively) were less than those for the binocular condition (.96 and .94), whereas the mean coefficients of variation seemed equivalent (.05 vs. .04). However, we performed a two-tailed, paired t test to compare the standard deviations in the monocular and binocular conditions, and the result was significant, $t(19) = 2.14$, $p < .05$. The precision of monocular reaches was less than that of binocular reaches, but the difference was a function of target distance. Monocular coefficients of variation were constant across distances in all of the experiments. For instance, a simple regression of mean distances (in arm-length units) on coefficients of variation in the monocular condition of Experiment 4 was not significant, and the slope was flat, $y = -.04x + .08$, $r^2 = .03$, $F(1, 18) = 0.5$, $p > .4$. The mean coefficient of variation was .06 at both .50 and .86 of maximum reach distance. Multiplying the proportions ($.06 \times .50 = .03$, and $.06 \times .86 = .052$) revealed that precision decreased from 3% to 5.2% of maximum reach as target distances approached maximum reach distance. Similarly, mean reaches increasingly undershot the targets (by 3.5 cm at the near target and by 9 cm at the far target). Accuracy covaried with precision. Nevertheless, given the results of Experiment 3, we cannot conclude that accuracy is a function of precision (that is, a result of participants' conforming to the instruction not to hit the target). After all, systematic errors were similar in the headcam conditions of Experiment 1 despite a distinctly different pattern and amount of variable error. When we performed a regression of mean distances on coefficients of variation in the binocular condition, the result was significant, and the slope was negative, $y = -.13x + .12$, $r^2 = .34$, $F(1, 18) = 9.1$, $p < .01$. In the binocular condition, the mean coefficient of variation dropped continuously from .06 at .50 of maximum reach to .02 at .86 of maximum reach. Multiplying these proportions ($.06 \times .50 = .03$, and $.02 \times .86 = .017$) revealed that precision increased from 3% to 1.7% of maximum reach as target distances approached maximum reach

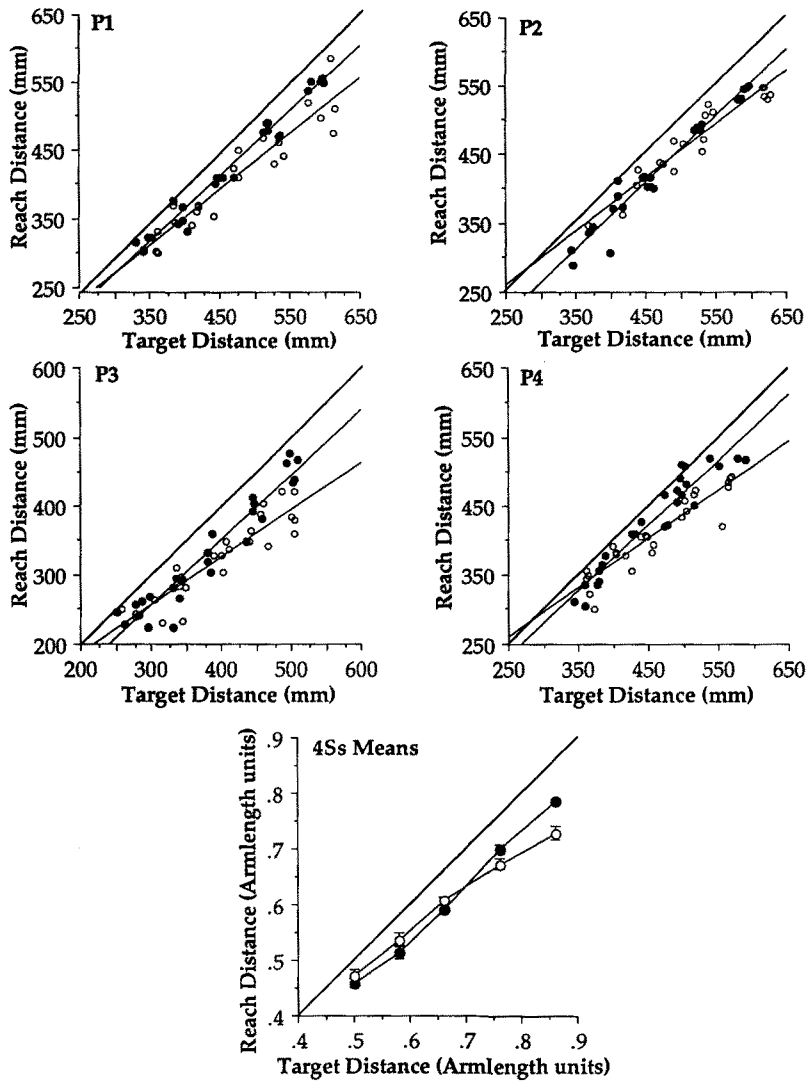

Figure 13. For each participant, the distances of the $V_x/V = .9$ points in each of the two viewing conditions are shown plotted against target distances. Also shown are overall means (with standard error bars) for each of the five target distances in each viewing condition plotted in armlength units. Monocular reaches = open circles; binocular reaches = filled circles. A line with a slope of 1 and an intercept of 0 is shown in each panel. Ss = subjects.

distance. Mean reaches stopped at almost the same distance, just 4 cm short of the target at all distances. We found no trends in proportional errors over trials.

General Discussion

At the outset, we argued for the necessity of a perception–action approach to definite distance perception. In this approach, perception is evaluated in the context of a commonly performed and therefore skilled action. We described two core tenets. First, definite distance perception entails calibration and therefore an action that provides both feedback and a standard of accuracy. Second, perception is a complex but coherent and functionally effective system that must be investigated via perturbation. To be able to evaluate the effects of specific perturbations, one must compare perturbed performance with normal, unperturbed performance, and perturbations should not be confounded with one another. Therefore, perturbation of visual information must ultimately be evaluated in the context of the recalibrating, or stability-inducing, effect of feedback.

We demonstrated the approach in studies of monocular distance perception in which participants reached to contact surfaces at various distances within reach. An immediate advantage of the approach is that we can generalize our results to an applied problem, namely, the control of reaching by monocular people. First, we needed to establish whether monocular people are really at a disadvantage in this context. The overarching conclusion of these experiments is that monocular vision is not equivalent to binocular

vision. In conditions representative of normal everyday reaching, reaches performed with monocular vision reflected compression of perceived distances and decreasing resolution of distances as distance increased. In contrast, binocular reaches were accurate and relatively precise. Neither systematic nor variable errors increased with distance. Haptic and visual feedback were not used to recalibrate monocular distance perception so as to eliminate underestimation that was progressively greater with distance. Nevertheless, feedback was used to eliminate underestimation produced by restriction of the size of the monocular visual field. Presumably, the decreased resolution of distances perceived via monocular vision prevented recalibration beyond the level achieved. We inferred that poor resolution also prevented recalibration in the headcam viewing conditions.

Second, we investigated whether optic flow generated by head movement toward a target would enable apprehension of the egocentric distance of a target. We used the headcam to isolate monocular optic flow projected from the target surface and to eliminate other potential sources of visual information. In particular, we varied target size so that image size varied independently of target distance. Results in the static-camera condition showed that all information about target distance, aside from that generated by head movement, had been eliminated successfully from the headcam display. Although image size was a significant factor in multiple regressions performed on headcam data, the effect was small. The effect was entirely absent in reaches performed with the static camera, although image size was the only property that varied in those displays. There was no effect presumably because image size failed to provide any information about target distance. Participants reported in debriefing that they performed the static-camera reaches by bringing the hand up into the visual field at a constant distance and then moving the hand toward the target while waiting for the stylus to make contact. The recorded hand trajectories were consistent with this description.

Only when participants moved their heads to generate optic flow in the headcam display were they able to produce reaches that varied with target distance. To evaluate how well participants were able to perceive target distance with a moving headcam, we compared headcam reaches to those performed using normal monocular vision. Monocular and headcam viewing produced similar systematic errors, which showed that participants were able to perceive egocentric distance by means of the headcam. However, reaches in the headcam and monocular conditions were different in two respects. First, headcam reaches exhibited greater variable error that was not proportional to distance, as variable error for monocular reaches was. Because headcam reaches were no more rapid than monocular reaches and both exhibited covariation of movement speed and distance, we inferred that the difference in the pattern of variable error reflected a perturbation of perception by headcam viewing. Second, systematic error in the headcam viewing condition exhibited larger undershoot than did systematic error in normal monocular viewing. Previous studies had suggested that the restricted visual field of the headcam might result in such relative underestimation. However, reaches in the headcam-ballistic condition did not exhibit this relative undershooting. If we could determine that the relative undershooting was indeed a function of the restricted size of the visual field, then because headcam viewing did not exhibit recalibration, we could infer that the lack of relative undershooting was an effect of blind reaching.

We did find that the restricted field produced relative underestimation. To test whether adaptation to the restricted field had occurred in the immediately preceding headcam trials, thus reducing the effect, we tested an isolated restricted-field condition in Experiment 2 and found a larger underestimation effect. Unlike the headcam condition and like the monocular condition, the variable errors in restricted-field viewing were proportional to target distance and smaller overall. Accordingly, we concluded that the restricted field was not responsible for the difference in variable errors between the headcam and monocular conditions and that the poor resolution of distances implied by the larger variable errors in headcam viewing prevented recalibration.

The restricted-field condition was the only one to exhibit an effect of feedback, that is, a decrease in errors over trials. One possible account is that this reflected progressive recovery from the perturbation entailed by the transition from headcam to restricted-field viewing. If so, then performing restricted-field reaches without preceding headcam reaches should not have produced such progressive improvements. When we tested isolated restricted-field viewing, however, we found the same improvement over trials. This implied that restricted-field viewing included structure, absent in headcam viewing, that enabled progressive improvement in performance. Observers may have used the regularities of the optical texture distributions together with feedback from reaching to calibrate perceived distances. In studies on size perception using the physically determined shapes of trees, Bingham (1993c) found that inclusion of optical texture gradients projected from a simulated ground surface produced progressive reduction in errors over trials. This trend was absent when the task was performed without the optical texture gradient. In both that study and the current study, the environmental elements projecting into the optical texture gradients were of stable and reliable size.

We concluded the following:

1. People can perceive egocentric distance via optic flow produced by voluntary head movement toward a target.
2. Headcam viewing substantially reduces the ability to resolve distances and therefore prevents progressive calibration over trials with the use of feedback from reaching.
3. Restricting the size of the monocular visual field produces underestimation of distance, but underestimation is eliminated by recalibration with the use of feedback from reaching.
4. Headcam viewing perturbs vision by restricting the size of the visual field and thus producing an underestimation effect, but the field restriction is not responsible for the drop in the ability to resolve distances.
5. Definite distance perception based on optic flow is not as stable as perception based on information in addition to optic flow.
6. Monocular viewing yields compression of definite

distance as well as diminishing resolution with increasing distance.

7. The compression from monocular viewing is not eliminated by recalibration via visual and haptic feedback from reaching.

8. No distortion results from dynamic binocular perception of definite distance, and resolution of distances does not diminish as maximum reach distance is approached; that is, binocular perception of reach distances is accurate and precise.

9. The position of a curve representing distance estimates is task specific, and attribution of over- or underestimation of distance to perception independent of task is inappropriate.

This last conclusion was taken from the comparative results of Experiments 1 and 3 as shown in Figure 12. The systematic errors in Experiment 3 were similar to those reported in previous studies of distance perception that were based on static binocular information. In those studies, perceived distances were described as overestimated in near space and underestimated in far space, but as illustrated in Figure 2, the slope of the judgment curves is similar to that found in studies of distance perception that were based on monocular optic flow. However, without calibration and explicit task-specific criteria for accuracy, no attributions of over- or underestimation of definite distance can be made. In Experiment 1, participants reliably used the same information as in Experiment 3 to avoid overshooting the target. Any inference from the results of Experiment 3 that monocular perception overestimates near distances must be incorrect.

The collective results of these experiments demonstrate the necessity of a perception–action approach to the study of definite distance perception. This is established specifically by the findings of compression and no recalibration for monocular vision despite the availability of feedback, lack of compression for binocular vision, and relative underestimation and recalibration for restricted monocular vision. The results show that calibration cannot be assumed to eliminate distortion of perceived distance and that simulation of calibration via a linear transform inappropriately trivializes its role. The results show that accurate perception of distances within reach space is achieved using normal (dynamic) binocular vision but that monocular vision introduces a *stable* distortion. It does not calibrate away. Restricting the size of the visual field, a condition characteristic of low vision, produces underestimation of distance, but the effect is *unstable* and is eliminated fairly quickly by feedback. The bottom line is that the effect of perturbations to visual information cannot be evaluated independently of the stability of the perception–action system so perturbed. How these effects might generalize to other actions and other tasks (e.g., targeted throwing or walking) remains to be investigated. However, we can safely generalize our results to the plight of monocular people confronted with manual tasks. Head movement toward a target does enable distance perception that can be used to guide a reach, although reaches will tend to undershoot. Additional studies will be required to determine whether strictly lateral head movement might enable comparable performance.

We found that feedback did not eliminate compression evident in reaches guided by monocular vision. This failure may be due to the fact that haptic perception of distances traveled by the arm is distorted in a way that is inverse to visual distortion. Haptically, distances in depth are expanded (Cheng, 1968; von Collani, 1979; Davidon & Cheng, 1964; Day & Wong, 1971; Deregowski & Ellis, 1972; Hogan, Kay, Fasse, & Mussa-Ivaldi, 1990; Marchetti & Lederman, 1983; Reid, 1954; Wong, 1977, 1979). Kay, Hogan, and Fasse (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 from near 0 immediately in front of the body to 30% at arm length. Kay et al. (1996) also measured the perceived stiffness of objects and found both results to be related to previous results on arm postural stiffness. They suggested, accordingly, that the distortion reflected the dynamics of arm posture and movement control. Although distance of travel in a reach may be haptically perceived as being longer than it is, monocular underreaching cannot be attributed strictly to haptics because we found no compression in binocular reaches. Nevertheless, haptic distortion may affect calibration of reaches when resolution of distances is reduced by monocular vision.

Targeted reaching necessarily entails both ego- and exocentric distance perception. Targeting a reach entails perception of the egocentric distance between observer and target surface. But, to avoid collision in the fast phase, a reach is characteristically aimed short of the target. The result is that the hand is positioned at a distance from the target. Reaching to the front of the target partitions an egocentric distance (eye to target) into egocentric (eye to hand) and exocentric (hand to target) components, and the components trade off. As one component shrinks (eye to hand), the other grows (hand to target). Visually, both components would be compressed. But haptically, the two components would compete if haptic distances were expanded. If visual distortion results in a compressed eye–hand distance, the haptic experience of that distance might equal the original egocentric distance to the target, and thus the tendency to shorten the reach might be increased. However, the increased error represented by the hand–target distance would be accentuated by the same haptic expansion, and feedback from contact with the target would presumably be about this latter distance. Nevertheless, if haptic expansion makes the initial reach feel too long, then the injunction not to hit the target might suppress the inclination to shorten the error distance despite its feeling long. This might especially be the case when coupled with the poorer visual resolution of distance allowed by monocular vision.

Finally, in our discussions, we have treated verbal magnitude estimation as a type of perception–action system. Verbal estimation is an action, but as we have pointed out, it is an unusual activity, is not likely to be skilled, and does not necessarily involve feedback. Pagano and Bingham (in press) have investigated verbal estimation with headcam viewing both with and without feedback from reaching. Their participants made verbal estimates before reaching, after reaching, while reaching, and then again without reaching (after calibration via concurrent reaching). The main conclusion to be drawn from their results was that verbal estimation is unstable and unreliable as a measure. As found previously by Foley (1977), verbal estimates were at

least twice as variable as reaches even with and after feedback from reaching. Furthermore, verbal errors were found to be uncorrelated with reaching errors when reaches and verbal judgments were performed concurrently. This implies that the two are relatively unrelated. Systematic errors for verbal judgments were malleable. They changed from underestimation with a low slope (≈.75) before reaching, to underestimation with a high slope (≈1.33) after reaching, to accurate with a slope near 1 during and after concurrent reaching. The latter result is especially troubling. We have found that reaching has consistently yielded a slope (≈.75) less than 1 with relatively low variable error in different monocular viewing conditions and in different tasks. In contrast, reaching with binocular vision has yielded a slope near 1. From this, we have inferred that monocular vision yields compression of definite distance. Pagano and Bingham (in press) suggested that the slope of 1 for verbal judgments was a result of an explicit restriction of the range of distances to distances within reach. The relative instability of verbal estimates renders them unreliable. Of course, this is not news to investigators of distance perception. Entire books have been written on the vagaries of verbal magnitude estimates (Poulton, 1989). Often, investigators have turned to matching methods to avoid these difficulties, but as we have argued, such methods cannot be used to study the perception of definite distance. Instead, we must use targeted actions.

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