

The Role of Familiar Size in the Control of Grasping

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Abstract

■ The present study examined whether the learned pictorial depth cue of “familiar size” could be used to plan a reaching and grasping movement in the absence of binocular vision. Sixteen right-handed subjects were presented with two different arrays, under monocular and binocular viewing conditions, in which a range of different “grasp-sized” spheres that were lit from within could be presented in an otherwise darkened environment. In the “familiar-size” presentation array, only one “standard” sized sphere was presented, which gave subjects an opportunity to learn the relationship between the standard sphere’s retinal image size and its distance. In the “multiple” spheres presentation array, subjects could not learn such a relationship because on any one trial, one of four different sphere sizes could be present. In a second experiment, the effects of this paradigm on six subjects’ perceptual reports of distance were examined by having subjects slide their index fingers apart along a horizontal rod to indicate the

estimated distance of the spheres. When familiar size could not be used as a cue to distance, subjects produced more on-line corrections in their reaching and grasping movements to the standard-sized spheres—but only under monocular viewing conditions. It appears that subjects are able to exploit the learned relationship between an object’s distance and its projected retinal image size to help program and control reaching and grasping movements when binocular vision is not available. Although the influence of familiar size on subjects’ perceptual estimates is less clear, it is clear that subjects’ perceptual estimates show poor absolute scaling for distance. This result further supports the notion that under normal viewing conditions the visuomotor system uses binocular information to program and control manual prehension, but is able to use pictorial information when binocular vision is denied. ■

INTRODUCTION

Previous studies have demonstrated that binocular vision is a critical source of distance information used by the visuomotor system to control object-directed grasping. Nevertheless, even in the absence of binocular vision, people are still able to reach out and pick up objects reasonably accurately using only monocular cues (Jackson, Jones, Newport, & Pritchard, 1997; Dijkerman, Milner, & Carey, 1996; Marotta, Perrot, Nicolle, & Goodale, 1995; Marotta, Perrot, Nicolle, Servos, & Goodale, 1995; Servos & Goodale, 1994; Servos, Goodale, & Jakobson, 1992). One source of monocular information that subjects can use to help calibrate reaching and grasping movements, is pictorial information from the goal object itself, or the scene in which it is embedded (Marotta & Goodale, 1998; Marotta, Behrmann, & Goodale, 1997). Pictorial (or static monocular) cues have been used by artists for years to give an impression of three-dimensional structure on a two-dimensional canvas. Local perspective and shape cues not only enable us to construct the spatial relations between objects in a scene, but with

experience, can be used to calculate the actual distance and size of objects we wish to pick up.

Marotta et al. (1997) examined the use of pictorial information in individuals with visual form agnosia. These individuals have damage to the ventral cortical stream of projections involved in visual perception that run from primary visual cortex (V1) to inferotemporal cortex but have an intact dorsal cortical stream that runs from V1 to posterior parietal cortex, which is believed to be involved in the visuomotor control of action (Milner & Goodale, 1995). Although these individuals had no problem calibrating their grasp when binocular vision was available, they failed to calibrate their grasp when one of their eyes was covered. Indeed, they seemed unable to make use of the pictorial cues that healthy subjects use when binocular information is unavailable (Marotta et al., 1997). Taken together, these findings suggest that pictorial cues are normally processed by the perceptual mechanisms in the ventral stream and then passed on to the visuomotor mechanisms in the dorsal stream.

In an investigation into the role that individual pictorial cues play in the programming and control of manual prehension, subjects made fewer on-line adjustments in the trajectory of their limb and the aperture of their fingers when the elevation of a target object in the visual scene could be used as a reliable source of distance

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information. This learned relationship between elevation and distance was used only under monocular viewing conditions. When binocular vision was available, the presence or absence of this learned pictorial cue did not influence the execution of the grasping movement.

Another potentially useful pictorial cue for the programming and control of reaching and grasping under monocular viewing conditions is the depth cue of "familiar size." The use of familiar size as a cue to distance is quite straightforward. The visual angle subtended by an object is inversely proportional to its distance. If an organism knows the retinal image size of an object at one distance, then it can use image size to calculate the distance of that object at any distance. This very simple method requires either that the observer is genetically endowed with knowledge of the size of the object or that the observer has an opportunity to learn its size (Collett & Harkness 1982; Hochberg, 1972; Schiffman, 1966). In other words, it is the knowledge of the relationship between an object's size and its retinal image that forms the basis for the pictorial cue of familiar size. For example, if we see an adult elephant in the zoo that projects a small retinal image size, then we assume that the elephant is far away from us. Of course, this conclusion would be untrue if it was the case that someone had replaced the real elephant with a small model of an elephant.

The role of pictorial cues in visual perception is part of a larger issue that turns on the traditional historical contrast between theories of "direct" and "indirect" perception. Indirect theories maintain that current sensory input cannot provide all that is required for perception and that the perceptual world is constructed instead through cognitive processes involving memory and inference that mediate or enrich that input (e.g., Rock, 1977; Helmholtz, 1890/1962). In contrast, theories of direct perception claim that visual perception is determined directly by the information present in the light reaching the eye, and is not mediated by higher-order inferences (e.g., Gibson, 1979). The depth cue of familiar size is particularly relevant to this debate because its effectiveness can be explained only by an indirect theory. The visual angle subtended by an object is determined jointly by an object's size and its distance from the observer; visual angle alone cannot specify distance. If an object's physical size is known, however, this knowledge can potentially be used to recover information for distance, since visual angle would then vary only as a function of distance. Perception of distance from familiar size, by definition, would involve enrichment of uninformative visual input by information stored in memory (Granrud, Haake, & Yonas, 1985).

Indirect cues, such as familiar size, are particularly useful when other direct cues are limited or unavailable. For example, Schiffman (1966) and Predebon, Wenderoth, and Curthoys (1974) have shown that familiar size has a bigger effect on perceived size and distance when

the number of direct cues is decreased. In contrast, when judging the distance of an object in a visually rich environment, it appears reasonable that subjects would make use of direct visual cues in the scene rather than first identifying the object and then referring to past experiences with similar objects to make the distance judgement. In a visually impoverished environment, however, the identification of the object and the memory of its size may become important for determining its distance.

A number of perceptual studies have demonstrated that familiar size influences subjects' judgements of object distance (O'Leary & Wallach 1980; Gogel, 1969; Gogel & Mertens, 1968; Gogel & DaSilva, 1987; Holway & Boring 1941). Traditionally, these studies have utilized off-sized examples of familiar objects (e.g., larger than normal playing cards) and have generally found that familiar size has an influence on the perceived size and distance of an object, particularly under monocular, or reduced-cue, viewing conditions (Holway & Boring, 1941). These studies lend further support to the indirect theory of visual perception. The observer uses knowledge stored in memory to extract information from otherwise uninformative visual input.

Although it is easy to see how indirect cues might play a significant role in perception, their use in the visual control of action is less obvious. As we have already discussed above, direct cues such as those provided by binocular vision appear to be the most important source of information about object size and distance in humans for planning and executing skilled movements such as object-directed grasping. Nevertheless, action systems are able to utilize more indirect sources of visual information, such as elevation in the scene (Marotta et al., 1998), when binocular cues are absent. Moreover, even familiar size, which is a quintessential example of an indirect cue, has been shown to play a role in the programming of movements in some animals. Gerbils, e.g., have been shown to use the familiar size of a landing platform to assist in the calibration of jumps that they have been trained to make to that platform (Goodale, Ellard, & Booth, 1990). After the gerbils had been trained with a standard-sized platform, off-sized probe platforms, which were slightly larger or smaller than the standard training platform, were inserted randomly during the testing sessions. The gerbils overjumped the edge of the platform when a small probe platform (which on the basis of their smaller retinal image size would appear farther away than they actually were) was presented but when a large probe platform (which would appear closer) was used, the gerbils underjumped and often fell short of the platform's edge. Moreover, this particular cue appears to be computed by visual mechanisms outside the geniculostriate pathway since gerbils with complete ablations of primary visual cortex are still able to use familiar size to compute their jumps, even though they cannot learn to tell apart large and small platforms in a traditional discrimination task

(Carey, Goodale, & Sprowl, 1990). These findings suggest that in some animals, at least, familiar size makes a fundamental contribution to the programming of visually guided movements.

The question remains, however, as to whether or not humans will use familiar size to program movements such as reaching and grasping. There have been some studies of reaching in infants that have looked at the role of familiar size. In most of these studies, however, the emphasis was on the decision to reach to one of two or more objects rather than on the actual kinematics of the movement itself. In other words, reaching was used as a “read-out” of the infant’s perceptual judgement of whether or not an object was within grasping distance. Yonas, Pettersen, and Grandrud (1982), e.g., showed that when infants were presented, one at a time, with larger-than-life-size and smaller-than-life-size photographs of adult female faces, they only reached to faces whose retinal image size indicated that the face was within range of their grasp. In other words, they reached significantly more for the large faces than for the small faces, suggesting that they perceived the large faces to be nearer than the small faces. In another set of studies (Grandrud et al., 1985), infants played with a pair of different-sized objects during a familiarization phase. During the test phase, two objects, identical to those seen in the familiarization phase but now equal in size, were presented to the infants side by side at a fixed distance. When the infants were reaching under monocular viewing conditions, they showed a reliable preference to reach for the “apparently nearer” object (the object that was smaller in the familiarization phase) in the test phase of the experiment. In contrast, under binocular viewing conditions, the infants showed no reaching preference, indicating that reaching preference observed in the monocular condition resulted from the perceived relative distances of the test objects and not from a preference acquired during the familiarization phase or from a preference to reach for the novel object in the test phase.

To date, there have been no investigations of the role of familiar size in the programming and control of grasping movements in humans, or any other animal, for that matter. The infant studies, as we have already emphasized, were more interested in effect of familiar size on the infants’ decisions rather than on the programming of the movements themselves. In the present study, therefore, we looked directly at whether or not human adults could use familiar size to plan a reaching and grasping movement, particularly in the absence of binocular vision. To do this, we created two different arrays in which goal objects, a range of different “grasp-sized” styrofoam spheres, could be presented. In the “familiar-size” presentation array, only one “standard” sized sphere was presented, which gave subjects an opportunity to learn the relationship between the standard sphere’s retinal image size and its distance. In the “multiple” spheres presentation array, subjects could

not learn such a relationship because on any one trial, one of four different sphere sizes could be present. In addition, we also directly tested whether or not subjects were using familiar size information to help program and control their reaching and grasping movements by “tricking” the system with larger and smaller off-sized probe spheres. These probe spheres were each presented at a distance so that they projected the same retinal image size as the “standard” sized sphere presented 44.5 cm from the observer.

Subjects were tested with each of these arrays under both monocular and binocular viewing conditions. We anticipated that subjects would have to rely on familiar size as a cue to distance only when binocular information was denied. Thus, when subjects viewed the two arrays monocularly, we expected them to show more on-line corrections when reaching to objects in which familiar size could not be exploited. In addition to the possible effects of familiar size on the programming of grasping movements, we also wanted to examine the effect of our familiar size paradigm on subjects’ perceptual reports of distance. Thus, we carried out a second experiment in which subjects were required to produce manual estimates of the distance of the spheres by sliding their index fingers apart along a horizontal rod placed perpendicular to the subject’s midplane until they were satisfied that the distance they were indicating matched the perceived distance of the sphere.

RESULTS

For each of the subjects, mean values of each of the dependent measures in each viewing condition were calculated. (Equipment failure resulted in some loss of data, but this constituted less than 4% of the trials). The on-line correction values were entered into separate 2×2 (presentation array \times viewing condition) repeated-measures analyses of variance. The peak velocity and estimated distance measures (from Experiment 2) were entered into separate $2 \times 2 \times 4$ (presentation array \times viewing condition \times distance) repeated-measures analyses of variance. All tests of significance were based upon an alpha level of 0.05. Post hoc Neuman–Keuls analyses were performed where necessary.

Experiment 1

Under monocular viewing conditions subjects produced more on-line corrections in their reaching and grasping movements when they were reaching to the standard sphere than they did when binocular vision was available. Monocular reaches exhibited significantly more peaks per trial [$F(1, 15)=70.44, p < .0001$] and plateaus per trial [$F(1, 15)=61.87, p < .0001$] in their velocity profiles than did binocular reaches (see Figure 1). Similarly, monocular grasping movements showed significantly more peaks per trial [$F(1, 15)=37.21, p <$

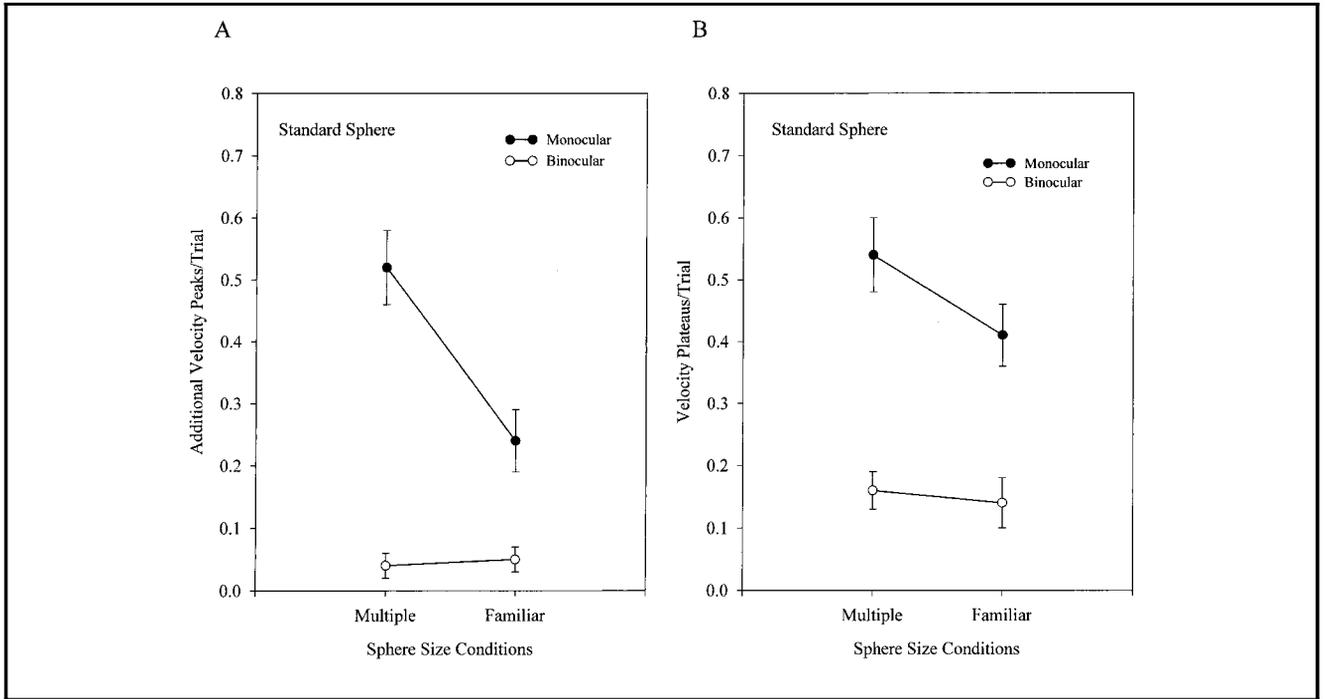


Figure 1. The effects of presentation array and viewing condition on (A) additional velocity peaks/trial and (B) velocity plateaus/trial made during reaches to the standard sphere (error bars = SEMs; closed circles = monocular viewing conditions; open circles = binocular viewing conditions).

.001] and plateaus per trial [$F(1, 15)=24.34, p < .001$] in their aperture profiles than binocular grasping movements (see Figure 2). In short, binocular reaches were simply more efficient than monocular reaches.

When the spheres were presented in the multisphere array, subjects showed significantly more peaks per trial

($p < .01$) and plateaus per trial ($p < .01$) in their velocity profiles than when the standard sphere was presented in the familiar-size array but only when they viewed the displays with one eye covered. Under binocular conditions, the number of additional velocity peaks per trial ($p > .05$) and plateaus per trial ($p >$

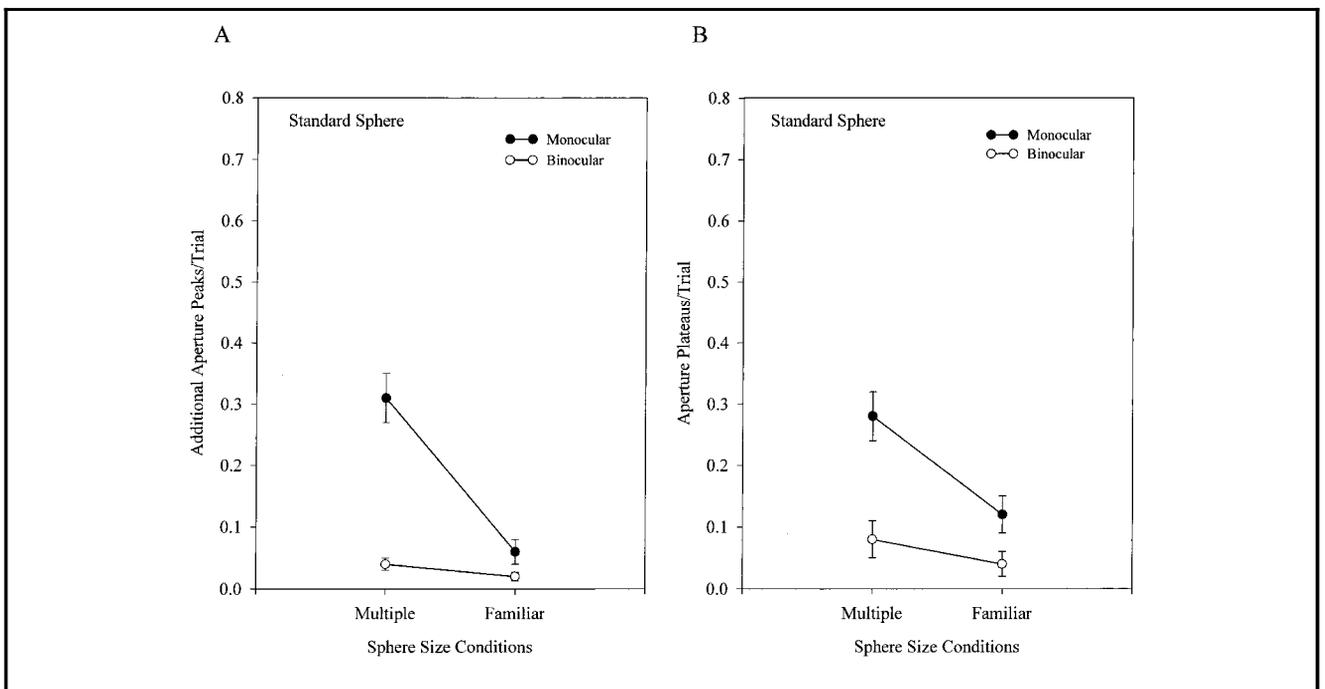


Figure 2. The effects of presentation array and viewing condition on (A) additional aperture peaks/trial and (B) aperture plateaus/trial made during reaches to the standard sphere (error bars = SEMs; closed circles = monocular viewing conditions; open circles = binocular viewing conditions).

.05) did not vary as a function of the presentation arrays. This interaction between the presentation arrays and the viewing conditions is evident in Figure 1 for both peaks [$F(1, 15)=34.33, p < .0001$] and plateaus [$F(1, 15)=7.82, p < .02$]. As can be seen in Figure 2, this pattern of results also holds for the number of additional aperture peaks ($p < .01$) and plateaus ($p < .01$) produced during these reaches [$F(1, 15)=52.20, p < .0001$; $F(1, 15)=14.12, p < .003$, respectively].

A rather different picture emerges for reaches to the large probe sphere. As before, subjects produced more on-line corrections in their reaching and grasping movements when they were reaching to the large probe sphere under monocular viewing conditions, than they did when binocular vision was available, but in only one measure, additional velocity peaks, was there an interaction between viewing and presentation conditions. Moreover, in this case, the pattern of mean differences was quite different to that seen with reaches to the standard spheres. In this case, the number of additional velocity peaks actually increased ($p < .01$) in the familiar size condition when subjects were reaching for the large probe spheres, but only under monocular viewing conditions. This interaction between the presentation arrays and the viewing conditions can clearly be seen in Figure 3, for the additional velocity peaks per trial produced during reaches to the large probe sphere [$F(1, 15)=16.98, p < .002$].

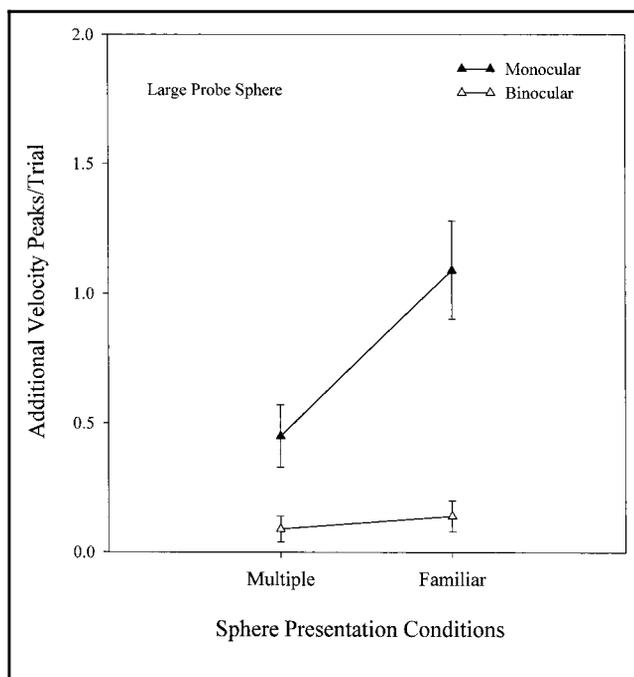


Figure 3. The effects of presentation array and viewing condition on additional velocity peaks/trial made during reaches to the Large Probe Sphere (error bars = SEMs; closed triangle = monocular viewing conditions; open triangle = binocular viewing condition).

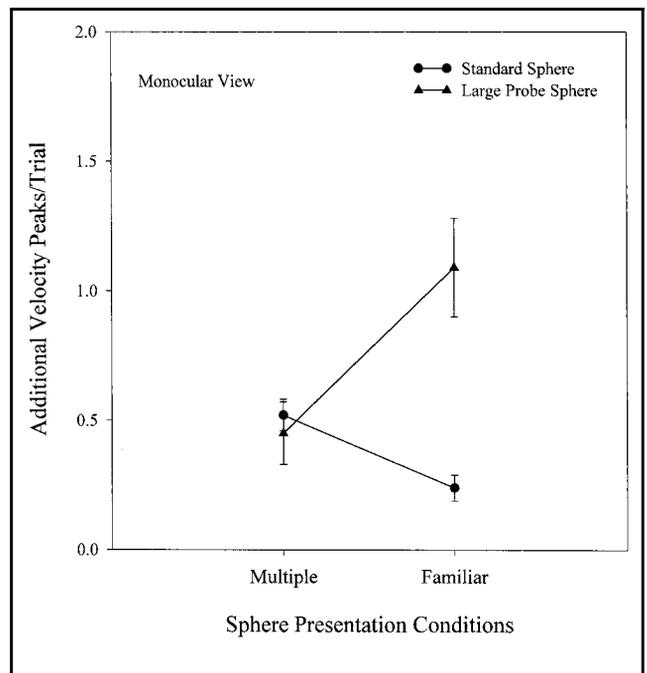


Figure 4. The effects of presentation array and sphere size on additional velocity peaks/trial made under monocular viewing (error bars = SEMs; closed circle = standard sphere; closed triangle = Large Probe sphere).

Figure 4 clearly illustrates the differing effects of familiar size on monocularly driven reaches to the standard sphere versus the larger probe sphere. When subjects reached to these two spheres under the multiple sphere presentation array, where familiar size could not be used as a cue to distance, the number of on-line corrections in their reaches did not differ ($t_{(15)}=0.703, p > .05$). When they reached to these same two spheres under the familiar size presentation condition, subjects now behaved very differently ($t_{(15)}=5.35, p < .0001$). Their performance with the standard sphere improved, because of course they could now use familiar size as cue. Their reaches to the large probe spheres, however, actually got worse, since the familiar size cue was now providing inaccurate distance information; in other words, they were treating the probe sphere as if it were the standard sphere closer to them. Reaches to the smaller probe sphere did not vary as a function of either view or presentation array. One would expect that if the subjects overestimated the distance of the small sphere and encountered it sooner than anticipated, they would be unable to decelerate properly and would collide with it with some force. On occasion, such collisions did occur, and when they did, were obvious to both the subjects and the experimenter. Unfortunately, such collisions (or near collisions) were difficult to measure unambiguously.

As can be seen in Figure 5, subjects show good relative and absolute scaling for distance in their peak velocity. In fact, when familiar size was available, subjects

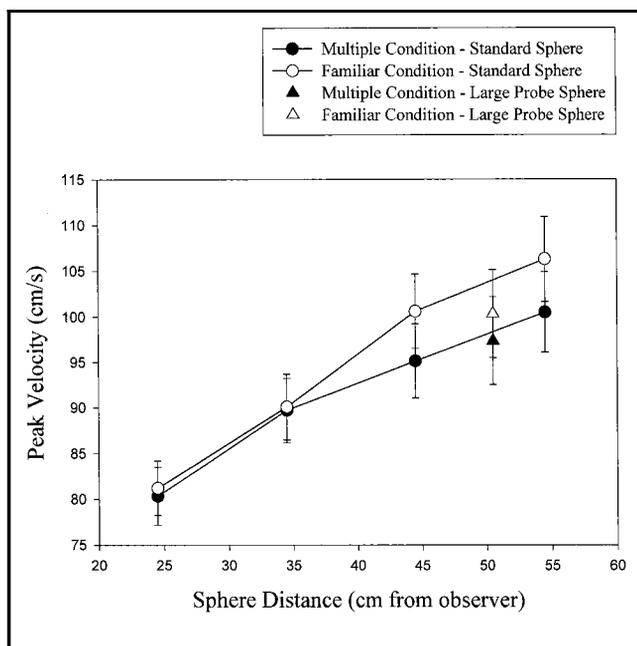


Figure 5. The effects of presentation array and sphere distance on peak velocity (error bars = SEMs; circle = standard sphere; triangle = Large Probe Sphere [closed = multiple presentation condition; open = familiar presentation condition]).

showed better velocity scaling for distance to the further spheres, although there was no significant difference ($p > .05$) in the peak velocity of reaches made to the large probe sphere and the standard sphere presented at 44.5

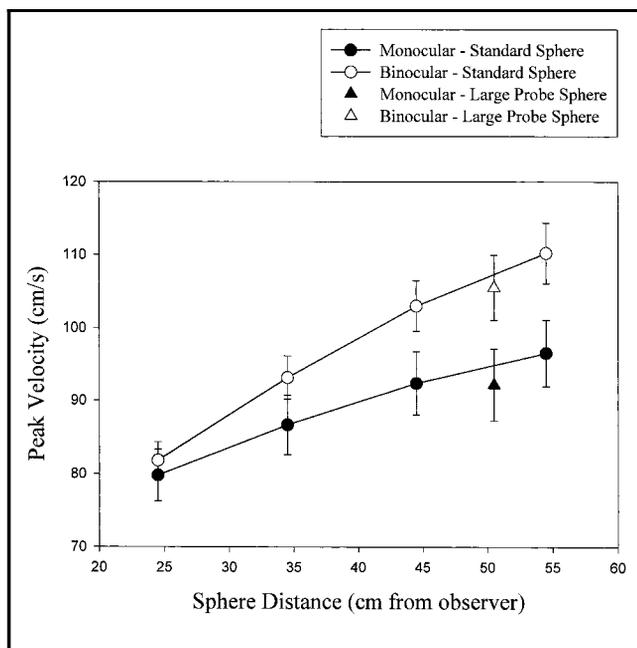


Figure 6. The effects of sphere distance and viewing condition on peak velocity (error bars = SEMs; circle = standard sphere; triangle = Large Probe Sphere [closed = monocular viewing condition; open = binocular viewing condition]).

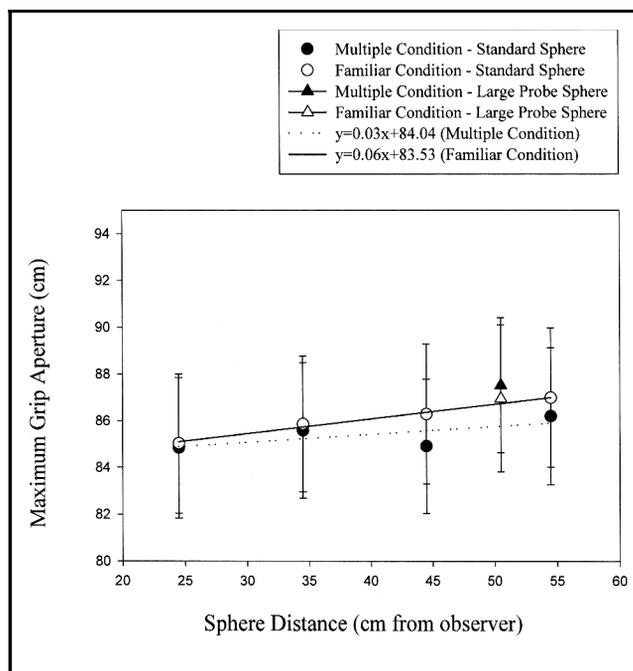


Figure 7. The effects of sphere distance and presentation array on maximum grip aperture (error bars = SEMs; circle = standard sphere; triangle = Large Probe Sphere [closed = multiple presentation condition; open = familiar presentation condition]).

cm. This was not the case under the multiple viewing condition, where subjects showed proper relative scaling but within a slightly compressed range [$F(4, 60)=5.33, p < .002$]. Figure 6 shows that subjects scaled better for distance under binocular than monocular viewing conditions [$F(4, 60)=16.87, p < .001$], where there was no significant difference ($p > .05$) in peak velocity to the large probe sphere and the standard sphere at 44.5 cm (see Figure 6). Further evidence for this good absolute scaling for distance can be seen in Figure 7, where subjects show excellent size constancy across distance in their grip aperture; in other words, they opened their hand the same amount for a given object independent of viewing distances.

Experiment 2

While subjects' manual estimates show good relative scaling for distance, absolute scaling was poor, with subjects overestimating the distance of closer spheres and underestimating more distant ones. Unlike Experiment 1, there was no significant interaction between the two presentation conditions (multiple and the familiar size arrays) and distance [$F(4, 20)=1.01, p > .05$] (Figure 8). There was an interaction between viewing condition (binocular and monocular) and distance [$F(4, 20)=2.94, p < .05$]. Under binocular viewing conditions, there was no significant difference in the reported distance of the probe sphere and the standard sphere at 44.5 cm ($p > .05$). Under monocular conditions,

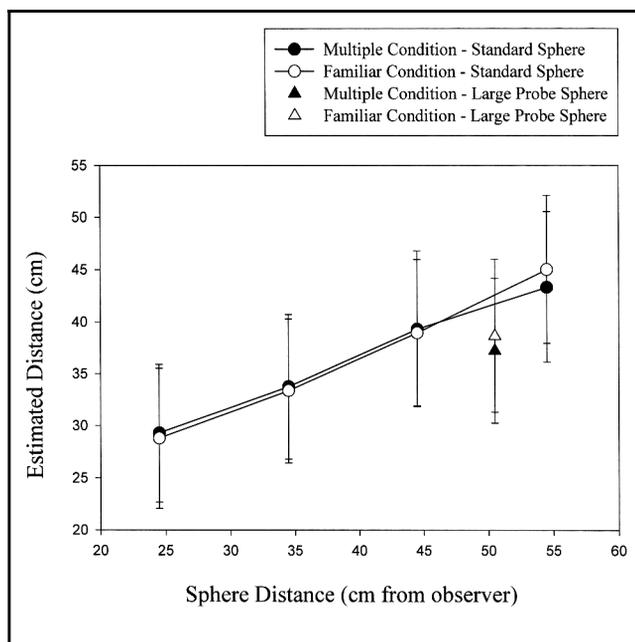


Figure 8. The effects of sphere distance and presentation array on estimated distance (error bars = SEMs; circle = standard sphere; triangle = Large Probe Sphere [closed = multiple presentation condition; open = familiar presentation condition]).

however, the manual estimate for the distance of the probe sphere was actually less ($p < .05$) than that of the standard sphere presented at 44.5 cm (Figure 9).

DISCUSSION

When familiar size could not be used as a cue to distance, subjects produced more on-line corrections in their reaching and grasping movements to the standard-sized spheres, corrections that were evident as additional peaks and plateaus in their velocity and aperture profiles—but only under monocular viewing conditions. It appears that subjects are able to exploit the learned relationship between an object's distance and its projected retinal image size to help program and control reaching and grasping movements when binocular vision is not available.

Marotta and Goodale (1998) reported that the addition of reliable pictorial cues such as elevation did not improve the performance of a reaching and grasping movement, if there was already binocular information available in the scene. It is possible, however, that pictorial information normally combines with binocular information but that a ceiling effect in performance was reached. In other words, binocular performance was so good on its own that the addition of reliable pictorial information had no noticeable effect. In the present study, we tested this possibility directly by pitting binocular information about the distance of the large off-sized probe sphere against information provided by familiar size. If the visuomotor system were to somehow com-

bine this faulty distance information gained from familiar size with the accurate binocular information, one might expect to see an impairment in performance (as measured by on-line corrections) when pictorial information is added to a binocular scene. Keep in mind that there is no way for the visuomotor system to know that the familiar size information is inaccurate prior to the first reach. In fact there were no differences in performance when pictorial information was added to the binocular scene. It appears, in the present experiment at least, that the visuomotor system ignored, or did not take into account, familiar size information in its calculations when binocular cues were available. In short, binocular cues seem primary in visuomotor control.

The importance of binocular information in the control of reaching and grasping fits well with the idea that direct cues, in which spatial information can be derived directly from the visual array, are the main source of information for the control of skilled movements. Nevertheless, when such cues are not available, the system appears to be flexible enough that it can marshal information about object size and distance from indirect sources, such as elevation and, as we have seen in this study, familiar size. Thus, the debate about whether human vision uses direct or indirect cues depends not only on whether one is talking about the visual control of action or visual perception but also on the task at hand.

But what about the perceptual estimates of distance that the subjects made in our second study? How were

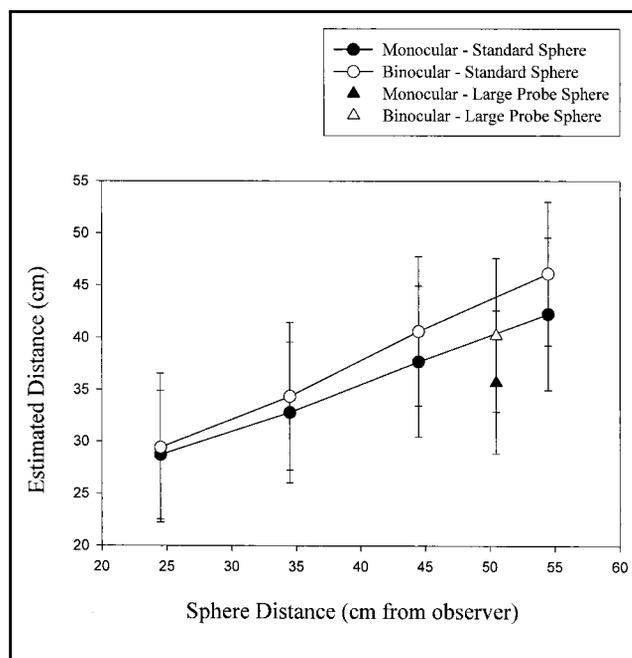


Figure 9. The effects of sphere distance and viewing condition on estimated distance (error bars = SEMs; circle = standard sphere; triangle = Large Probe Sphere [closed = monocular viewing condition; open = binocular viewing condition]).

they influenced by the availability of familiar size and binocular cues? The answer, in fact, is not entirely clear. Subjects did not differ in their performance with the multiple and the familiar size arrays. With both arrays, their absolute distance estimates were quite compressed, a finding that has been documented and discussed before (Philbeck & Loomis, 1997; Gogel, 1961; Gogel & Tietz, 1973).

It is possible that when subjects were asked for a perceptual estimate of distance, they were able to use familiar size information in the multiple presentation array as well as the familiar-size array. In other words, the subjects were able to learn and categorize the four different spheres and then perform the appropriate size–distance computation. This conclusion is supported by the fact that subjects were fooled by the off-sized probe sphere even under the multiple presentation array. Another possibility is that subjects could be using some other indirect cues to distance, such as texture. For example, since the styrofoam of the large spheres had the same texture as the styrofoam of the small spheres, it would be possible to use the grain of texture on the retina combined with image size to compute distance (Sedgwick, 1986).

It appears either that subjects used different cues for their perceptual estimates than they did during grasping, or that the same cues were being processed in different ways. Whatever the case, it is clear that subjects behaved differently when making their estimates than they did when programming their grasp. Unlike their reaching and grasping performance, subjects' perceptual estimates show poor absolute scaling for distance; it may be that the perceptual system needs to have explicit knowledge about the size of an object to make efficient use of perceptual cues to distance, such as familiar size. As discussed in the Introduction, in previous perception studies this explicit knowledge has been achieved by using more "familiar" objects, like playing cards or a soda can.

In summary, the influence of familiar size on reports of distance in our paradigm (where subjects had to learn a size–distance relationship for an object that had never been encountered before) still remains unclear. Nevertheless, the study does provide clear evidence that they have no problem using this learned relationship to program and control their reaching and grasping movements—but only when binocular information is not available. Moreover, this learning appears to take place quite implicitly since they show no conflict between binocular information and the incorrect information provided by the large probe sphere. These results further support the notion that under normal viewing conditions the visuomotor system uses binocular information to program and control manual prehension but is able to use pictorial information, presumably processed by the ventral stream, when binocular vision is denied.

METHOD

Experiment 1

Subjects

Sixteen right-handed subjects (eight males, eight females; age range = 19–33 years old; mean age = 25.7 years) with normal or corrected-to-normal vision participated in the experiment, for which they were paid. Subjects were strongly right-handed, as determined by a modified version of the Edinburgh Handedness Inventory (Oldfield, 1971). All subjects had stereoscopic vision in the normal range with assessed stereoacuity of 40" of arc or better as determined by the Randot Stereotest (Stereo Optical, Chicago).

Apparatus

Four sizes of styrofoam spheres (6.4, 7.6, 8.9, and 10.2 cm in diameter) were presented one at a time on a rod that could be positioned in a vertical matte black presentation board (183 by 120 cm). The center of each sphere contained four light-emitting diodes (LEDs) controlled by computer. The voltage sent to each sphere was controlled so that the surface luminance levels for each size sphere was equivalent (10 cd/m², as measured by a light meter). [It should be noted that perfect spheres would offer no retinal disparity cues to depth or distance. Of course, the styrofoam spheres used were not perfect and in addition they had a textured surface. Moreover, even with perfect spheres, other binocular cues such as convergence would provide depth information.]

The spheres were presented one at a time, at eye level (24.5, 34.5, 44.5, and 54.5 cm from a start key located 69.5 cm in front of the board, 57 cm below eye level). The spheres were presented in two different presentation arrays. In the familiar-size presentation condition, subjects reached only to the 7.6-cm sphere, which will be referred to as the "standard" sphere size. This condition gave subjects an opportunity to learn the relationship between the standard sphere's retinal image size and its distance. In the multiple spheres presentation condition subjects could not learn such a relationship because on any one trial one of four different sphere sizes could be present. In addition, larger (8.9 cm) and smaller (6.4 cm) off-sized probe spheres were presented in each array on a few trials towards the end of a block of regular trials. Each probe was presented at a distance from the observer such that its retinal image size was equivalent to that of the 7.6-cm sphere presented 44.5 cm away; thus, the large probe was presented 50.5 cm from the observer and the small probe was presented 39 cm from the observer. Reaches to the standard-sized sphere and the off-sized probes were compared between conditions.

Subjects sat in an adjustable chair with their hand on the start key. They wore PLATO spectacles (Translucent

Technologies, Toronto) throughout the testing sessions. These liquid-crystal shutter spectacles permitted monocular or binocular viewing and when both shutters were closed prevented subjects from viewing the spheres being put into position. Subjects also wore earphones that emitted white noise between trials to prevent subjects from using any audible cues from the spheres being put into position. The room was dark and subjects reached for the spheres, which remained lit for 2.5 sec under monocular and binocular viewing conditions.

Three 8-mm-diameter infrared light-emitting diodes (IREDs) were attached to the subject's right hand. Subjects wore a watchband on which an IRED was mounted on an aluminum extension 3 cm above the radius at the wrist, another aluminum extension raised an IRED 2 cm above the ulnar border of the thumbnail and the final IRED was placed on the distal portion of the index fingertip. The aluminum extensions were used to allow the infrared-sensitive camera system (OPTOTRAK) an optimal view of each IRED.

The IREDs were monitored by an OPTOTRAK positioned approximately 2 m from the subject. The 3-dimensional coordinates of the IREDs were stored by the OPTOTRAK's data acquisition unit and later filtered off-line (with a low pass second-order Butterworth filter with a 7-Hz cut-off).

Procedure

At the beginning of the test session, subjects were given a handedness questionnaire and tested for eye dominance (viewing preference). Subjects were then seated in front of the presentation board with the tips of their index finger and thumb of their right hand on the start button. Their chair was adjusted so that the spheres would fall along the same line of sight at eye level. Subjects were instructed to reach out quickly, accurately and as "naturally" as possible to the sphere as soon as it appeared and to grab hold of it with their whole hand but not to pull it off the rod. They were instructed to hold onto the sphere until they heard a tone signaling the end of the trial. The experimenter initiated the start of a trial by signaling the computer simultaneously to activate the goggles, which allowed the preferred eye to view the scene, and to illuminate the spheres for a period of 2.5 sec.

Subjects were administered four testing blocks. The two "multisphere" testing blocks consisted of 70 experimental trials, with seven instances of the standard 7.6-cm-diameter sphere at each of the four presentation distances, three instances of each of the remaining size \times distance combinations, four instances of the large probe trials, and two instances of the small probe trials. The two familiar-size testing blocks consisted of 34 experimental trials, with seven instances of the standard 7.6-cm-diameter sphere at each of the four distances, four instances of the large probe trials and two instances

of the small probe trials. Trial presentation was pseudorandomized with probe trials placed in the second half of each block. Each testing block was preceded by five practice trials. Testing took place over two sessions, with one day between test sessions, the multisphere session lasted for approximately 90 min and the familiar-size session lasted for approximately 40 min. All presentation conditions and test sessions were counter-balanced across subjects.

Dependent measures

Velocity. In a typical reach, subjects accelerate smoothly to a peak (or maximum) velocity and then decelerate as their hand approaches the object to be grasped. Occasionally, however, subjects show on-line adjustments in the reach that are evident as "additional peaks and plateaus" in the velocity profile (Marotta et al., 1998). The number of these additional velocity peaks and plateaus can be used as a measure of "efficiency" of the reach and of the quality of the subjects' absolute scaling for distance. The fewer on-line corrections that occur, the more efficient the reach, and the more accurate the absolute distance estimate was. The number of additional peaks and plateaus were recorded for each trial. In addition, subjects' peak velocity was also used as a measure to determine subjects' relative scaling for distance during a reach.

Aperture. In a typical grasp, subjects open their hand smoothly to a peak (or maximum) aperture and close it as their hand approaches the object. As with their reach, occasionally subjects adjust their grasp on-line. Again these adjustments are reflected as additional peaks and plateaus in the aperture profile. The number of these additional aperture peaks and plateaus were recorded for each trial.

Experiment 2

Subjects

Six subjects participated in the experiment (four males, two females; age range = 26–31 years old; mean age = 27.8 years old). All subjects participated for financial compensation, were strongly right-handed and had normal or corrected-to-normal visual acuity and stereoscopic vision.

Procedure

The apparatus and procedure were identical to those used in Experiment 1, except that instead of reaching to the spheres, subjects were required to produce manual estimates of the presented sphere's distance by sliding the forefinger of each hand along a horizontal white rod mounted in front of the start key (parallel to the presentation board). Subjects began with their two fingers on the rod just in front of the start button

used in Experiment 1. When the sphere was illuminated, they separated their fingers by an amount that matched the perceived distance of the sphere from their head. They were instructed to hold their fingers still when they were satisfied with their estimate. Two 8-mm IREDs were placed on each forefinger to accurately record their manual estimates. In addition, the number of trials per presentation block were reduced. The two “multisphere” testing blocks consisted of 46 experimental trials, with four instances of the standard 7.6-cm-diameter sphere at each of the four presentation distances, two instances of each of the remaining size \times distance combinations and six instances of the large probe trials. The two familiar-size testing blocks consisted of 22 experimental trials, with four instances of the standard 7.6-cm-diameter sphere at each of the four distances and six instances of the large probe trials. All blocks were run in the same session, which lasted approximately 90 min.

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