Perception & Psychophysics
1997, 59 (7), 1153-1159

Holding an object one is looking at: Kinesthetic information on the object's distance does not improve visual judgments of its size

ELI BRENNER, WIM J. M. VAN DAMME, and JEROEN B. J. SMEETS
Erasmus Universiteit, Rotterdam, The Netherlands

Visual judgments of distance are often inaccurate. Nevertheless, information on distance must be procured if retinal image size is to be used to judge an object's dimensions. In the present study, we examined whether kinesthetic information about an object's distance—based on the posture of the arm and hand when holding it—influences the object's perceived size. Subjects were presented with a computer simulation of a cube. This cube's position was coupled to that of a rod in the subject's hand. Its size was varied between presentations. Subjects had to judge whether the cube they saw was larger than, smaller than, or the same size as a reference. On some presentations, a small difference was introduced between the positions of the rod and of the simulated cube. When the simulated cube was slightly closer than the rod, subjects judged the cube to be larger. When it was farther away, they judged it to be smaller. We show that these changes in perceived size are due to alterations in the cube's distance from the subject rather than to kinesthetic information.

To judge an object's dimensions from the size of its retinal image requires a measure of the object's distance.[1] There are many potential sources for information on distance. However, none of these sources on their own appear to be very good at specifying the absolute distance (for monocular sources, see Sedgwick, 1986; for binocular sources, see Collewijn & Erkelens, 1990). Presumably, numerous retinal and oculomotor sources of information are combined with all sorts of assumptions to obtain a better estimate of the distance. When one holds an object in one's hand, kinesthetic information from the arm could provide additional information on the object's distance (we use the term *kinesthesia* to cover all information one acquires from holding or grasping an object; for an overview, see Clark & Horch, 1986). Does this additional information improve our visual judgments of the object's size? A recent study by Carey and Allan (1996) suggests that it may.

In a first attempt to answer this question (Brenner, van Damme, & Smeets, 1995), we asked subjects to set the size of a ball that they could see but not feel (an image on a computer screen) to match the size of a ball that they could feel but not see. We compared performance when the ball they felt and the one they saw were at very different positions with performance when the two coincided (the image was presented via a mirror) and with performance when the felt position was slightly nearer or farther away than the visual simulation (in an attempt to induce systematic errors). Neither the average nor the variability in the set size of the visible ball was affected.

The felt distance did not influence the visually perceived size. Was this because it cannot, or because subjects were too aware that the ball they felt was not the one they saw?[2] There were at least three reasons for subjects to be aware that it was not the same ball. The first is implicit in the task itself: asking subjects to match the seen and felt size implies that they are seeing and feeling separate entities. The second is that the felt size did not change when they changed the size of the visible ball. The third is that their hand never occluded their view of the ball.

In the present study, we avoided these issues by having subjects feel the size of one object—a cube—with their left hand while they moved another, visible cube with their right hand. The task was to compare the two sizes rather than to match them. To provide as much kinesthetic information about the visible cube's distance as possible without letting subjects feel its size, the subject held the visible cube by a rod. To avoid conflicts with dynamic touch when wielding the rod (Burton, Turvey, & Solomon, 1990), a real cube—identical to the one in the subject's left hand—was attached to the rod at the position of the visual cube. In the rest of the manuscript we will use the phrase *the position of the rod* to refer to the position of the real cube attached to the rod.

EXPERIMENTS 1 AND 2

Two experiments were conducted in separate sessions, several weeks apart. The main difference between the two experiments was whether subjects were allowed to move the rod and cube around or had to hold it still. Freedom to move the rod around could add both kinesthetic and

Correspondence should be addressed to E. Brenner, Erasmus Universiteit, Vakgroep Fysiologie, Postbus 1738, 3000 DR Rotterdam, The Netherlands (e-mail: brenner@fys1.fgg.eur.nl).

visual information on distance. This might lead to more accurate judgments, but it is not a priori evident whether it would lead to more or less influence of kinesthesia.

Method

Subjects were given a 5-cm cube that they were asked to look at before the experiment started and to hold under the table in their left hand during the experiment. In their right hand, they held an 11-cm-long, 2-cm-diameter rod attached to a copy of that cube. A simulated cube was presented on a computer monitor (34.2 × 26.8 cm; 1,280 × 492 pixels). A vertical mirror that receded to the left at an angle of 45° made the image on the monitor appear to lie in front of the subject (see Figure 1A). The room was dark, so subjects were unable to see anything except for the image on the screen. A piece of black cardboard prevented subjects from seeing the image on the monitor directly, rather than by way of its reflection in the mirror.

The subject's arm could pass under the mirror so that the rod and cube could be moved around behind it. The cube was either simulated at the exact position at which the cube attached to the rod was held, 25 mm closer to the subject, or 25 mm farther away. The simulated cube always had the same orientation as the one in the subject's hand, but its size varied from 30 to 70 mm (in 5-mm steps) between trials. Holding the cube by a rod, rather than holding the cube itself, ensured that haptic information on the cube's size could not influence vision when the simulated cube was larger or smaller than 5 cm, and circumvented the problem of the image not being occluded by the subject's hand.

The simulation was of a cube with lambertian surfaces illuminated by a distant light source, 60° above and behind the subject, and a diffuse illumination (nine times weaker). Images were presented at a rate of 120 Hz. Liquid crystal shutter spectacles ensured that alternate frames were presented to the left and right eyes (with the appropriate perspective for each eye). The simulated cube was red because the liquid crystal shutter spectacles work best at long wavelengths (resulting in a maximal luminance at the eye of about 1 cd/m^2). Each eye received a newly calculated image every 16.7 msec. To have as little as possible conflict with accommodation, the screen was placed at the distance—as seen through the mirror—at which we expected subjects to hold the cube.

We did not restrict head movements because doing so has been shown to impair both hand and eye movements (Biguer, Prablanc, & Jeannerod, 1984; Collewijn, Steinman, Erkelens, Pizlo, & van der Steen, 1992). Changes in the position and orientation of the cube and of the head were accounted for with a delay of less than 50 msec. To be able to do so, the positions of active infrared markers attached to the cube and to the shutter spectacles were determined to within 0.1 mm with a movement analysis system (Optotrak 3010, Northern Digital, Inc.).

Procedure. In both experiments, the subject looked at a cube for some time and then moved a small marker that replaced the cube (after a 500-msec dark interval) toward one of three panels to indicate whether the cube he/she had seen was larger, the same, or smaller than the one in his/her left hand (Figure 1). The marker was a small block that was simulated at the center of the cube in the right hand. The three simulated choice panels were aligned horizontally in a frontal plane just comfortably within reach with the rod and marker.

In the first (dynamic) experiment, the subject looked at a moving cube for 7 sec. On the trials of the three above-mentioned conditions (visible cube coincides with rod, is 25 mm nearer, or is 25 mm farther away), the subject was free to move the cube around in his/her right hand as he/she liked. The simulated cube moved accordingly. On trials of the fourth condition the subject was instructed to put down the rod and cube. The simulated cube that appeared when he/she did so moved according to the way he/she had moved his/her hand on one of the previous trials (selected at random from all prior trials of the other three conditions, but each only used once). After 7 sec it disappeared and the subject picked up the rod and cube and selected the appropriate response panel. Note that the cube in the fourth condition was simulated to be at the position of

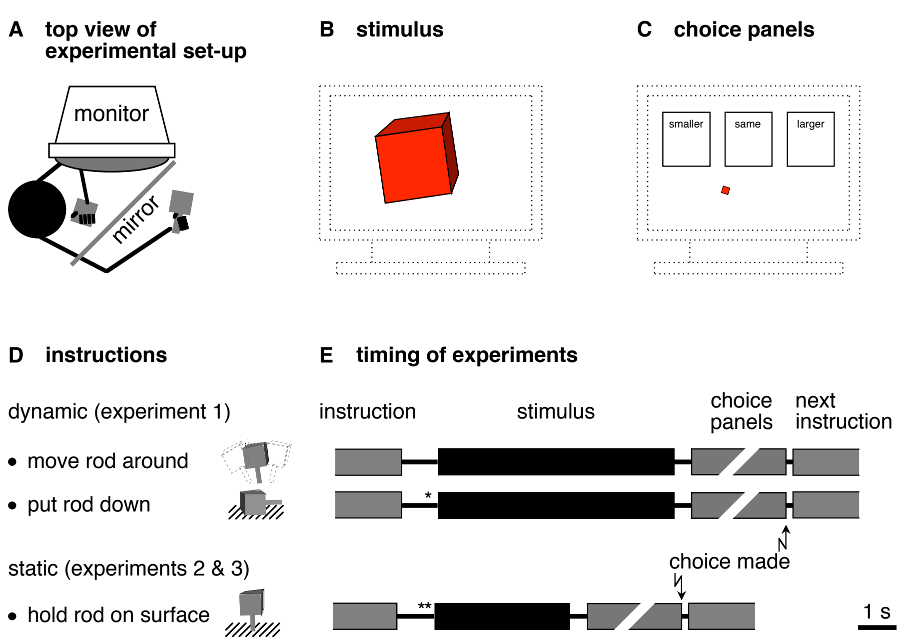

Figure 1. Schematic representation of the setup (A), of the image during (B) and after (C) each presentation, of the instructions (D), and of the timing of the experiments (E). When necessary, the instructions were repeated until the rod was lying (*) or standing (**) on the surface as instructed. The subject made his/her choice by moving the rod (and small visible marker) to the appropriate choice panel. The thick lines in (E) denote dark intervals of, consecutively, 1, 0.5, and 0.1 sec.

the rod (not of the sumulated cube) on the previous trial. Moreover, the image was obviously rendered in accordance with the actual position of the head, not its position during the selected trial.

In the second (static) experiment, there were only three conditions, corresponding with the first three conditions of the dynamic experiment. The subject now had to place the rod on a surface (with the cube on top) and hold it still for 4 sec. If the cube moved more than 10 mm from its initial position, the trial was aborted. Trials (in both experiments) were also aborted whenever the infrared markers fell out of sight of the measuring device. Whenever trials were aborted, a message on the screen informed the subject of what had happened, and the trial was repeated at some later stage of the experiment. For each condition, subjects were presented with nine sizes of the simulated cube. Each size was presented six times. Within each experiment, the trials (three or four conditions, nine sizes, six times each) were conducted in random order.

Subjects and Instructions. Seven subjects took part in each experiment, including two of the authors. All had normal binocular vision and were right-handed. The two authors were obviously aware that the distance of the cube in their right hand could differ by 25 mm from that of the simulated cube, but were unable to detect when this was so. The other subjects received no information on this matter. Only 1 subject reported that the simulation did not correspond with where she held the rod (this was the subject with the most extreme systematic error in the static experiment). Subjects were instructed to indicate whether the cube they saw was larger, the same, or smaller than the one they held in their left hand. In the first experiment, they were encouraged to move the rod (except for during trials in which they were asked to put it down). In the second experiment, they were instructed to keep the rod still.

Analysis. A measure of response frequency was calculated for each subject, condition, and size of the simulated cube. The response frequency is the difference between the number of times the subject responded "larger" and the number of times the subject responded "smaller" divided by the total number of responses (including the times the subject responded "same"). Thus, the response frequency varied from −1 to 1 (indicating that the simulated cube changed from always looking smaller to always looking larger) as the size of the simulated cube increased. A response frequency of zero indicates that the simulated cube was judged to be the same size as (or as frequently judged to be larger as judged to be smaller than) the reference.

From the response frequencies we estimated the matching size: the size of the simulated cube at which a linear fit to the relevant part of the data intersects the response frequency of zero. We defined the relevant part of the data as the section between the minimal and maximal obtained values of response frequency, including each of these values once. An example is shown in Figure 2. The filled circles show the values used for the fit. The arrow indicates the matching size.

As a measure of the accuracy with which subjects could make the required comparison, we determined the range of simulated sizes for which subjects were not certain of the simulation being larger or smaller on 50% of the presentations. This was done in a manner analogous to the way we determined the matching size—by taking the difference between the simulated sizes that lead to response frequencies of −0.5 and 0.5 (this is the reciprocal of the slope of the fit line in Figure 2).

Wilcoxon signed rank tests were used to compare performance (matching size and accuracy) when the simulated cube was at the same position as the one in the subjects' hands with their performance in each of the other conditions.

Results

Figure 3 shows the matching sizes for all 7 subjects in each condition of each experiment. Each line (and filled circle) shows the data for 1 subject. The left part shows the values for the first (dynamic) experiment. The right part shows the values for the second (static) one. The dotted lines connect the data for the 3 subjects (including two of the authors) who took part in both experiments. It is evident from the vertical separation of the lines that subjects made distinctive systematic errors when comparing what they saw with the reference. Most subjects underestimated the size of the simulation relative to that of the reference.

Displacing the simulated cube away from the rod clearly influenced the comparison with the reference (the lines in Figure 3 are not horizontal). The median changes are shown in Table 1. For the seen and felt cubes to appear to be the same size, the simulated cube had to be significantly larger when it was farther away than the rod ($p < .05$ for both the dynamic and the static experiment). It had to be significantly smaller when the simulated cube was nearer ($p < .05$ for both experiments). The size that matched the reference was not significantly different when the motion of the simulated cube was unrelated to the movement of the arm at that moment (symbols; rod on table in dynamic experiment) than when the simulated cube was at the same position as the rod ($p > .05$).

The accuracy with which subjects could make the required comparison is summarized in Table 2. Subjects tended to be more accurate when the simulated cube coincided with the one they were holding, but none of the differences were statistically significant ($p > .05$).

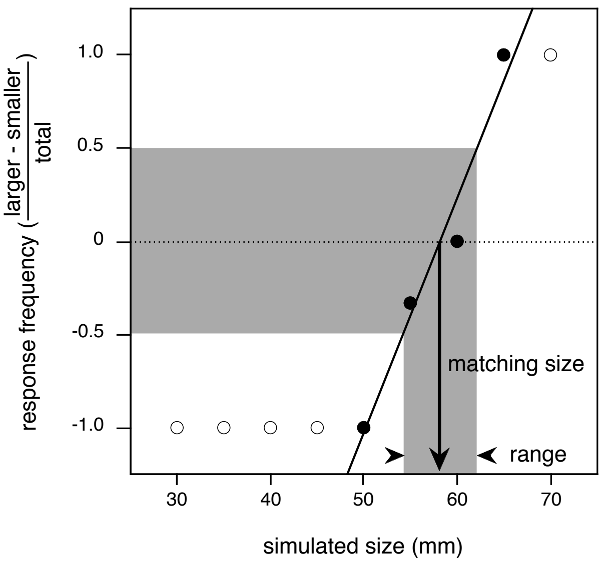

Figure 2. Summary of 1 subject's choices when the simulated cube was 25 mm farther away than the real—but invisible—cube at the end of the rod. The subject was free to move the rod around as he pleased. His response frequencies (calculated from the number of times he judged each simulated size to be the same as, larger than, or smaller than the reference) were used to determine the size at which the simulation matched the reference—when the linear fit to the values between the extremes (including each once; filled circles) intersected the response frequency of zero. Similarly, the range of simulated sizes that could be considered the same as the reference was estimated from the fit line's intersections with the response frequencies of −0.5 and 0.5.

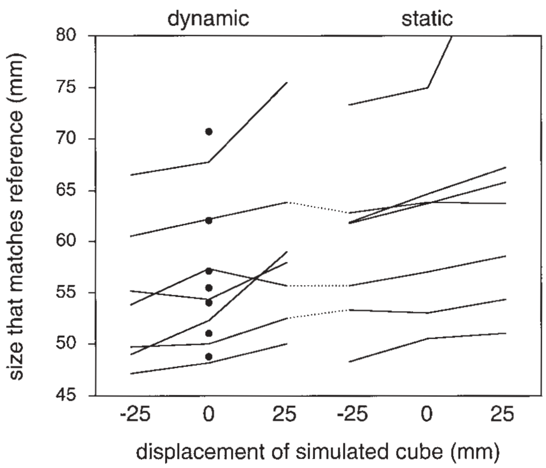

Figure 3. Matching sizes of all subjects in all conditions of Experiments 1 and 2. The lines connect individual subjects' values. A negative displacement indicates that the simulated cube was nearer than the cube attached to the rod in the subject's hand. A positive displacement indicates that it was farther away. During dynamic trials (Experiment 1), subjects moved the rod around for 7 sec before responding. During static trials (Experiment 2), the subjects held the rod still for 4 sec. The dotted lines connect the data for the 3 subjects who took part in both the static and the dynamic experiments. The filled circles show the matching sizes when the subject put the rod down on the table and watched the simulated cube move as it had during an earlier trial. The order of the subjects (increasing matching size) was the same for the consistent trials (line at no displacement of simulated cube) and for the simulation-only trials (filled circles).

Discussion

Subjects made considerable systematic errors, even when kinesthesia was consistent with vision. The size of the reference (50 mm) was often not even within the range of simulated cube sizes that were deemed to match it (see, e.g., Figure 2). We cannot explain these systematic misjudgments. There is reason to believe that it is the felt size of the reference that is misperceived (e.g., Teghtsoonian & Teghtsoonian, 1970), but not all studies support this opinion (e.g., Abravanel, 1971). Moreover, the misperception could be due to unforeseen aspects of the experiment (e.g., Kelvin & Mulik, 1958). We circumvented having to find an explanation for the systematic errors by comparing individual subjects' performance under different conditions.

The results are consistent with a tendency to consider the visible cube to be where it is held. When the simulated cube is 25 mm nearer than the rod, the decrease in simulated distance increases the simulated cube's retinal image size. If the retinal image is considered to belong to a cube that is farther away—closer to where the rod is held—the cube will appear to be larger than simulated, and a smaller cube will match the reference. Conversely, when the cube is simulated 25 mm farther away than the rod, a larger simulated size is needed to match the reference.

If subjects had relied completely on kinesthetic information about the cube's distance when interpreting the retinal image, the size misjudgment would have been almost 3 mm (for a viewing distance of about 45 cm). Table 1 shows that the actual influence was about 1.7 mm. Thus the perceived size corresponds with a distance about half-way between the rod and the simulated cube.

Although these results appear to support an important role for kinesthesia, there are reasons to doubt the validity of concluding that kinesthetic information from the arm influences the visually perceived size. Foremost is the surprising finding that neither the matching size nor the accuracy was different when a moving cube was shown with the rod on the table than when the simulated cube was at the position at which the subject held the rod.

The influence of the position of the simulated cube—relative to the rod—on the perceived size is evident. However, this influence is not necessarily due to kinesthetic information from the arm. If subjects always held their hands at about the same distance, the simulated cube would have been nearer than average when presented too near, and farther than average when presented too far away. A nearer cube would have given a larger retinal image, and one that was farther away would have given a smaller one. For veridical size perception, information about the cube's distance may be used to scale the retinal image so that this does not influence the perceived size. If only part of the change in distance is accounted for, however, the simulated cube will appear to be larger when nearer, and smaller when farther away. Thus, a tendency to underestimate the range of simulated distances—irrespective of the position of the rod—could account for our results.

Subjects have been reported to underestimate the range of presented distances when a target is seen in isolation, albeit under more limited conditions than those used in the present study (see, e.g., Collett, Schwarz, & Sobel, 1991; Gogel & Tietz, 1973; Johnston, 1991; van Damme & Brenner, 1997). Our results are consistent with this tendency to underestimate the range of presented distances of visual stimuli. The third experiment examined whether the range of distances of the simulated cube was underestimated and if so, whether this was because kinesthetic information indicates a smaller range.

EXPERIMENT 3

We repeated Experiment 2, but this time we determined the average distance between the subject and the simulated cube on each presentation. This enabled us to examine how variability in the distance between the subject and the simulated cube influences the perceived size when there is no conflict with kinesthesia. Moreover, by selecting trials with the same average distance of the

Table 1
Median Increase in Matching Size When the Simulated Cube Was Nearer or Farther Than the Rod (mm)

Condition	Dynamic	Static
Simulated 25 mm nearer than held	−1.2	−1.7
Simulated 25 mm farther away than held	2.5	1.5

Table 2
Range of Simulated Sizes That Were Considered the Same as the Reference*: Mean ± *SE* (mm)

Condition	Dynamic	Static
Simulated at same position as held	12 ± 1	11 ± 1
Simulated 25 mm nearer than held	13 ± 2	12 ± 1
Simulated 25 mm farther away than held	13 ± 2	15 ± 3
Simulation only	13 ± 1	

*For explanation, see third paragraph of the Analysis section.

simulated cube from trials in which the position of the simulation coincided with that of the rod and from ones in which it was displaced from the rod, we could directly determine whether the position of the hand makes any difference.

Method

The most important innovation was that we kept track of the distance between the subject's left eye and the center of the simulated cube. This distance depended on where the subject put the rod and how he/she moved his/her head (the position of the left eye was determined from the instantaneous positions of the infrared markers on the LCD spectacles, taking all translations and rotations of the head into account). We selected fewer sizes (six rather than nine) centered on the subject's matching size (for the subjects for whom this was known from Experiments 1 and 2) or on the average of the other subjects' matching sizes (for the new subjects), and included three times as many consistent trials as in the preceding experiments. Otherwise, the procedure was identical to that of Experiment 2 (rod held static).

Subjects. Twelve subjects took part in the experiment, 5 of whom had participated in one, and 3 in both, of the previous experiments. Subjects were not specifically instructed to vary the position at which they placed the rod.

Analysis. The first step in the analysis was to average the distance between the subject and the cube within each trial. The average standard deviation within trials was 1.3 mm. The average distance was 46 cm. The overall standard deviation in this distance (between trials) was 4.6 cm. Because we needed many responses to estimate a perceived size, we had to group the data in some manner. We chose to select sets of trials with the same average distance between subject and simulated cube, but with different positions of the hand relative to the cube. This is illustrated in Figure 4.

Figure 4 shows the distribution of occurrences of distances between 1 subject and the simulated cube for each of the three conditions. Within each condition, fluctuations in where this subject placed the rod (and held her head) on different trials caused considerable variability in the simulated cube's distance. The systematic difference between the conditions is a result of the cube being simulated 25 mm nearer or farther away than the rod. To select trials with the same average distance, we first calculated the average distance of the simulated cube for trials in which the cube was nearer or farther than the rod, and then found a matching set of consistent trials for each of these conditions. These sets are identified by their shading.[3] The difference between the average distance of the cube when it was nearer or farther than the rod and its average distance during the matching set of consistent trials was never more than 0.24 mm.

The number of trials in a matching set of consistent trials depended on the variability in the distance between subject and cube. With little variability, the number of trials in a matching set is small. Moreover, some of these trials do not contribute to the final value of the matching size because the simulated size is not within the range deemed relevant (see Figure 2; only the filled circles contribute to the matching size). Of the 12 subjects, 2 subjects' data were not included in the further analysis because one or both of their values for the perceived size would have been based on the responses on fewer than six trials.

Wilcoxon signed rank tests were used to verify that simulating the cube nearer or farther than the rod influences the size that matches the reference (as found in Experiment 2), to examine whether spontaneous variations in the distance of the rod could influence the perceived size of the simulated cube (by comparing the matching sizes for the two selected sets of consistent trials), and to compare the matching size when the rod was at the same position as the simulation with its size when the rod was closer or farther away (while the simulation was at the same average distance from the subject's eyes). A significant effect in the last comparison would provide true evidence for a role of kinesthesia in visually perceived size.

Results

The size that matches the reference was determined for each of the two pairs of matching sets of trials. The average of the 10 subjects' values is shown in Figure 5. Not surprisingly, when the cube was simulated 25 mm nearer than the rod, it was—on average—5 cm nearer to the subject than when it was simulated 25 mm farther away than the rod. This led to a change in the size that matched the reference of about 2 mm. The same change in size was found when trials with an equivalent average distance were selected from the consistent trials. In both cases, the influence of the average distance of the simulated cube was statistically significant ($p < .01$). Most importantly, for the same average distance, it was irrele-

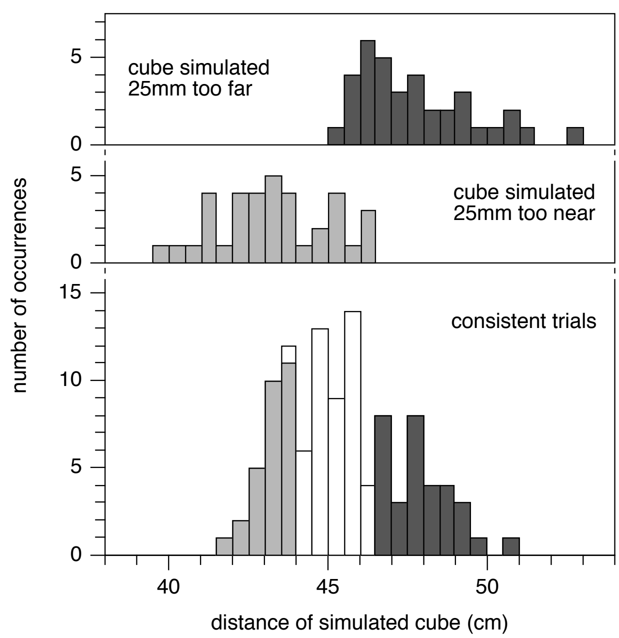

Figure 4. The spontaneous variation in rod placement—and head position—was used to select sets of data with the same average distance between the subject's eyes and the simulated cube. The figure shows the distribution of the latter distances for 1 subject. Logically, the average distance of the simulated cube was smaller when it was nearer than the rod and larger when it was farther away. To examine whether this in itself was responsible for the difference found in Experiments 1 and 2, subsets of the consistent trials were selected to match each of the other two sets. The shaded bars show the two groups of selected trials.

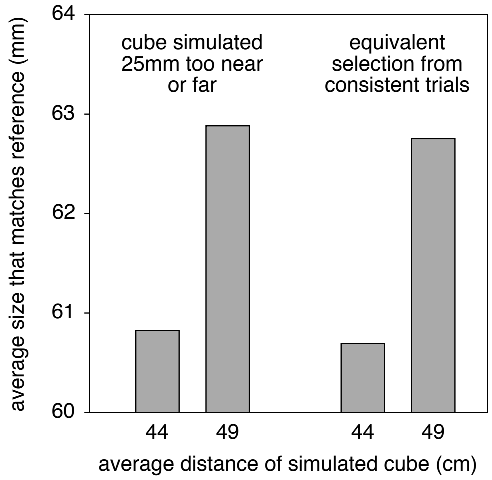

Figure 5. Average matching size of the 10 subjects when the simulated cube was nearer or farther away than the cube attached to the rod in the subject's hand, and when it was at the same distance but the subject held the rod nearer or farther away.

vant whether the cube was simulated too near or too far away, or whether the simulation was consistent with the position of the rod ($p > .75$ for both comparisons).

Discussion

The third experiment demonstrated that kinesthesia does not contribute to the information on distance that is required for visual judgments of size. At the same time, it demonstrates how poorly visual information on distance fulfills this role, which makes the finding all the more surprising.

In the static experiments, small movements of the rod were visible in the simulation, providing a compelling sensation of holding the virtual cube. Moreover, in the consistent trials, the subjects themselves were responsible for all the variability in the distance of the simulated cube. At the same time, the visual information was rather limited. Together, this should have made the conditions optimal for the use of kinesthetic information. Nevertheless, in the third experiment, it made no difference whether a systematic difference in the distance of the simulation was accompanied by a systematic difference in where the rod was held (consistent trials) or not (other trials).

GENERAL DISCUSSION

From Experiment 3, we conclude that the systematic misjudgments of size in Experiments 1 and 2 were due to a general failure to account for the variations in distance, independent of the kinesthetic information. We therefore feel confident in concluding that kinesthetic information on distance did not contribute directly to the visual judgments of size. This is in line with previous demonstrations of vision dominating completely over touch when both are present (Gibson, 1933; Rock & Harris, 1967; Rock & Victor, 1964; Teghtsoonian & Teghtsoonian, 1970; Welch & Warren, 1986).

The extent of the failure of size constancy is consistent with previous reports. The 2-mm larger matching size at 49-cm than at 44-cm distance (Figure 5) represents an increase in size of about 3%. For the same change in distance, the retinal image increases by about 11%. Thus about 27% of the change in distance is accounted for in the perceived size of the cube. Similar values have been found for judgments of size (including depth) using computer images of cylinders (26%–27%; Johnston, 1991), spheres (32%; van Damme & Brenner, 1997), and planes (Collett et al., 1991).

If kinesthesia does not contribute to the perceived size, and size constancy is so poor, why did the cube not appear to grow and shrink as it moved around during the first experiment, in which subjects were free to move the rod around as they pleased? Hershenson (1992) has proposed that this is due to a tendency to perceive objects as rigid, resulting in size constancy *during* dynamic presentations. An alternative is that the changing size itself influences the measure of distance in a manner that prevents this from happening: We have recently shown that changing size contributes to the subsequently perceived distance (Brenner, van den Berg, & van Damme, 1996), so it may also contribute to the measure used for scaling retinal image size. Neither of these suggestions makes the perceived size more veridical, but only ensures that the initially perceived size is maintained throughout the trial.

REFERENCES

Abravanel, E. (1971). The synthesis of length within and between perceptual systems. *Perception & Psychophysics*, **9**, 327-328.

Biguer, B., Prablanc, C., & Jeannerod, M. (1984). The contribution of coordinated eye and head movements in hand pointing accuracy. *Experimental Brain Research*, **55**, 462-469.

Brenner, E., van Damme, W. J., & Smeets, J. B. J. (1995). Feeling the distance of an object does not help one judge its size. *Perception*, **24** (Suppl.), 134.

Brenner, E., van den Berg, A. V., & van Damme, W. J. (1996). Perceived motion in depth. *Vision Research*, **36**, 699-706.

Burton, G., Turvey, M. T., & Solomon, H. Y. (1990). Can shape be perceived by dynamic touch? *Perception & Psychophysics*, **48**, 477-487.

Carey, D. P., & Allan, K. (1996). A motor signal and "visual" size perception. *Experimental Brain Research*, **110**, 482-486.

Clark, F. J., & Horch, K. W. (1986). Kinesthesia. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. 1. Sensory processes and perception* (pp. 13.1-13.62). New York: Wiley.

Collett, T. S., Schwarz, U., & Sobel, E. C. (1991). The interaction of oculomotor cues and stimulus size in stereoscopic depth constancy. *Perception*, **20**, 733-754.

Collewijn, H., & Erkelens, C. J. (1990). Binocular eye movements and the perception of depth. *Reviews of Oculomotor Research*, **4**, 213-261.

Collewijn, H., Steinman, R. M., Erkelens, C. J., Pizlo, Z., & van der Steen, J. (1992). Effect of freeing the head on eye movement characteristics during three-dimensional shifts of gaze and tracking. In A. Berthoz, W. Graf, & P. P. Vidal (Eds.). *The head–neck sensory motor system* (pp. 412-418). New York: Oxford University Press.

Gibson, J. J. (1933). Adaptation, after-effect and contrast in the perception of curved lines. *Journal of Experimental Psychology*, **16**, 1-31.

Gogel, W. C., & Tietz, J. D. (1973). Absolute motion parallax and the specific distance tendency. *Perception & Psychophysics*, **13**, 284-292.

Hershenson, M. (1992). Size–distance invariance: Kinetic invariance is different from static invariance. *Perception & Psychophysics*, **51**, 541-548.

Johnston, E. B. (1991). Systematic distortions of shape from stereopsis. *Vision Research*, **31**, 1351-1360.

Kelvin, R. P., & Mulik, A. (1958). Discrimination of length by sight and touch. *Quarterly Journal of Experimental Psychology*, **10**, 187-192.

Rock, I., & Harris, C. S. (1967). Vision and touch. *Scientific American*, **216**, 96-104.

Rock, I., & Victor, J. (1964). Vision and touch: An experimentally created conflict between the senses. *Science*, **143**, 595-596.

Sedgwick, H. A. (1986). Space perception. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. 1. Sensory processes and perception* (pp. 21.1-21.57). New York: Wiley.

Teghtsoonian, R., & Teghtsoonian, M. (1970). Two varieties of perceived length. *Perception & Psychophysics*, **8**, 389-395.

van Damme, W. J. M., & Brenner, E. (1997). The distance used for scaling disparities is the same as the one used for scaling retinal size. *Vision Research*, **37**, 757-764.

Welch, R. B., & Warren, D. H. (1986). Intersensory interactions. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. 1. Sensory processes and perception* (pp. 25.1-25.36). New York: Wiley.

NOTES

1. Note that this measure need not be veridical and that it does not necessarily correspond with the perceived distance (although it may).

2. We thank H. A. Sedgwick for bringing this question to our attention.

3. The matches were based on the actual distances. The distances were pooled into 5-mm bins only for Figure 3.

(Manuscript received July 28, 1995;
revision accepted for publication November 27, 1996.)