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How vertical disparities assist judgements of distance

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Abstract

The ratio of the vertical sizes of corresponding features in the two eyes' retinal images depends both on the associated object's distance and on its horizontal direction relative to the head (eccentricity). It is known that manipulations of vertical size ratio can affect perceived distance, size, depth and shape. We examined how observers use the vertical size ratio to determine the viewing distance. Do they use the horizontal gradient of vertical size ratio, or do they combine the vertical size ratio itself with the eccentricity at which it is found? Distance scaling (as measured by having subjects set an ellipsoid's size and shape to match a tennis ball) was no better when the judged object was 30° to the right of the head (where vertical size ratios vary considerably with distance) than when it was located straight ahead. Distance scaling improved when vertical disparities were presented within larger visual fields, irrespective of where this was relative to the head. Our results support the proposal that subjects use the horizontal gradient of vertical size ratio to estimate the distance of an object that they are looking at.

Keywords: Stereopsis; Binocular vision; Depth; Size; Shape; Human

1. Introduction

The ease with which we move our hand toward objects in everyday life suggests that we are very good at judging where they are. Many of the potential sources of information about spatial layout, such as texture gradients, motion parallax, and horizontal disparities, only provide information about relative distances, so they have to be scaled to obtain actual positions. Extra-retinal information about the orientation of the eyes could be used for such scaling, but studies in which subjects had to estimate the distance of isolated targets in the dark suggest that this source of information is quite unreliable. There are other options. When we are standing, our eye height could be used to scale the other information. If a familiar object is visible, somewhere in the scene, we could use its image size to determine the scaling factor. If we are moving, the extent of self-motion could be used to scale information from motion parallax.

Binocular vision provides alternative, purely retinal possibilities to obtain information for such scaling. One is by combining information from horizontal disparities with information from texture gradients or motion parallax. Since horizontal disparities scale differently with distance than the other two depth cues, actual positions could be judged by finding the egocentric distance at which the horizontal disparities are consistent with the other information. We previously failed to find evidence for the use of a combination of binocular disparity and motion parallax (caused by object motion) for judging distance (Brenner & Landy, 1999; Brenner & van Damme, 1999). A second possibility is by also considering vertical disparities.

Determining objects' positions is not the only task for which reliable judgements of distance are essential. Most perceptual judgements cannot be based directly on the object's retinal image. They require additional information. For example, to judge an object's width, the horizontal extent of its retinal image must be scaled by information about its egocentric distance. Similarly, to estimate an object's depth extent, relative horizontal disparities must be scaled by information about both

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egocentric distance and direction. All these judgements are presumably based on the same measure of distance (Brenner & van Damme, 1999; van Damme & Brenner, 1997). It is known that extra-retinal information about the orientation of the eyes contributes to this measure. However, considering the limitations of retrieving distance from extra-retinal information alone (Brenner & van Damme, 1998), it is evident that other sources of information must also play a role. Here, we examine the role of vertical disparity. In particular, we attempt to determine how vertical disparities are used to scale retinal extent and horizontal disparities for judging size and shape.

It has been known for some time that one could theoretically retrieve the whole three-dimensional structure of our environment from the two images that reach our eyes, without extra-retinal information about the orientation of the eyes. This requires consideration of both horizontal and vertical disparities (Mayhew & Longuet-Higgins, 1982; Bishop, 1989). And indeed, vertical disparities can influence perceived slant (Backus, Banks, van Ee, & Crowell, 1999), size (Bradshaw, Glennerster, & Rogers, 1996), depth (Bradshaw et al., 1996), curvature (Rogers & Bradshaw, 1995) and distance (Rogers & Bradshaw, 1995). However, this need not be the result of vertical disparities being used to improve an estimate of distance, and this improved estimate being used to scale horizontal disparities and retinal extent when making these judgements. It could also be the result of using separate specialised mechanisms for processing binocular information about each of these properties (e.g. Rogers & Bradshaw, 1995). There is evidence that vertical disparities are pooled across large image areas (Stenton, Frisby, & Mayhew 1984; Adams et al., 1996; Porrill, Frisby, Adams, & Buckley, 1999), which is consistent with them being used to calculate a single scaling distance. However, at least for judgements of slant, disparities may not be pooled across the entire image (Kaneko & Howard, 1996; but see Erkelens & van Ee, 1998).

The proposal that separate, specialised mechanisms are involved in different judgements is supported by the discrepancy between the modest extent to which judged depth (Sobel & Collett, 1991; Bradshaw et al., 1996) and size (Bradshaw et al., 1996) are influenced by vertical disparity, and the high degree of scaling of perceived slant (Backus et al., 1999) and curvature (Rogers & Bradshaw, 1995). It is also supported by the fact that when the vertical disparities specify an eccentric viewing direction, subjects do not report having the impression of looking in that direction, although the disparities are interpreted as if they were doing so; i.e. viewing direction is not misjudged in accordance with the misperceived slant (Frisby, 1984).

In the present study, we try to determine how subjects use vertical disparities. We will adopt the terminology introduced by Gillam and Lawergren (1983) and Rogers and Bradshaw (1993, 1995), and refer to the ratio of the separations between corresponding features in the two eyes as their size ratio. The components of the separation that are parallel to the inter-ocular axis give rise to the horizontal size ratio, whereas the components in the orthogonal direction give rise to the vertical size ratio. The term *size* should not be taken too literally. When using random dot patterns, the distance between the dots will be considered as the size. This terminology has a number of attractions. The vertical size ratio is simple to compute, because it is approximately proportional to the ratio of the distances from the two eyes. Moreover, it is defined relative to the positions of the eyes, which determine the ratio between the retinal image sizes, independent of the eyes' orientations. When thinking about mechanisms to pick up such information, we assume that the images on the (spherical) retinae do not change when the eyes rotate. The vertical size ratio therefore depends on the direction relative to the head (which we will be calling the eccentricity) and the egocentric distance, but not on the position of the images on the retina, and thus not on the orientation of the eyes. There is evidence, at least for perceived slant, that the use of vertical disparity is indeed largely independent of the orientation of the eyes (Backus & Banks, 1998).

Early studies on perceived depth (Cumming, Johnston, & Parker, 1991; Sobel & Collett, 1991) found no evidence for vertical size ratios being used to retrieve the scaling distance. Presumably, this was because the field of view was too small (Rogers & Bradshaw, 1993). But why should the field of view matter? Fig. 1A shows that vertical size ratio increases with eccentricity and decreases with distance (Bishop, 1989). Perhaps the vertical size ratio is ineffective for small field sizes because the vertical size ratios are too small to detect.

One way in which subjects could use vertical size ratios to judge an object's distance is by combining vertical size ratios with the corresponding horizontal eccentricities. If subjects know the object's eccentricity relative to the head (for example from a combination of its retinal eccentricity and extra-retinal information about the direction of gaze), they could judge the object's distance from its vertical size ratio (e.g. Howard, 1970). At a larger eccentricity, there are larger changes in vertical size ratio for the same change in distance (Fig. 1A). Since the resolution with which vertical size ratio can be determined is not unlimited, a larger change in vertical size ratio with distance will give a higher resolution for judging distance. A small error in judging the eccentricity will also have far less devastating consequences for judgements of distance that are based on the vertical size ratio for more eccentric objects.

If the mechanism proposed above is used, it is not surprising that we are bad at judging the distance of objects that are straight in front of us: the vertical size ratios involved hardly depend on the distance, while they do depend on eccentricity. Consequently, a small error in perceived eccentricity will lead to a large error in perceived distance.

Sobel and Collett (1991) had a very large range of vertical size ratios despite having a relatively small field of view, because they simulated incredibly nearby surfaces (12.5 cm), and still failed to find an influence of vertical disparity. This may be because of the large conflict with extra-retinal information about distance in their study. There is ample evidence that conflicts with extra-retinal information can limit the extent to which vertical disparities are used (Gillam, Chambers, & Lawergren, 1988; Bradshaw et al., 1996; Banks & Backus, 1998; Backus & Banks, 1999).

Stronger evidence against the magnitude of vertical size ratios being the critical factor is the finding that subjects do not make much better use of vertical size ratios when they are free to look around than when they have to fixate straight ahead (Rogers, Bradshaw, & Glennerster, 1994; Rogers & Bradshaw, 1995). Freedom to look around allows subjects to direct their gaze toward the area with the largest vertical size ratios. Thus, if retinal resolution in determining the vertical size ratio were the limiting factor in judging distance, we would have expected a better performance when eye movements were not restrained. However, if judgement of eccentricity is the limiting factor, it is not clear what to expect, because we do not know whether (and, if so, how) judgements of eccentricity depend on whether eye movements are restricted.

An alternative to using the vertical size ratio itself to judge the distance is to use the horizontal gradient in the vertical size ratio (Fig. 1B). This gradient hardly changes with eccentricity for a given egocentric distance (see Gillam & Lawergren, 1983 and Rogers & Bradshaw, 1995 for similar reasoning for frontal planes). Use of this measure would explain the lack of sensitivity to the direction of gaze. Although the magnitude of the vertical size ratio at the fovea changes with the direction of gaze, the gradient remains the same when the direction of gaze changes, because it is the same across the visual field. Thus, even if the central visual field is the most important for judging the gradient, due to its high resolution, where in the display that the central visual field is directed does not matter. The need for a large field of view is less obvious. Presumably, a large field is needed to estimate the gradient reliably. This in turn suggests that retinal resolution may not be the limiting factor.

A mechanism that judges distance from the horizontal gradient of vertical size ratio (Fig. 1B) can be purely retinal. It does not require extra-retinal information about the orientation of the eyes; nor does it provide any information other than the distance. Developing a retinal measure specifically for judging distance makes sense if we consider that extra-retinal information is far worse for distance than for direction (for geometric reasons; Brenner & Smeets, 2000).

To summarize: we have proposed two possible mechanisms for judging distance from vertical size ratios: combining vertical size ratios with the eccentricity relative to the head, and using the horizontal gradient in vertical size ratio.

Comparing studies in the manner we have just done can be misleading. The stimuli and experimental conditions vary considerably between studies, so that seemingly irrelevant differences may be overlooked. For instance, in studies in which flat frontal surfaces are simulated (e.g. Bradshaw et al., 1996), there is a correlation between the range of horizontal disparities and the viewing distance. Also, subjects could be using monocular texture cues, either alone or by combining them with horizontal disparities, to estimate the distance.

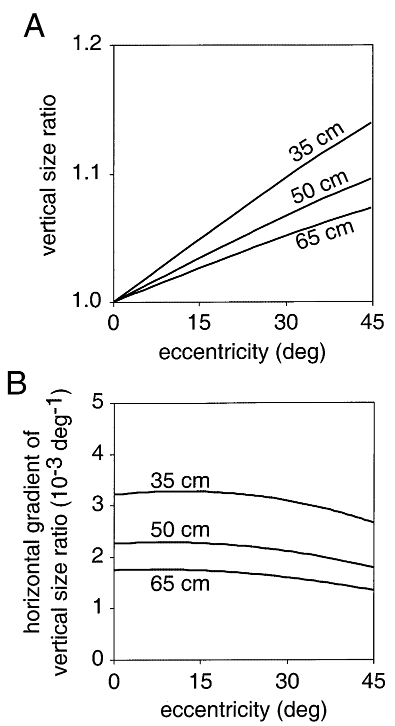

Fig. 1. Vertical size ratio as a function of horizontal eccentricity with respect to the orientation of the subject's head, calculated for an inter-ocular distance of 6.5 cm for structures at three egocentric distances. (A) Ratio itself. Note that vertical size ratios could be used to retrieve the distance from the observer if the eccentricity is known, or vice versa. Moreover, the vertical size ratio increases almost linearly with eccentricity for each distance. (B) Change in the vertical size ratio with horizontal eccentricity [the slope of the curves in (A)]. This measure is almost constant for each egocentric distance, and could therefore be used to estimate distance independent of eccentricity.

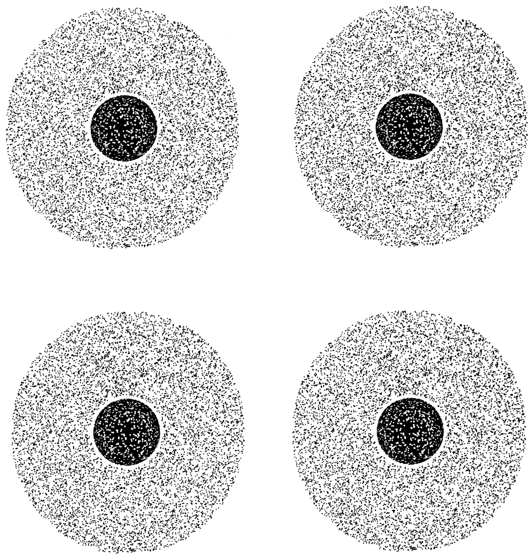

Fig. 2. Example of what the stimulus with an isovergence surface looked like, for viewing with crossed (upper pair) or uncrossed (lower pair) fusion.

In the present study, we determined the distance that our subjects used to scale horizontal retinal disparities and retinal size to estimate object depth and size (Brenner & van Damme, 1999). Rather than intentionally introducing conflicts in the stimulus, which may prevent certain information from being used, we determined the extent to which vertical disparities reduce naturally occurring systematic errors. It is known that when single targets are presented at eye height straight in front of the observer, the range of distances that are used to scale horizontal retinal disparities and retinal extent is compressed with respect to the range that is simulated (e.g. Johnston, 1991; van Damme & Brenner, 1997). We examined whether we could reduce this compression by providing better opportunities to use vertical size ratios.

In the first experiment, we examined whether looking sideways to see the target reduces the compression of the range of scaling distances. This is to be expected if vertical size ratios are combined with eccentricity to judge the target's distance. The scaling distance is expected to be closer to the physical distance for targets that are off to one side, because of the stronger dependence of vertical size ratio on distance for larger horizontal eccentricities with respect to the head. This expectation was not confirmed.

In the second experiment, we did confirm that vertical disparities reduce the compression of the range of perceived distances if the field of view is large. We took care to ensure that subjects could not use gradients of horizontal disparity or monocular texture to estimate distance. Instead of using a simulated frontal plane (e.g. Rogers & Bradshaw, 1995), we presented dots on a simulated isovergence torus (eliminating the gradient of horizontal disparities; Fig. 2). The points were distributed uniformly and randomly in terms of cyclopean direction (so that texture cues were always consistent with an iso-distance surface). One peculiar aspect about having to have a large field of view is that in our normal environment, we are seldom faced with a single large surface at or near a single distance. We therefore also examined whether it was essential that all the points are on a surface. In our third experiment, we examined whether it made a difference where in the visual field the points were located (see Westheimer & Pettet, 1992).

2. Methods

In all three experiments, subjects set the size and shape of a binocular simulation of a randomly textured ellipsoid to match a tennis ball (see van Damme & Brenner, 1997; Brenner & Landy, 1999; Brenner & van Damme, 1999). From these settings, we determined two scaling measures: the distance at which a tennis ball would match the observer's retinal size setting (size-scaling distance) and the distance at which the observer's setting of object depth (i.e. the range of horizontal disparities) would combine with the setting of retinal size to form a sphere (shape-scaling distance). Note that misjudging the size of the reference (i.e. of a real tennis ball) only influences the former. The extent to which reference size is systematically misjudged can be estimated by determining the size of the sphere that corresponds with the shape-scaling distance (see Brenner & Landy, 1999).

2.1. Equipment

Images were presented using a Silicon Graphics Onyx RealityEngine on a high resolution monitor (120 Hz; horizontal size: 39.2 cm, 815 pixels; vertical size: 29.3 cm, 611 pixels; spatial resolution refined with anti-aliasing techniques). Subjects sat with their head stably fixed by a dental impression bite-board that was placed so that the average position of their eyes was 50 cm from the centre of the screen. At that distance, 1 pixel corresponds to 3 min arc. Anti-aliasing with a 10 bit luminance resolution probably reduces the effective display resolution to well below 1 min arc. The images were viewed through liquid crystal shutter spectacles that were synchronised with the refresh rate of the monitor. Alternate images were presented to the left and right eye, so that each eye received a new image every 16.7 ms (60 Hz). Each image was presented in accordance with the way in which an ellipsoid would be seen from the position of the eye for which it was intended (taking the individual's inter-ocular distance into consideration). Thus, both the subject's ocular convergence when fixating the ellipsoid and the images on his or her retinae were appropriate for an ellipsoid at the simulated distance. Red stimuli (and additional red filters in front of the spectacles) were used because the shutter spectacles have the least cross-talk at long wavelengths. In some parts of the experiments, lateral gaze was imposed by changing the position and orientation of the bite board (see inset in Fig. 3C). In those cases, we rendered the images in accordance with the asymmetric eye positions.

2.2. Stimuli

The stimuli consisted of computer simulations of a red ellipsoid with 1800 randomly oriented black triangles, about half of which were visible, 'painted' onto its surface (see Fig. 2). The triangles 'stretched' along with the surface of the ellipsoid (in the simulation) when the ellipsoid's shape was changed, thus minimizing the change in texture when the disparity was adjusted. When the ellipsoid was spherical, the triangles were equilateral (with sides of 6% of the sphere's radius) and were distributed and oriented at random on the surface. In the first experiment, only the ellipsoid was visible. In the second and third experiments, the ellipsoid was surrounded by a simulated surface of dots (about 10,000). The surface was a section of the isovergence torus that passed through the ellipsoid's centre. Since the ellipsoid extended through the surface, we made a circular hole in the surface by not drawing any dots within that region. The hole was 10% larger than the ellipsoid. The surface itself was either circular with a diameter of 33 deg (Experiment 2), or square with sides of 33 deg (Experiment 3). The dots' directions from the subject were chosen at random, so that both texture and horizontal disparities were identical for all viewing distances.

The simulated distance of the ellipsoid was 35, 50 or 65 cm from the subject. The rendered disparities and the vergence required to fixate the ellipsoid were always appropriate for the simulated distance. We intentionally chose a modest range, close to the screen distance, so as not to introduce large conflicts with accommodation. We used modest distances because that is where we

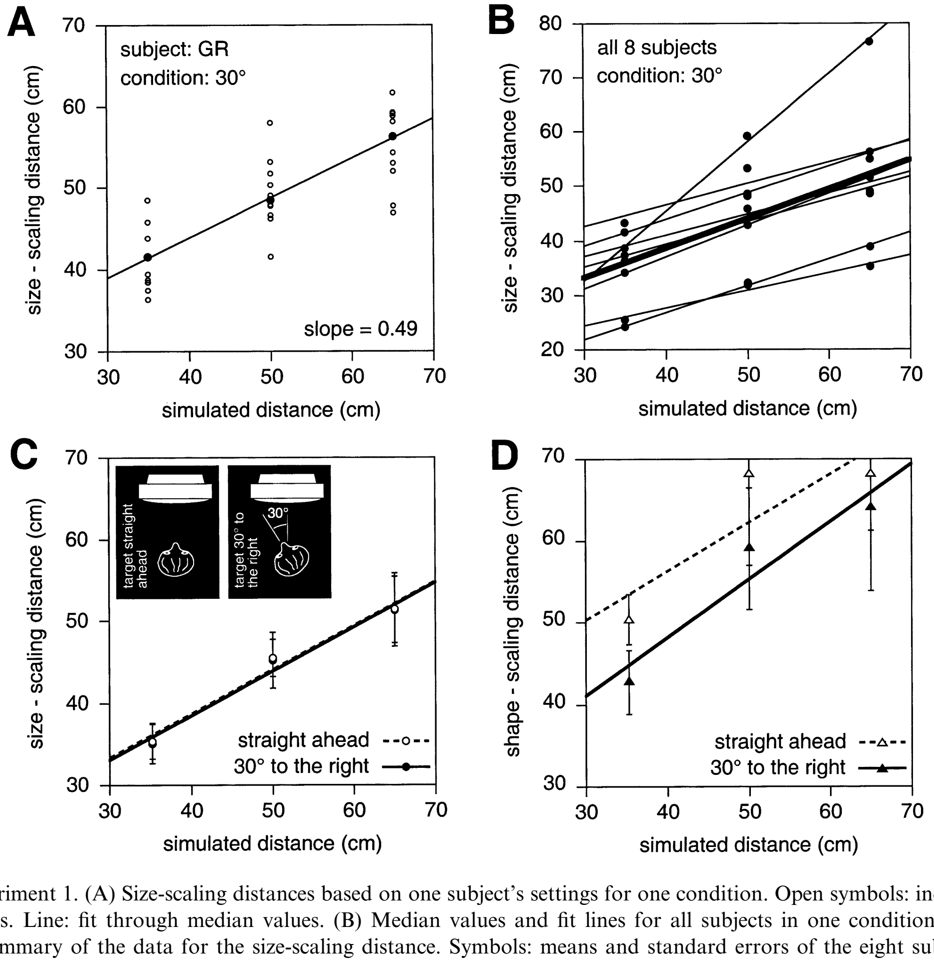

Fig. 3. Results of Experiment 1. (A) Size-scaling distances based on one subject's settings for one condition. Open symbols: individual values. Solid symbols: median values. Line: fit through median values. (B) Median values and fit lines for all subjects in one condition. Thick line: average across subjects. (C) Summary of the data for the size-scaling distance. Symbols: means and standard errors of the eight subjects' median values for each simulated distance. Lines: average fit lines for the two viewing conditions. Inset: Schematic representation of the two conditions. In both cases subjects were free to look where they pleased. (D) Corresponding data for the shape-scaling distance.

expect subjects to need accurate metric information (for manipulating objects). Which of the distances was presented on a given trial was determined at random. Subjects could independently vary the width and depth of the ellipsoid, the depth being the extent along the line of sight, and the width being its angular subtense (the height was always identical to the width).

Care was taken to ensure that no structures other than the simulated ellipsoids and the surrounding simulated surface were ever visible. The ellipsoid contained texture cues as well as binocular disparities. If the width and depth of the ellipsoid were set correctly, the texture, the binocular disparities, and the required ocular convergence were all consistent with a tennis ball at the simulated distance. However, accommodation obviously always indicated a distance of 50 cm, whereas the most likely interpretation of the shading was that the ellipsoid was flat (because surfaces were rendered with uniform illumination).

Since we wanted to avoid conflicts within the stimuli, we could not examine the role of vertical size ratios directly. Changing the simulated distance always influenced both vertical size ratios and ocular convergence. In Experiment 1, we therefore compared distance scaling for ellipsoids that were straight ahead (with respect to the orientation of the head) with ellipsoids that were 30° to the right. In Experiment 2, we also compared these two viewing directions, but the main purpose was to examine whether introducing vertical size ratios in the surround makes a difference. Unfortunately, it is impossible to introduce vertical size ratios without introducing some structure. In a pilot study, we found that subjects responded differently when the ellipsoid was presented in isolation than when it was presented within an 'informationless' surround. Presumably, the presence of a surround with a certain retinal extent is enough to influence the perceived distance. We therefore compared performance in the presence of the above-mentioned section of an isovergence torus, with performance within a surround with no correlation between the eyes (independent random dot patterns with similar monocular structure). With our large number of dots, this gave the impression of a sort of 'cloud'.

Both in Experiment 2 and in Experiment 3, we had conditions in which only part of the background was correlated. This was done to examine how vertical disparities are pooled to determine the scaling distance, and whether some regions in the visual field are more effective than others for doing so. In Experiment 2, the part of the background that was correlated was either a random selection of 25% of the dots, or a radial pattern containing 25% of the dots. The latter consisted of a pair of 45° sectors containing correlated dots that radiated in opposite directions from the centre of the ellipsoid, while the other sectors contained uncorrelated dots. The radial pattern of correlated dots had a random orientation on each trial. These two cases were compared with the conditions in which all dots were either correlated or not. In Experiment 3, the correlated part of the background was either a horizontal or a vertical bar through the centre of the image, or a vertical bar 12° to the left of the centre. Its width was 25%, 12.5%, 6.25% or 3.125% of the linear extent of the surround. The rest of the background was filled with uncorrelated dots. Note that since the points were distributed at random, changing bar width also changed the number of correlated dots. The 12 combinations of bar type and width were compared with a condition in which there were no correlated dots.

2.3. Procedure

The subjects' task was to set the size and shape of the simulated ellipsoids to match a tennis ball (diameter = 6.6 cm). During the experiments, they held a real tennis ball in their left hand and the computer mouse in their right hand. Subjects were encouraged to look at the tennis ball before each experiment, but they were not allowed to do so during the experiment. They adjusted the simulated ellipsoid's width and depth by moving the computer mouse. Horizontal movements of the mouse changed both the width and depth of the simulated ellipsoid (the simulated size was related linearly to the position of the mouse). Vertical movements changed the depth relative to the width (the ellipsoid's elongation was related quadratically to the position of the mouse). These manipulations were seen as changing size and shape, respectively. The width could vary between 1.32 and 16.5 cm (in the simulation). The depth could vary between 0.2 and 2.5 times the width. The initial width and depth were determined at random from within this range for each trial.

2.4. Subjects

Eight subjects took part in the first experiment, and five in each of the other two. One of the authors was a subject in all three experiments. The other subjects were all naïve as to the purpose of the experiments. All reported normal binocular vision. In the first experiment, each subject made 10 settings for each of the three simulated distances with the target straight ahead, and another 10 for each distance while looking 30° to the right, giving a total of 60 settings. In the second experiment, each subject made five settings for each simulated distance for each of the four conditions with the target straight ahead, and another five for each distance and condition while looking 30° to the right, giving a total of 120 settings. In the final experiment, each subject made five settings for each simulated distance for each of the 13 conditions, giving a total of 195 settings (the target was always straight ahead).

2.5. Analysis

The first stage in our analysis was to transform the observers' settings of width and depth into a *size-scaling distance* and a *shape-scaling distance*. The *size-scaling distance* is the distance for which the retinal size setting would correspond with a tennis ball (see van Damme & Brenner, 1997). The *shape-scaling distance* is the distance for which the settings of retinal size and horizontal disparity would match to form a sphere (see Brenner & Landy, 1999). The size of this hypothetical sphere can be calculated by combining the shape-scaling distance with the retinal size. The validity of the shape-scaling *distance* can therefore be evaluated by checking whether the calculated *size* is more or less consistent across trials, and whether it corresponds to that of a tennis ball. The mean values and standard deviations of the calculated size gave us no reason to doubt the validity of the calculated distance. The mean diameters were 9.1, 6.0 and 7.0 cm, and the mean standard deviations were 1.9, 0.9 and 0.8 cm, for Experiments 1, 2 and 3, respectively (a real tennis ball's diameter is 6.6 cm).

For each combination of subject, condition, and simulated distance, we determined the median value of each scaling distance. Next, we determined the slope and the value at 50 cm for a linear fit of median scaling distance as a function of simulated distance (for each subject and condition; see Fig. 3A and B). The slopes and the values at 50 cm were then averaged across subjects. The rest of the results figures show the lines that one obtains by combining these mean slopes with the mean values at 50 cm, together with the mean and standard deviations (across subjects) of the above-mentioned median values for each simulated distance. To evaluate whether the manipulations influenced the settings, and whether they did so in the same manner for both measures of distance scaling, the above-mentioned slopes were analysed with repeated measures analyses of variance. We used the type of scaling measure, the direction of gaze (Experiments 1 and 2), and the kind of background (Experiments 2 and 3) as within-subject factors. In the third experiment, we conducted separate analyses to evaluate whether the place and the size of the portion of the background providing the information were relevant.

3. Results

Fig. 3C and D show the results of Experiment 1. The two scaling distances are shown as functions of the simulated distance. When subjects looked straight ahead (open symbols and dashed lines), they underestimated the range of distances (as in Johnston, 1991, for example), giving a too shallow slope (perfect performance would result in a line of slope 1). The slope did not appear to increase when the ellipsoid was presented 30° to the right of the subject (solid symbols and lines). Note that subjects were always free to look at the ellipsoids. The 30° eccentricity is the position relative to the head and not a retinal eccentricity. The analysis of variance on the slopes showed no significant effects (viewing direction: $P = 0.33$; type of scaling distance [size or shape]: $P = 0.67$; interaction: $P = 0.43$). Thus, having larger differences in vertical size between the two eyes did not improve the distance scaling.

Fig. 4 shows the results of Experiment 2. The differences between the slopes of the lines in Fig. 4 confirm that vertical size ratios can influence scaling distances. Subjects clearly perceived the scene more veridically when both eyes saw the same dots, with the latter distributed on an isovergence surface, than when each eye saw a different set of dots. The analysis of variance showed a significant effect of background condition ($P = 0.001$) but not of viewing direction ($P = 0.06$) or type of scaling distance ($P = 0.07$). None of the interactions were significant (condition × direction: $P = 0.29$; condition × type of scaling distance: $P = 0.07$; direction × type of scaling distance: $P = 0.43$; condition × direction × type of scaling distance: $P = 0.55$).

Performance when only 25% of the dots were correlated in the two eyes was between that with full correlation and that with no correlation. It did not appear to make much difference whether the correlated dots were grouped together or distributed over the whole background. The latter finding is consistent with a global mechanism for extracting the viewing distance from vertical size ratios. However, since the grouped radial pattern had a different orientation on each trial, we cannot tell from this experiment whether it matters where the correlated points are situated.

Fig. 5 shows the results of Experiment 3. It shows that the scaling distances improve as the extent of the surface providing vertical size ratios increases (C, D), but that the position and orientation of the surface are irrelevant (A, B). For the statistical evaluation, we excluded the uncorrelated condition, and conducted two analyses of variance (this was necessary because we have too many degrees of freedom for including all the manipulations in a single analysis; to do so, we would require data for at least two more subjects). In the first, we considered the three surface positions and the two types of scaling distance, pooling over surface widths. There were no significant effects (surface position and orientation: $P = 0.15$; type of scaling distance: $P = 0.09$; interaction: $P = 0.42$). In the second, we considered the four surface widths and the two types of scaling distance, pooling over surface positions. There was a significant effect of surface width ($P = 0.01$), but not of type of scaling distance ($P = 0.08$) or interaction ($P = 0.47$).

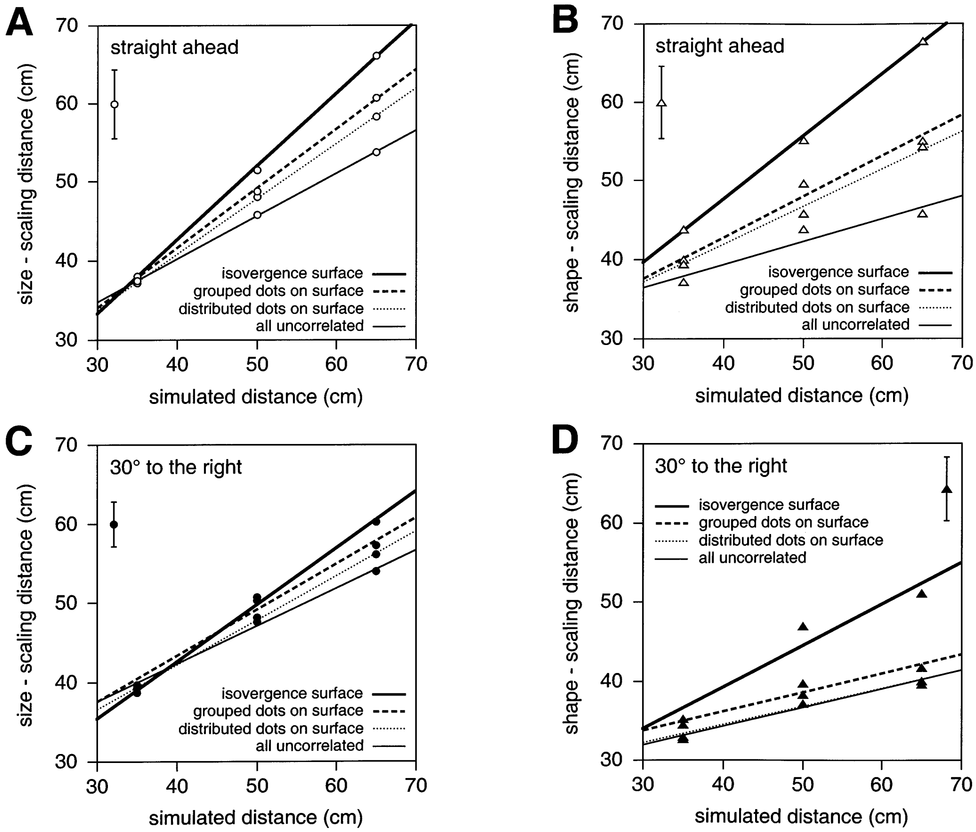

Fig. 4. Results of Experiment 2. (A) Size-scaling distances when looking straight ahead for the four background conditions: a single surface, uncorrelated dots in the two eyes, and two combinations with 25% of the dots on the surface (either grouped in a radial pattern of random orientation or distributed at random). The symbols and lines show means of five subjects with the average fit (see explanation in Fig. 3). The isolated symbol shows the mean standard error in these points. (B) Similar data for the shape-scaling distance. (C) Similar data as in (A) for the head oriented to one side. (D) Similar data as in (B) for the head oriented to one side.

Experiment 3 confirmed that the position at which vertical size ratios are presented is not critical. Distance scaling appears to increase gradually as more information is presented. There is again a tendency for the shape-scaling distance to be less veridical, although again, this is not statistically significant. This experiment shows conclusively that subjects do not need the large vertical size ratios that are to be found at large horizontal eccentricities.

4. Discussion

The second experiment verified earlier reports that vertical size ratios can be used to achieve better scaling of size and shape with distance (Rogers & Bradshaw, 1995; Bradshaw et al., 1996). The tendency to reach more veridical performance (slopes closer to 1) when looking straight ahead is probably an artefact: the cross-talk in the LCD spectacles increases with the viewing angle. Moreover, some of our subjects wore spectacles, so that part of the *background* fell beyond their range of sharp vision when looking to the side. Though subjects hardly noticed either of these, they may have influenced the results to some extent. In any case, they did not perform better when looking sideways, despite the vertical size ratios being larger. This is consistent with use of the horizontal gradient of vertical disparities, which is identical in the two conditions.

More than half our subjects wore spectacles. The corrections varied from negligible (less than ± 1D) to quite severe (-8D). We encouraged subjects to wear the spectacles during the experiments if they normally would for the viewing distances involved, because we expect them to make best use of the available information under the conditions that they are most used to. Spectacles result in magnification of the image. Equal magnification in both eyes does not change the vertical size ratio. Unequal magnification does, but by a constant factor. Magnification influences the orientation of the eyes when fixating a given object. Moreover, since the distance to the spectacles inevitably depends on the eccentricity, the magnification depends on the direction of gaze, leading to a deformation of the image. This influences the horizontal gradient of vertical size ratio in a manner that depends on the precise positioning of the spectacles. Thus, the way in which vertical size ratio depends on distance and horizontal eccentricity will be slightly different when wearing spectacles. We expect spectacle wearers to have adjusted to these deformations. Nevertheless, we checked whether there were any conspicuous differences between the performance of subjects with and without spectacles in the first experiment (where we had enough subjects for such a comparison). There were none.

We have no real explanation for the tendency toward less veridical performance for the scaling of shape. Shape scaling involves more kinds of information than size scaling. Beside an estimate of distance and the retinal extent, it also involves horizontal disparities. Since the poor shape scaling is primarily seen for the uncorrelated background, it is unlikely to have anything to do with the use of vertical size ratios. One possibility is that subjects have difficulties estimating the ellipsoid's depth because the visible outline depends on the ellipsoid's distance as well as its shape. The background surface may help subjects locate the centre of the ellipsoid. Some differences between the two scaling measures were to be expected, because misjudging the size of the real tennis ball only influences the size-scaling distance. Systematic over- or underestimation of the size of the real tennis ball could explain why the lines do not always intersect at the same value for both measures. Moreover, a factor such as curvature contrast may directly influence the perceived shape, while it should not influence the perceived size.

In the last experiment, subjects did just as well with a thin vertical strip of correlated points along the midline, in which vertical size ratios were very small, as with the strip elsewhere. Thus, they did not benefit from the larger vertical size ratios that were present when the vertical strip was at a larger horizontal eccentricity. Neither did they benefit from the larger *range* of vertical size ratios present when the strip was horizontal. This supports the notion that subjects use the horizontal gradient of the vertical size ratio to judge distance, because this gradient is the same throughout the field of view. Subjects appear to be able to extract this gradient within about 2° at most (the influence was already clearly evident with a bar width of 6.25% of 33° and did not depend on the orientation of the bar). Note that the surface of the 2° bar fills about 0.02 sr of the visual field, which is more or less the same as does the tennis ball for an average setting. Thus, presumably, the gradient of vertical size ratio from the surface of the ball is also considered. However, the relationship shown in Fig. 1 only holds for points at a constant egocentric distance. The ball's surface is curved, which influences

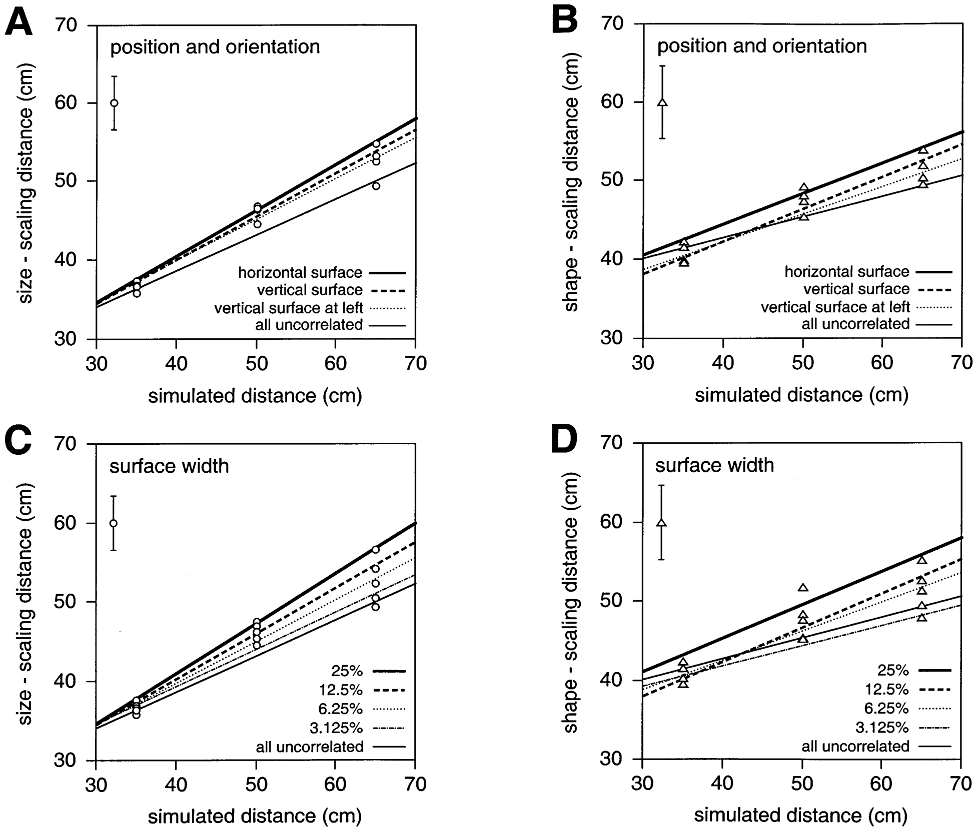

Fig. 5. Results of Experiment 3. The 13 conditions are grouped either by surface position and orientation (A, B) or by surface width (C, D). Further details as in Fig. 4.

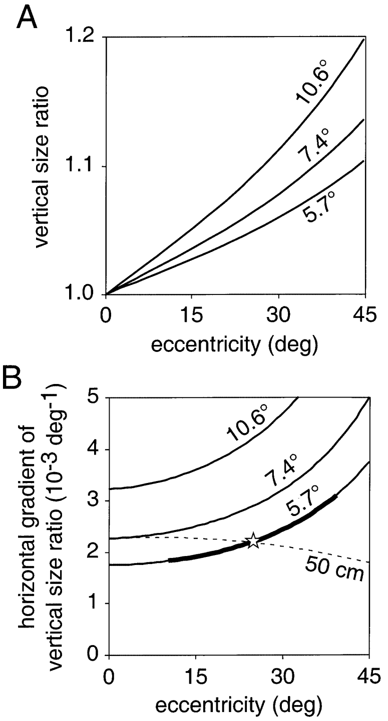

Fig. 6. Vertical size ratio as a function of horizontal eccentricity with respect to the orientation of the subject's head. Calculations for an inter-ocular distance of 6.5 cm for structures on various isovergence circles. (A) Ratio itself for three vergence angles. (B) Change in ratio with horizontal eccentricity [i.e. the slope in (A)] for the same three vergence angles. The star indicates a fixated object at 25° eccentricity and an egocentric distance of 50 cm. The dashed curve shows the slope for an egocentric distance of 50 cm as in Fig. 1B. The thick section of the solid curve shows the vertical size ratio of structures with no horizontal disparity within 15° to either side of fixation.

the gradient. Our visual system must somehow deal with such changes in depth within the scene, because most scenes contain structures at many distances (see below).

As already mentioned in Section 1 (see Fig. 1), the relation between egocentric distance and the horizontal gradient in the vertical size ratio is practically independent of eccentricity. The conclusion that subjects use this measure is therefore consistent with the orientation of the subject's head having no effect in Experiments 1 and 2. It is also consistent with the finding that eye movements make little difference (Rogers & Bradshaw, 1995). It supports van Ee and Erkelens' (1996) prediction that disparity measures are used that are insensitive to eye and head movements.

However, it is not that simple. Local estimates of the gradient in the vertical size ratio obviously depend on the distance of the surface at that position. Pooling such local estimates across the scene to judge distance therefore does not make sense. However, since the vertical size ratios are presumably determined by the same cells that determine the horizontal disparity (Gonzalez, Relova, Perez, Acuña, & Alonso, 1993), and cells respond to a limited range of horizontal disparities (relative to fixation), such cells will only pool the vertical size ratios of surfaces with modest horizontal disparities. Fig. 6 shows how the vertical size ratio changes as a function of horizontal eccentricity for points with approximately the same horizontal disparity (i.e. for points on an isovergence torus). We suggest that only structures close to this range will be considered when pooling gradients of vertical size ratio, because only these will be fused (see Allison, Howard, & Fang, 2000, for support from a study on vertical vergence). Fig. 6 therefore represents the vertical size ratios that will contribute to the judgements of scaling distance.

The gradient varies more with eccentricity for an isovergence surface (Fig. 6) than for points at equal egocentric distances (Fig. 1). Nevertheless, if an observer fixates a point at an egocentric distance of 50 cm and an eccentricity of 25° (star in Fig. 6B), then the average horizontal gradient of vertical size ratio along a symmetrical section of the 5.7° isovergence curve (average value of the thick curve in Fig. 6B) will be approximately the same as the value at the fixation point (star). Thus, this average value will also correspond with the fixation distance in accordance with Fig. 1 (dashed line). The deviation of the gradient along the 5.7° isovergence curve from the gradient along the 50 cm egocentric distance curve increases with the eccentricity relative to fixation. Thus, the scaling distance should only be severely misjudged if all structures that are considered (i.e. all that have small horizontal disparities relative to the fixated object) are located far to one side of fixation. In our experiment 3, we had an asymmetrical condition, but the surface in question was only 12° to the left of the central fixation point, which is too little to expect an influence on our measures of scaling distance (Fig. 6B). The need to 'select' structures with little horizontal disparity, and to average across structures within this range, explains why the measure must be global if it is also to work in a normal cluttered environment.

Vertical size ratios were manipulated experimentally within the object that is being judged in some studies (e.g. in the induced effect and in our Experiment 1), but only in the surround in others (e.g. when comparing visual field sizes and in our Experiments 2 and 3). The fact that manipulating vertical size ratios in the surround makes a difference for perceived size and shape implies that the judged egocentric distance of an object can be influenced by information from the whole scene. This supports the notion that it is the judgement of the viewing distance that is improved, rather than just local slants or curvatures. One attractive aspect of this specific proposal is that it provides an estimate of distance that is independent of gaze eccentricity. This estimate can be combined with extra-retinal estimates of distance, or can even be used to calibrate the latter (Brenner & van Damme, 1998).

Using the horizontal gradient in the vertical size ratio to judge the viewing distance can explain the influence of manipulations in the background on judgements of size, shape, distance and even curvature. We found a clear influence of vertical size ratios with quite a modest field of view. Presumably, this was because the distance specified by the vertical size ratios was not in conflict with that specified by extra-retinal information, but complemented it in specifying the simulated distance (Bradshaw et al., 1996; Backus et al., 1999). In that case, there is a natural interpretation of the signals reaching the brain.

Using the horizontal gradient in the vertical size ratio to judge the egocentric distance cannot explain the induced effect. Magnifying the image in front of one eye vertically probably (explicitly or implicitly) invokes mechanisms that normally deal with horizontal gaze eccentricity (Gillam et al., 1988; Backus & Banks, 1999; Backus et al., 1999). The influence on perceived slant is much stronger and less sensitive to conflicts within the stimulus than is the influence of vertical size ratios on judgements involving distance. Thus, the induced effect is probably caused by a completely different mechanism than that studied here.

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