

Objects can be localized at positions that are inconsistent with the relative disparity between them

The presence of a more distant object helps judge an object's position in depth. To find out why, we examined whether misjudging a distant cube's location induces a corresponding misjudgment of a nearer sphere's location. Various configurations of a distant cube and a near sphere were presented in total darkness. Each configuration was presented twice: in one presentation subjects localized the sphere with their unseen index finger and in the other presentation they localized the cube in the same way. Three cube sizes were used. Most subjects judged a larger cube to be nearer than a smaller one that was at the same position. For about half of the subjects, cube size had a significantly smaller effect on the judged distance of the sphere in terms of target vergence. Thus, the distance between the judged positions of the two objects was inconsistent with the relative disparity between them. This contradicts claims that the furthest object is localized and used as an anchor point for distance judgments based on correctly perceived relative disparity.

Judgments of one's distance to a single object in the dark are generally biased (Poulton, 1981; Gogel, 1961; Tresilian et al., 1999; Foley, 1977; Johnston, 1991; Brenner & Van Damme, 1999). Observers tend to see objects in the dark at a certain distance. Objects that are further away than this distance appear to be nearer and objects that are nearer appear to be further away. The resulting underestimation of the range of presented distances is referred to as a contraction bias. The presence of a second object that is further away than the object of which the distance is to be judged improves distance judgments in the sense that there is a reduction of the contraction bias (Gogel, 1972; Bank, 1958; Foley, 1985, Sousa et al., 2010).

It has been suggested that the reduction of the contraction bias is related to the relative disparity between the two objects. Blank (1958) assumed that relative disparities are judged correctly, and proposed that relative disparity is used to localize all objects relative to the most distant object, which in turn is localized at a fixed distance unless it is very nearby. Gogel (1972) and Foley (1985) presented additional evidence that the furthest object is used as an anchor point for distance judgments and that nearer objects are related to the anchor point on the basis of relative disparity. We will refer to this proposal as the anchoring hypothesis. It may seem counterintuitive to use the most distant object as an anchor point, because the resolution of localization is known to decrease with distance. However, the decrease in resolution with distance is primarily caused by the geometry of translating angles into metric distances (Brenner & Smeets, 2000) so using the most distant object is not unreasonable when dealing with angles, as one does when relating positions to an anchor point through relative disparities.

Binocular cues are not the only ones to provide information about objects' distances. Although retinal image size is only a reliable cue for distance if the associated object's true size is known, image size can influence the judged distance if observers consider certain object sizes to be more likely than others (Epstein, 1963; Collett et al., 1991; Sousa et al., 2010). We therefore presented pairs of objects in otherwise total darkness. Each pair consisted of a sphere and a more distant cube. The cube had one of several sizes. Subjects were asked to indicate the position of the cube as well as that of the sphere. We expected subjects to indicate a nearer position for larger cubes. The critical question is whether misjudging the cubes' positions in depth leads to a corresponding misjudgment of the spheres' locations. If the cube is used as an anchor point for judging the sphere's distance it should, because otherwise the perceived relative disparity will not match the real relative disparity.

Methods

Subjects

20 subjects participated in the experiment. All were naive about the purpose of the experiment and had normal binocular vision.

Apparatus

We used a set-up with mirrors that reflect the images from two CRT monitors (1096 x 686 pixels, 47.3 x 30.0 cm) to the two eyes to produce simulations of three-dimensional objects (see figure 1). New images were created for each eye with the frequency of the refresh rates of the monitors (160 Hz). The 3D positions of the subject's head and right index finger were recorded at 250 Hz using Infra-Red Emitting Diodes (IREDs) and an Optotrak 3020 system (Northern Digital, Inc.).

One IRED was attached to the nail of the subject's right index finger and three others to a bite-board. The bite-board was not attached to anything besides the subject's mouth, so subjects could move their head freely during the experiments (although they could not move very far since they had to look into the mirrors). The positions of the subject's eyes relative to the bite-board were determined in advance (using a sighting device to determine the line of sight for various orientations of the eye in the head). During the experiment, the images were adapted to the positions of the subject's eyes as determined from the positions of the markers attached to the bite-board. The calibration procedure is described in detail in Sousa et al. (2010).

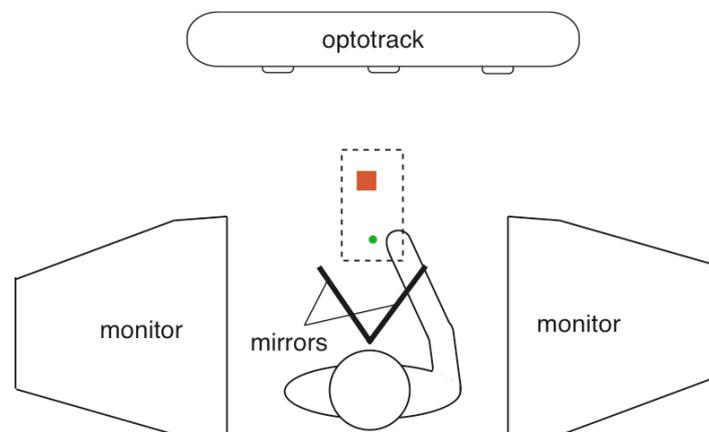


Figure 1. The top view of the set up. The dashed rectangle indicates the area within which the objects could appear.

Stimuli

On each trial, two objects were presented in total darkness: a cube and a sphere. We used two sets of 30 configurations of object positions. The sphere appeared at random positions within a volume of space of 8x8x20cm (width x height x depth). The cubes appeared at random positions within a volume of 16x8x20cm, but always further away than the sphere. The two volumes were centered at the same fixed position in space. This position was lower than the subjects' eyes, to ensure that the objects were at a suitable height to which to move the index finger. The volumes were oriented downwards by about 30° so that subjects were looking down their longest (depth) axis. The objects' distances from the subjects depended on exactly where their head was. On average, the sphere's position in depth was 44.6 cm and that of the cube was 50.8 cm from the subjects' eyes.

The sphere's angular size varied independently of its simulated distance. Its diameter varied randomly between 0.26 and 0.52 degrees. Approximately aligning the long axes of the volumes of possible object positions with the eyes ensured that there was no straightforward relationship between height in the visual field and simulated distance (although the height in the visual field was more variable for nearby objects). The cube had one of three different simulated sizes: sides of 0.8, 1.2 or 1.6 cm. On each trial one of the objects was red and the other green.

Procedure

The subjects were instructed to bring their index finger to the center of the red object. In the remainder of this paper we will refer to this as *pointing*. The object that subjects were to point at could either be the sphere or the cube. They started each pointing movement with their right hand near their body. When the target appeared, they moved their unseen index finger to where they saw the target, and held the finger steady until the trial ended with the target disappearing. At that moment the finger position was recorded. The trial ended if the hand was within 30 cm of the centre of the volume of possible cube positions, and had not

moved more than 1 mm in 300 ms. After the target disappeared, the subjects had to bring the hand back near to their body and wait until a new target appeared at another location.

Conditions

The six conditions only differed in the size of the simulated cube and in which of the two objects was red and was therefore to be pointed at (figure 2). The same 30 pairs of positions (and the same sphere sizes) were used for all six conditions. The conditions were randomly interleaved within each session. Each subject took part in two sessions with different sets of object positions.

cube size	0.8 cm	1.2 cm	1.6 cm
Pointing at sphere			
Pointing at cube			

Figure 2. The six conditions. The same 60 pairs of object positions were used in each condition.

Analysis

The influence of the sphere’s angular size on the pointing distance (in cm) when pointing at the sphere was evaluated with multiple regression with angular size (degrees) and simulated distance (in cm) as independent variables. A separate regression was conducted for each subject. To evaluate whether each of the independent variables (distance and size) had a consistent influence across subjects we examined whether the 20 subjects’ slopes were significantly different from zero with *t*-tests. A similar analysis was conducted for the influence of the cube’s angular size on the pointing distance when pointing at the cube, although it is important to realize when interpreting the results of this analysis that the cube’s angular size is not independent of its distance.

According to the anchoring hypothesis perceived distances primarily depend on relative disparity, which is an angular measure, so we converted the indicated positions to the ocular convergence that would be required for the eyes to fixate the objects for all further analysis. For each pair of object positions, we quantified the magnitude of the effect of cube size on cube pointing by determining the angular difference between the indicated cube positions for the 0.8 cm and 1.6 cm cubes. A similar procedure was used for determining the effect of cube size when pointing at the sphere. For each subject we then tested whether the effect of cube size on cube pointing was significantly different from its effect on sphere pointing (with paired *t*-tests across the 60 matched pairs of object positions). For each subject, we also averaged the differences between the indicated cube positions, and those between the indicated sphere positions, across all 60 pairs of object positions (and determined the corresponding standard errors).

The variability in head position was ignored when comparing the matched conditions, because the standard deviation (across trials) in the head position at the time of pointing was only about 0.8 cm, and there was no systematic difference in head position related to cube size (the median difference between the subjects' mean head positions at the time of pointing in the presence of a large or a small cube was 0.02 cm). Possible effects of misjudging the finger's position in depth were also ignored, because one advantage of comparing the influence of cube size on pointing at objects that are at the same simulated position is that systematically misjudging the unseen finger's position hardly matters (because it influences pointing at both objects similarly so the difference will hardly change).

Results

Subjects pointed further away when pointing at more distant spheres (mean slope of regression analyses: 0.77; $p < 0.001$). The sphere's angular size did not have a systematic effect on the pointing distance (mean slope: -7.5 cm/°; $p = 0.36$). Subjects also pointed further away when pointing at more distant cubes (mean slope: 0.44; $p < 0.05$) as well as when pointing at smaller cubes (mean slope: -42.5 cm/°; $p < 0.05$). Figure 3 shows raw pointing data for two subjects, both for pointing at the sphere and for pointing at the cube. For subject A, the cube's size influenced its judged position in depth: for the same simulated cube position in

depth, the subject pointed nearer for the 12 mm cube than for the 8 mm cube, and nearer still for the 16 mm cube (the blue curves are clearly separated). There was no corresponding effect of distant cube size when pointing at the sphere (the green curves are on top of each other), contrary to the prediction of the anchoring hypothesis. For subject B, the cube's size had little effect on the pointed position in depth when pointing at the cube (the blue curves are on top of each other). The same lack of effect of cube size is seen for pointing at the sphere (the green curves are also on top of each other) in accordance with the anchoring hypothesis.

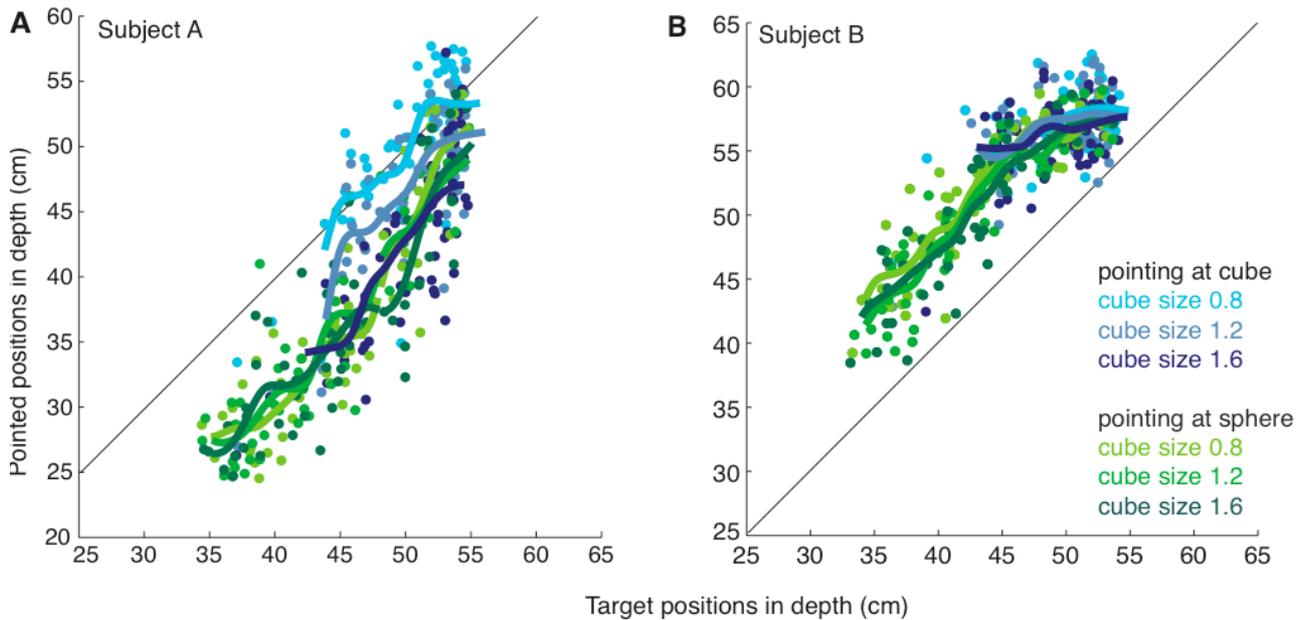


Figure 3. Target distances and pointed distances for different cube sizes. A. Subject A was influenced by cube size when pointing at the cube but not when pointing at the sphere. Each point is one response. The curves are smoothed averages of the pointing distances as a function of target distance, with weights determined by a moving Gaussian window ($\sigma=10\text{cm}$). The smooth curve is only shown if there were at least 5 data points within ± 4 cm of the target distance in question. B. Subject B was hardly affected by cube size, both when pointing at the cube and when pointing at the sphere.

Figure 4 summarizes the effect of cube size on pointing at the cube and on pointing at the sphere. Each subject is represented by one point. According to the *anchoring hypothesis*, the points should be located along the diagonal line that corresponds to relative disparity being judged correctly (same cube size effect for pointing at the sphere as for pointing at the cube). Most points lie below the diagonal line. For 8 subjects the effect of cube size on pointing at the distant cube is significantly larger than its effect on pointing at the nearer sphere. Thus, about half of the subjects misjudge the positions in a manner that is inconsistent with judging the sphere's position from a combination of the cube's apparent position and the (correctly perceived) relative disparity. Their data are therefore inconsistent with the *anchoring hypothesis*.

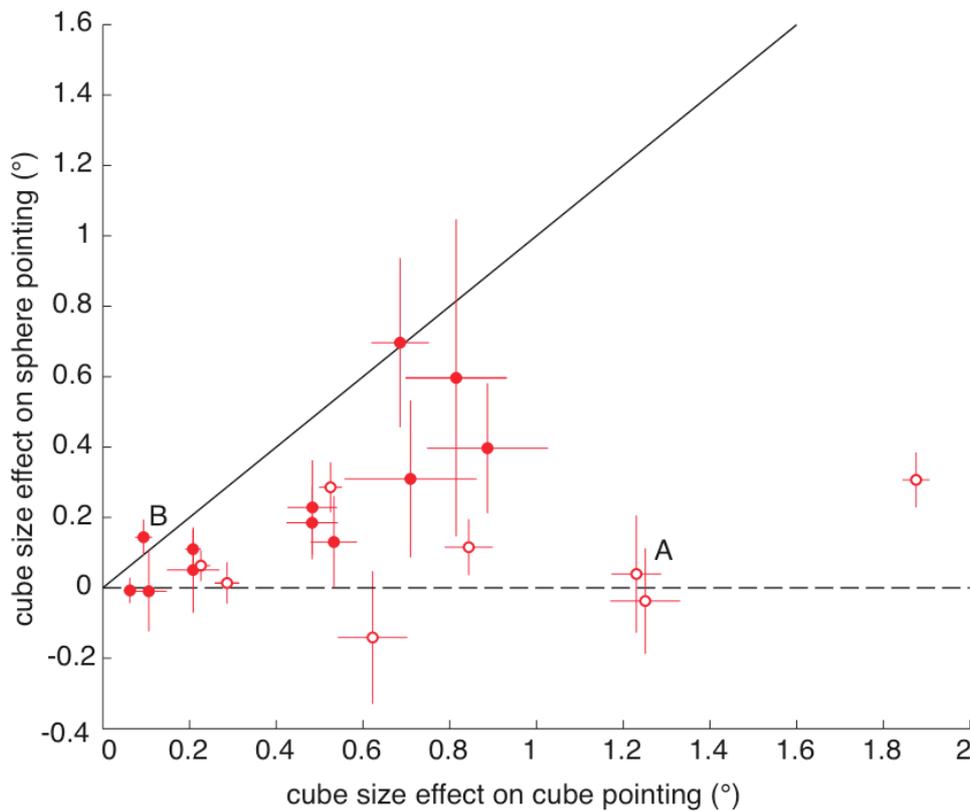


Figure 4. Plot of the effect of cube size on pointing at the sphere as a function of the effect of cube size on pointing at the cube (each dot represents the averages with standard errors of one subject; open dots represent subjects for whom the effect of cube size is significantly larger for pointing at the cube than for pointing at the sphere). The effects are expressed as changes in the ocular convergence that would be required to fixate the pointing index finger when cube size is changed. If relative disparity were judged correctly the points would all be along the diagonal line. If the cube size had no effect on sphere pointing the points would be on the horizontal dashed line. The points marked A and B represent the example subjects shown in figure 2.

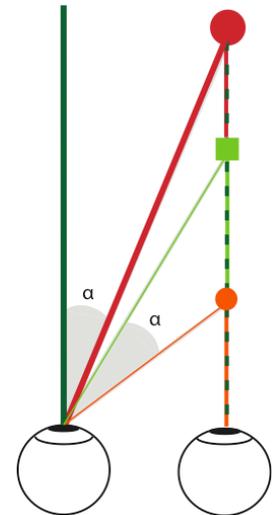
Discussion

A distant object is known to influence the judged distance of a nearer one (Gogel, 1972; Bank, 1958; Foley; 1985, Sousa et al., 2010). We show that influencing the further object's judged position in depth does not necessarily affect the nearer one correspondingly. Thus, the relative disparity between the perceived positions is not always consistent with the relative disparity between the objects' simulated positions (for an explanation of why people tolerate this see Smeets et al, 2008). This contradicts the idea that relative disparities are judged correctly (e.g. Foley, 1980) with the furthest object used as an anchor point (Blank, 1958).

We (Sousa et al., 2010) proposed a different explanation for how relative disparity influences distance judgments: the *limiting factor hypothesis*. The same relative disparity can arise from many different pairs of

object positions in depth. Given a value of relative disparity (α), and considering that the furthest possible position of the farther object of the pair of objects is infinitely far away, which corresponds to parallel lines of sight, there is a geometric limit to the possible positions in depth of the nearer object of the pair (shown by the dark red point in Figure 5). Therefore, the presence of the farther object reduces the range of possible positions of the nearer one without the farther object having to be localized. Similar reasoning can be applied to other distances than infinitely far away when one is within an enclosed environment, where the farther object can be assumed not to be further away than a certain distance (e.g. the estimated distance to the wall).

Figure 5. The same relative disparity (α) could arise from many pairs of object positions. One possible pair is that shown as a light red sphere and a light green cube. Since the lines of sight approach being parallel for a very distant object, the relative disparity presents a geometric limit to the nearer object's position in depth (dark red sphere).



If the above-mentioned influence were the only way the distant cube influences the nearer sphere's distance judgment, there would be no influence of cube size when pointing at the sphere because the cube does not need to be localized. In that case the data points would have been on the horizontal dashed line in figure 3. That is not the case. Manipulating the cube's size influenced pointing at the sphere to some extent: most points are above the horizontal line. Thus even if the limiting factor hypothesis is correct, the distant object must have some additional influence on the perceived distance of the nearer one. This could mean that the cube's size influences the range of distances that are considered possible (or how much weight to give to this cue), which would bring together the two hypotheses. However, the *anchoring hypothesis* in its original formulation Blank (1958) is rejected by the critical finding that the perceived positions do not comply with the relative disparities.