

# Binocular depth discrimination and estimation beyond interaction space

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The benefits of binocular vision have been debated throughout the history of vision science yet few studies have considered its contribution beyond a viewing distance of a few meters. In the first set of experiments, we compared monocular and binocular performance on depth interval estimation and discrimination tasks at 4.5, 9.0 or 18.0 m. Under monocular conditions, perceived depth was significantly compressed. Binocular depth estimates were much nearer to veridical although also compressed. Regression-based precision measures were much more precise for binocular compared to monocular conditions (ratios between 2.1 and 48). We confirm that stereopsis supports reliable depth discriminations beyond typical laboratory distances. Furthermore, binocular vision can significantly improve both the accuracy and precision of depth estimation to at least 18 m. In another experiment, we used a novel paradigm that allowed the presentation of real binocular disparity stimuli in the presence of rich environmental cues to distance but not interstimulus depth. We found that the presence of environmental cues to distance greatly enhanced stereoscopic depth constancy at distances of 4.5 and 9.0 m. We conclude that stereopsis is an effective cue for depth discrimination and estimation for distances beyond those traditionally assumed. In normal environments, distance information from other sources such as perspective can be effective in scaling depth from disparity.

Keywords: stereopsis, distance perception, depth perception, cue combination, binocular vision, depth constancy, scaling

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## Introduction

Since the eyes are horizontally separated in the head they view the world from two different vantage points. Thus, the images of a scene differ on the two retinas. In stereopsis the image differences, or binocular disparities, are used by the visual system to obtain a percept of depth (Wheatstone, 1838). These binocular disparities are greater when a given object is viewed at a nearer distance. Conventional thinking, as expressed in many undergraduate psychology textbooks, notes this fact and makes the presumption that stereopsis is only useful in near space (e.g. less than 30 m, Palmer, 1999). Several authors propose that stereopsis is most useful for interacting with objects at arms length or in ‘grasp’ or ‘personal’ space (e.g., Arsenault & Ware, 2004; Cutting & Vishton, 1996; McKee, Levi, & Bowne, 1990; Morgan, 2003) and Gregory (1966, p. 53) asserts that we ‘are effectively one-eyed for distances greater than about twenty feet’ (approx. 6 m). However, humans are extremely sensitive to binocular disparities and can detect depth differences corresponding to horizontal image width disparities of a

few seconds of arc (Howard, 1919). Given this precise stereo acuity, geometrical analysis suggests that it should be possible to obtain useful information from stereopsis at much larger distances than conventionally assumed.

There has been little empirical investigation of stereopsis at large distances. Most work at distances beyond 1–2 m has concentrated on depth discrimination, many simulating large distances via vergence in a stereoscope or haploscope (Amigo, 1963; Dees, 1966; Kaufman et al., 2006; Ogle, 1958). Studies with real depth intervals have described substantial binocular improvements when monocular cues are weak (Crannell & Peters, 1970 to 30.0 m; Hirsch & Weymouth, 1948 at 17 m; Howard, 1919 at 6.0 m) or more modest binocular improvements with salient monocular cues (Jameson & Hurvich, 1959 to 48 m; Teichner, Kobrick, & Dusek, 1956 to 30 m; Teichner, Kobrick, & Wehrkamp, 1955 at 30.0 to 914.0 m). Beyond basic studies, clinical and applied researchers have infrequently used distance stereoacuity measures, typically at 3.0 or 6.0 m (Adams et al., 2005; Bauer, Dietz, Kolling, Hart, & Schiefer, 2001; Kaye et al., 1999; Lam, Tse, Choy, & Chung, 2002; Rutstein & Corliss, 2000; Wong, Woods, & Peli, 2002).

While there has been some work on stereoscopic depth discrimination, there has been almost no study of perceived depth magnitudes or depth estimation beyond 2 m. Loomis, Da Silva, Fujita, and Fukusima (1992, at 1–4 m) and Durgin, Proffitt, Olson, and Reinke (1995, at 1–3 m) found binocular improvements for 3-D aspect ratio judgements but neither study attempted to isolate disparity as a cue. In the former study, since the L-shaped stimulus arrangements lay on a textured ground plane, monocular information about slant and depth within the stimulus was available from perspective, occlusion, ground contact and other cues. In the latter experiment, the real cones used were patterned with equally spaced contours and thus perspective-based texture compression gradient cues were potentially available (as were disparity gradient cues in the binocular case), although the poor constancy (and small depth sensitivity) they observed under monocular viewing conditions suggests these cues had little influence (see also Gogel, 1960). In both experiments, vergence and accommodation cues to distance and possibly relative depth were available at the relatively short distances used. The only study of perceived depth from disparity at large distances using natural scenes is that of Cormack (1984). However he had observers set a probe to the depth of the further object. Unfortunately this task tells us nothing about perceived depth but does show that observers can depth/disparity match at large distances. Our focus in the present experiments is to address this gap in our understanding by measuring accuracy and precision of stereoscopic judgments of the size of depth intervals at longer distances than previously studied.

## Distance and the utility of disparity

Figure 1 plots the disparity of an object at a given distance relative to a point at infinity for a typical value of interocular separation. When this disparity is less than an observer's stereo acuity the distance of the object cannot be reliably discriminated from a point at infinity based on stereopsis. Helmholtz (1909) appreciated this fact over a century ago and estimated that humans could stereoscopically discern a near target from a point at infinity if it were at a distance of 240 m or less. However, Helmholtz did not have an accurate measure of stereo acuity. With modern estimates for typical stereo acuity of better than ten seconds of arc, we predict that an observer should have a maximum useful range of stereopsis of greater than a kilometer. The dotted line in Figure 1 estimates maximum range of stereopsis for an observer with a good stereoacuity of 5.0 seconds of arc that has been reported for some observers (McKee, 1983).

The binocular disparity ( $\delta$ ) associated with a given depth difference ( $\Delta d$ ) increases proportionally with the interocular distance ( $I$ ) and inversely with the square of viewing distance ( $D$ ). For stimuli located near the midline

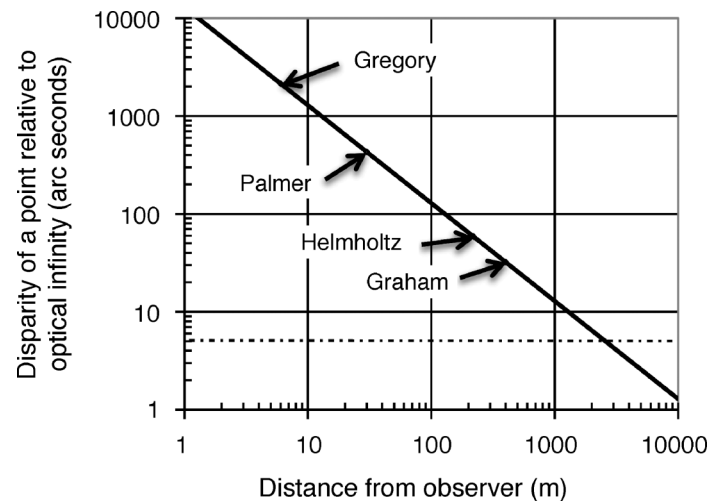


Figure 1. The disparity of a target at various distances relative to a point at infinity (plotted on log–log scales). The dots show estimates of the useful range of stereopsis from the literature. The estimate from Palmer (1999) is typical. The estimate from Graham (1965) is more reasonable but assumes a poor stereo acuity. The dotted line corresponds to a stereoacuity of 5.0 seconds of arc and a 62.5 mm interocular distance.

and at a large distance relative to  $I$ , disparity can be approximated as:

$$\delta \approx \frac{\Delta d \cdot I}{D^2} \quad (1)$$

Due to the inverse square dependence on distance, the depth separations discriminable stereoscopically at large distances would be large, but one only needs to discriminate large depth differences at great distances. Thus the decrease in depth sensitivity of stereo cues is partly compensated for by the fact that the scale of interest increases with the observation distance.

Walking through the bush, the required scale of interest becomes apparent. When looking at a near tree, we want to know which branch is near to grab and climb or to avoid becoming entangled. At modest distances, we need to know the depth order of individual trees to find our way through the forest. At larger distances, we need to estimate the depth relation between various thickets and hills. Thus stereo should be useful at considerable distances.

Figure 2 illustrates this point. The linear or physical size of a depth interval corresponding to a just noticeable difference (J.N.D.) in disparity predicted from stereoacuity increases with distance to the configuration. However as a fraction of the viewing distance this interval remains modest to tens or hundreds of meters. It remains a viable cue until distances approaching the theoretical maximum useful range where the J.N.D. interval begins to approach the distance itself—conditions

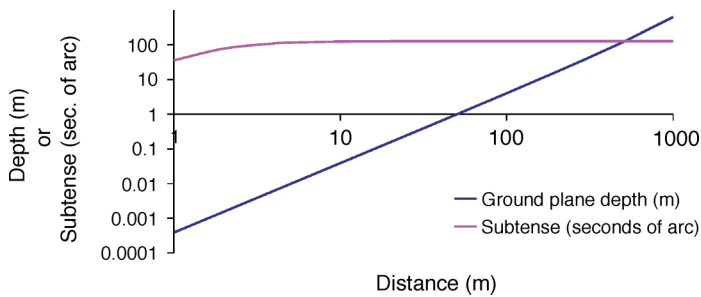


Figure 2. Depth and angular subtense of a ground plane interval corresponding to a difference of 5 seconds of arc disparity—i.e., a good stereo acuity. Notice that as distance increases the calculated linear size of a depth interval corresponding to a just noticeable difference in stereoscopic depth increases but the angular subtense of the interval stays constant at all but near distances (for example, less than 1–2 eye heights).

under which it is unlikely to be useful except in the crudest of judgements.

## Stereopsis in rich, natural environments

Although viable, the actual use of stereopsis presumably depends on the availability and reliability of other cues to depth and the demands of the task. While theoretical arguments can be made (e.g., Cutting & Vishton, 1996) evaluating the relative contributions of stereopsis and other cues as function of distance is essentially an empirical question. However, some observations can be made.

For instance, one powerful cue for three-dimensional layout is the so-called ‘height in the field’. Due to perspective projection the retinal image of more distant objects lying on the ground plane fall nearer the horizon than the projection of closer objects. This is a compelling distance cue and can specify the relative depth order and quantitative depth between stimuli based on the vertical gap between them in the image. As with all perspective based cues the precision of this cue degrades with distance. Figure 2 also shows that at moderate to large distances the subtense of a stereoscopic J.N.D. on the ground plane remains essentially constant (this can easily be demonstrated from the viewing geometry). Thus, we predict that the effectiveness of stereopsis relative to the height in the field cue will be effectively constant at all distances. Which cue is objectively more reliable depends on relative sensitivity to disparity and image separation and the degree that the flat ground plane and attached object assumptions implicit in use of the height in the field cue hold.

## Motivation

Although one can predict a large theoretical range for stereopsis, no valid studies have been undertaken to

investigate the properties of suprathreshold stereopsis beyond 4.0 m and very few have studied any aspect of stereopsis beyond two meters. Thus, empirical determination of the useful range of stereopsis is an open problem and a careful study is long overdue. This paper is a first step toward a characterization of stereopsis at moderate to large distances and focuses on binocular depth perception at moderate distances of 4.5 to 18.0 m. Our major motivation was to measure degree of depth, something other studies have not done, although we also measure depth thresholds at the same distances.

## Experiment 1: Depth discrimination

Numerous studies of stereoscopic depth thresholds at near distance demonstrate our exquisite sensitivity to the relative horizontal disparity between two points. A number of investigators have also measured sensitivity to relative depth between targets at longer but still modest distances (Amigo, 1963; Brown, Ogle, & Reiher, 1965; Crannell & Peters, 1970; Foley, 1966; Lit & Finn, 1976; Ogle, 1958). In this experiment observers judged the relative depth (sign) of a target with respect to a reference surface. Depth discrimination performance under monocular versus binocular viewing conditions was compared. Our stimulus was designed so that the task could not be performed based upon relative size judgments between similar elements. Thus, Experiment 1 allows for comparison of discrimination performance with earlier literature where relative size was a task relevant cue. Further it provides an important measure of baseline stereoscopic performance for the depth estimation studies to follow.

## Methods

### Apparatus and stimuli

The laboratory was a large lightproof tutorial room, used for perception and sensation courses, that was cleared of furniture and other objects. Viewing distances to 9.0 m were possible in the lab itself and viewing at 18.0 m was possible using the adjacent hallway. The observer sat at a table with head supported on a chin rest. Binocular or monocular viewing conditions were run in separate blocks of trials. Monocular viewing was facilitated by occluding the non-dominant eye with a black eye patch. An aperture was located at a distance of 82 cm from the observer. The aperture subtended  $8^\circ$  in width and  $7.9^\circ$  in height. The aperture occluded the observer’s view of the floor, ceiling, and walls of the room and any extraneous visual features. An upright white acrylic septum was placed in front of the observer



extending from near the mid-point of the eye toward the aperture. This resulted in a horizontal monocular field of view of  $4.2^\circ$  for each eye with a nearly identical binocular field of view.

The reference stimulus was an architectural panel (244 cm high by 122 cm wide) viewed against a homogenous beige background. The background extended beyond the reference stimulus to fill the rest of the observer's field of view through the aperture. A flood lamp illuminated the background surface, provided uniform lighting and eliminated visible cast shadows from the reference or test stimuli. Due to this illumination the reference panel appeared as a darker surface on a light background (note that the contrast relation appears opposite in [Figure 3](#) due to the effects of the camera flash). The panel was placed so that only one edge was visible and this edge extended beyond the border of the aperture. The face of the panel

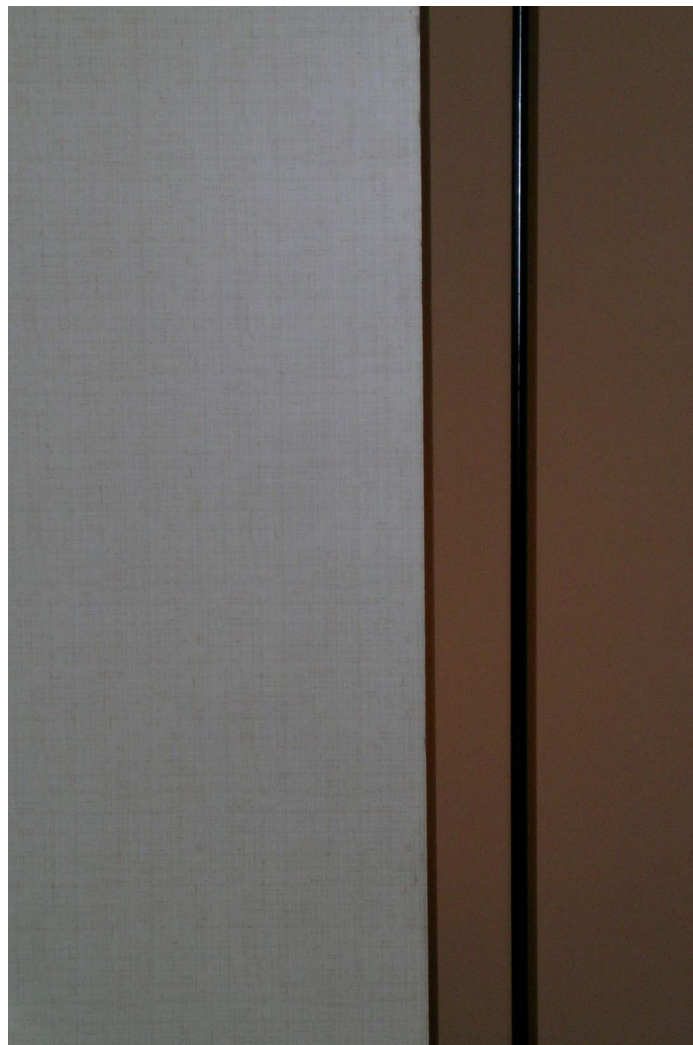


Figure 3. Observer view showing the reference panel on the left and the test stimulus (black). The shadows are due to the camera flash and were carefully avoided with lighting in the experimental conditions.

was placed perpendicular to the observer's straight-ahead line of sight and the edge was offset 4 cm from the center of the aperture to allow a gap between the panel and target (test stimulus). The target was a 16 mm diameter, 220 cm long rigid steel pipe, painted matte black and mounted length aligned to gravity on a custom machined carrier that ensured stability and alignment. It was placed at a variable depth (see below) about the distance of the panel and was offset 4 cm from the lateral center of the aperture in the opposite direction from the panel. Through the aperture the target appeared to be a long tube or line with no visible top or bottom (due to occlusion from the top and bottom of the aperture). The aperture view was arranged to eliminate viewing the top or bottom of the target or reference stimulus ([Figure 3](#)).

The panel was located at a distance of 900 cm from the observer's vantage point. The fixture holding the rod was mounted on a precision linear bearing that could be moved in depth with respect to the reference surface and aligned with a scale marked in 1.0 mm increments. Maximum travel of the bearing was  $\pm 150$  cm. The experimenter positioned the linear bearing manually. A shutter flap was attached to the aperture. The shutter completely blocked the observer's view of the stimuli and could be raised or lowered remotely by the experimenter. Between each trial the shutter was closed while the stimuli were positioned. Opening of the shutter signaled the next trial to the observer.

### Observers

Six observers with normal stereopsis participated. All observers had normal or corrected to normal vision except for one observer who had reduced visual acuity (20/25) in one eye due to early cataract. Additional scrutiny was paid to this observer's data that indicated the observer performed at a similar performance level to the other observers.

### Task

On each trial, observers judged whether the test rod was located in front or behind the reference plane. Based on whether the response was in front or behind, the depth interval was adjusted using three simultaneous randomly interleaved transformed up-down staircase procedures in order to estimate depth intervals producing 21%, 50% and 79% nearer responses (3up/1down, 1up/1down and 1up/3down procedures, respectively; (Levitt, 1971)). The staircases were run until each had obtained at least eight reversals and the convergence level was estimated by the average of trials after the fourth reversal. To eliminate response bias, thresholds were calculated by averaging the unsigned depth intervals corresponding to the convergence points of the 3up–1down and the 1up–3down staircases.

Viewing was monocular or binocular in separate blocks with order counterbalanced across observers. Viewing distance to the reference stimulus was 900 cm.

## Results and discussion

Depth discrimination thresholds at 9.0 m were lower for binocular than monocular viewing for all observers. The binocular improvement in depth sensitivity was a factor of 10 or more for some observers and greatly in excess of that predicted from mechanisms such as binocular probability summation (Figure 4).

Generally, previous research has found that near stereoacuity has predicted distance stereoacuity (e.g., Brown et al., 1965), although several studies found a slight increase at distances of less than 40 cm (Bradshaw & Glennerster, 2006 to 4.5 m; Brown et al., 1965 to simulated 6.0 m; Lit & Finn, 1976 to 1.5 m; Ogle, 1958 to simulated 10.0 m).

In agreement with these studies, binocular thresholds in this experiment were compatible with predictions from threshold estimates obtained at near distances. A stereoacuity of 5.0–10.0 seconds of arc predicts a depth sensitivity of 3–8 cm, which corresponds to the results for five of six of our observers. Several of our observers have previously achieved disparity thresholds at similar levels on near stereoacuity tasks. The clinical test we used

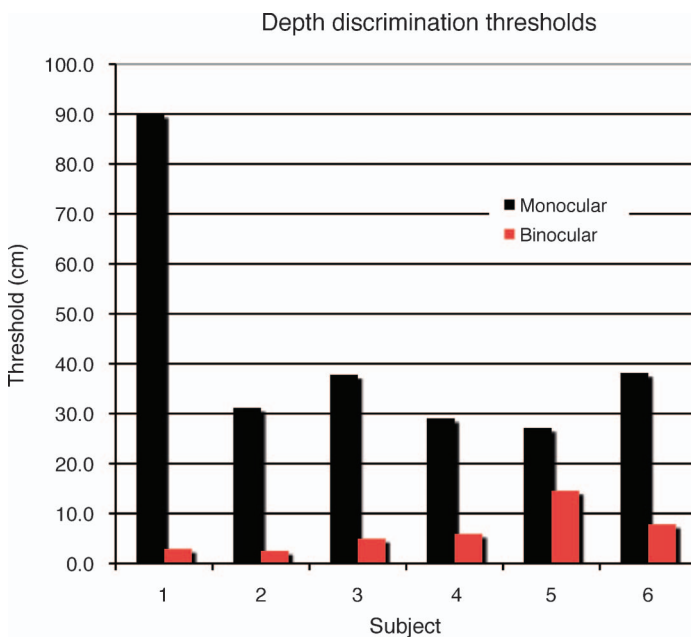


Figure 4. Binocular and monocular depth discrimination thresholds for six observers obtained using adaptive staircase procedures at 9.0 m. For comparison, a 5.0–10.0 second of arc disparity threshold predicts binocular depth thresholds in the range of 3–8 cm based on stereopsis.

for screening had a lower bound of 20 seconds of arc and all the binocular depth discriminations at 9.0 m were at least at this level.

## Experiment 2: Depth interval estimation

As Equation 1 shows, the relationship between disparity and depth is a function of distance. At close observation distances we are not only able to discriminate depth but also able to judge the size/magnitude of the depth separation between two objects. As relative disparity increases at a given distance geometry leads us to predict that observers should perceive monotonically increasing depth intervals.

While increasing disparity implies increasing depth at any given distance, recovery of quantitative depth requires scaling disparity for the observation distance. The scaling factor increases with the square of the observation distance. It is known that the magnitude of depth intervals is seen according to this geometry up to distances of about a meter (Wallach & Zuckermann, 1963) indicating that the scaling of depth magnitude for absolute distance is good at close distances. This is referred to as stereoscopic depth constancy.

In this experiment we explore the accuracy and precision of depth interval estimations made at various distances. The enhancement of stereoscopic depth constancy under enriched environmental conditions is investigated in Experiment 3.

## Methods

The apparatus was the same as in Experiment 1 except that the reference panel was located at a distance of 450, 900, or 1800 cm from the observer's vantage point. Further, at the 18 m viewing distance, the aperture was reduced to 2.8° height to prevent the observer from seeing the ground.

Observers judged the location of a target stimulus with respect to the reference surface. On each trial, observers indicated verbally the perceived depth interval between the reference and the target in centimeters and also indicated which was nearer.

Between each trial the shutter was closed while the stimuli were positioned. Opening of the shutter signaled the next trial to the observer.

Six observers with normal stereopsis participated. Prior to each trial, the depth interval was set by the experimenter to a value between  $\pm 100$  cm with 1 mm precision using the linear bearing. The values were chosen by dividing this range into 10 cm bins and repeating each bin

twice (one repeat per bin for intervals between 60 and 100 cm). On each trial a bin was chosen without replacement and the depth assigned randomly within the range corresponding to the bin. Viewing was monocular or binocular in separate blocks with order counterbalanced across observers.

### Results and discussion

Figure 5 shows estimated depth as a function of true depth for one observer at distances of 9.0 and 18.0 m. Reported depth increased monotonically with true depth in all cases and the relationship was well fit by a linear regression. Depth estimates based on binocular vision tended to be larger and less variable than monocular estimates.

Regression analysis provided measures of the scaling between perceived depth and actual depth (the slope or ‘gain’) as well as the precision. As can be seen in Table 1, binocular gains were higher on average than monocular (at 4.5 m: paired  $t(5) = 4.99, p = 0.004$ ; 9.0 m: paired  $t(5) = 3.60, p = 0.015$ ; and 18.0 m: paired  $t(5) = 6.59, p = 0.001$ ) although slopes were less than unity under both viewing conditions. The means at 18.0 m exclude the data of one

Distance (m)	Monocular slope	Binocular slope
4.5	0.33	0.89
9.0	0.30	0.86
18.0	0.07	0.46

Table 1. Mean regression slopes (cm depth perceived per cm of actual depth, ideally unity) for binocular and monocular viewing as a function of viewing distance.

observer who had much larger binocular and monocular gains (2.26 and 2.92 respectively). The pattern of results does not change but, if included, the average gains would be 0.45 monocularly and 0.87 binocularly at 18.0 m.

Interestingly, there was evidence for depth constancy even under these reduced conditions in that gains at 4.5 and 9.0 m were similar although they were significantly reduced at 18.0 m. We did not expect robust depth constancy since cues to the distance of the configuration were relatively weak. Previous studies of absolute distance perception have shown vergence and accommodation ineffective at signaling distance beyond 2 m. Presumably, observers were using monocular cues and familiarity with the stimuli (due to the within subjects design) to scale across the distance conditions. However,

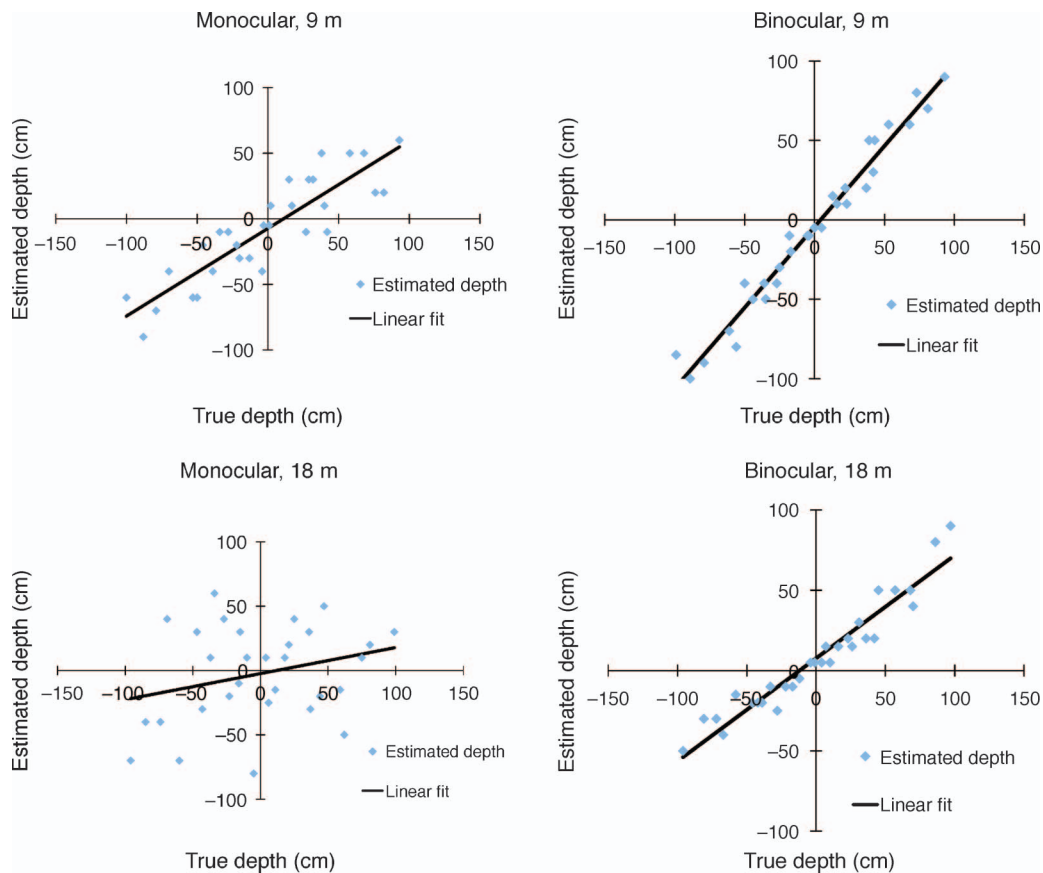


Figure 5. Example depth estimates as function of true depth for an observer at viewing distances of 9.0 and 18.0 m. Left hand panel shows monocular viewing and right hand panel shows binocular viewing. This observer had atypically good monocular depth interval estimates.

at a given distance the depth perceived for a given physical interval was larger for binocular stimuli.

Did observers simply perceive a more compelling sense of depth or were the binocular depth estimates more precise or reliable? Figure 5 shows a relatively modest binocular improvement as this observer had atypically good monocular estimates. Nevertheless, it is clear that the data is more tightly clustered around the regression line for the binocular compared to the monocular conditions.

We used the root-mean-square (RMS) residuals from the regression to quantify the spread of error around the line of best fit in order provide a measure of the repeatability and precision of the estimates. A problem with this approach is that the interpretation of the RMS error depends on the slope of the function (gain of the depth estimation). To equate the signals one can normalize the data, for each condition and observer, by dividing by the regression slope scaling it to unity gain. Use of normalized data results in an increase in the estimated noise compared to the subject's reports (since gains were typically less than one). However, the normalized data is easier to interpret as it is expressed in terms of the actual depth and hence can be interpreted as the amount of change in real depth that would be required to obtain a reliable difference in response. Further it equates the binocular and monocular responses in terms of the independent variable. We compared both the raw and the normalized RMS errors between conditions.

Mean normalized RMS error for binocular viewing was 10.82, 15.34 and 25.34 cm for the 4.5, 9.0 and 18.0 m conditions, respectively. Recall from Experiment 1 that expected stereoscopic threshold at 9.0 m was 3–8 cm for sensitive observers and this range was obtained in the discrimination experiment. The larger RMS error obtained in this experiment likely reflects 1) the added uncertainty of making repeatable metric estimates compared to simply signing the depth and 2) the fact that stereoscopic threshold

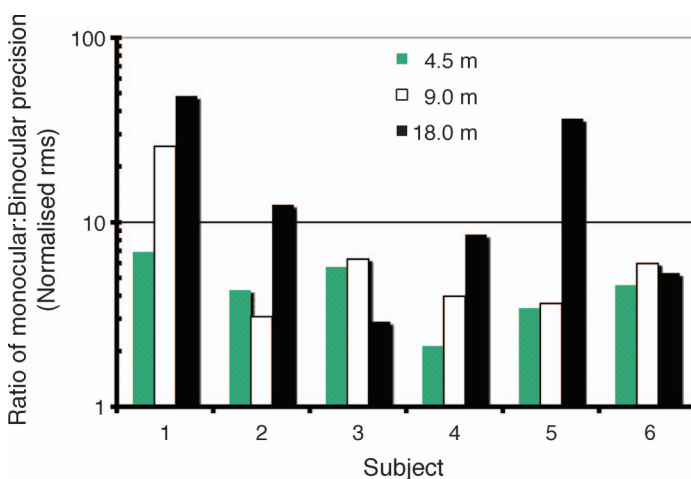


Figure 6. Relative degradation in precision with monocular versus binocular viewing at various viewing distances.

is lowest at zero disparity and falls with disparity offset/pedestal (i.e. depth step relative to a standing disparity).

Both raw precision measures and those normalized by the gain were better for binocular compared to monocular conditions. Generally raw RMS errors were larger monocularly than binocularly except in cases where monocular gains were very low (e.g., 0.1) and the range of estimates very constrained. Figure 6 shows the ratio of normalized monocular to binocular RMS errors and shows that for all observers and distances monocular errors are much larger. Improvements range from approximately a factor of 2 to 40 and indicate significant binocular advantage in precision (two-tailed one-sample  $t$ -tests on log-ratios:  $t(5) = 8.55, p = 0.0003, 4.5$  m;  $t(5) = 5.63, p = 0.0024, 9.0$  m; and  $t(5) = 5.55, p = 0.0026, 18.0$  m).

## Experiment 3

As distance increases, the geometrically perceived depth for a given disparity should increase (see Equation 1). The ability to accurately scale depth for distance depends on the availability of a sensory correlate of distance. Vergence and absolute disparity are ineffective as indicators of distance beyond 2 m. Experiment 2 showed some stereoscopic depth constancy beyond this range even in reduced stimuli. In this experiment we further explore constancy for stereoscopic depth beyond this oculomotor range. We also asked to what extent rich natural distance cues improve stereoscopic depth constancy.

## Methods

### Apparatus and stimuli

The testing room was a large lightproof computer laboratory (Figure 7). Computers, monitors, tables, and chairs were arranged in a regular fashion along the long sides of the room with regularly spaced chairs between the observer and the test stimuli. A series of upright posts were placed along the sides of the room in line and at regular intervals providing strong perspective cues and sense of space in the room.

The stimuli were pairs of red LED targets (RL5-R5015, 634 nm peak wavelength, 5 mm diameter, Super Bright LEDs Inc, St. Louis, Missouri, USA) illuminated in a box that was painted matte black and light proof except for an opening at one end (box dimensions 30 cm wide by 2.5 cm high by 175 cm deep; opening 2.5 cm high by 30 cm wide) and aligned with the LEDs at the observers' eye level. At the end of the box was a two-part curtain mounted vertically normal to the observer's line of sight. The only opening to the light proof box was aligned with a narrow horizontal slit in the black curtain that allowed the illuminated LEDs to be seen. The dark slit against the



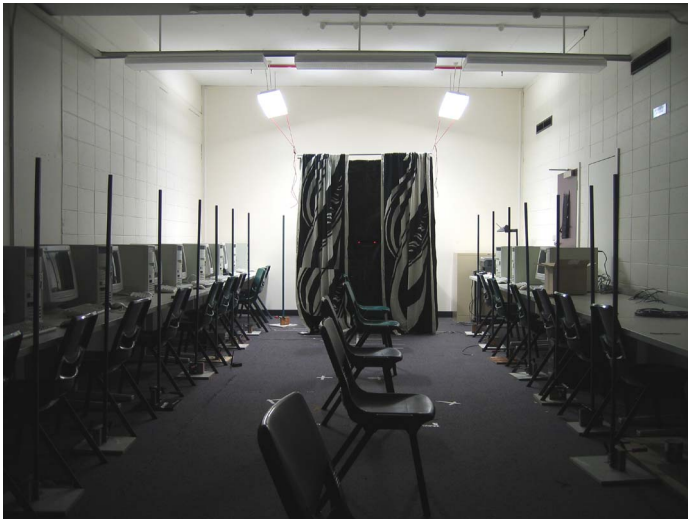


Figure 7. Experimental setup for [Experiment 3](#). The LED reference and target can be seen through the slit in the black curtain, which was located at eye height (approximately camera height). In the light off condition, only the LEDs were visible. In the light on condition a variety of cues also indicated the true distance of the curtain/slit where the reference LED was located.

black curtain was not apparent to the observers. At the sides of the curtain, further panels of high contrast, patterned material extended to touch the floor clearly delineating the position of the curtain in the room.

LEDs were lit in pairs with one LED being aligned at the depth of the slit in the curtain, which acted as the reference, and the other, offset laterally and in depth within the box, serving as the test stimulus. Lateral offsets of the test stimuli relative to the reference stimulus were jittered so that monocular gap was not informative to depth. The lights were small, aligned to eye level and presented in the light proof box. As a result there was minimal if any monocular information to the relative depth of the LEDs. Thus, under binocular viewing these were essentially stereoscopic stimuli. In contrast there was rich information to the depth and distances of the curtain and hence the light configuration when the lights were on. This paradigm allows for the controlled introduction of natural monocular and binocular cues to distance and evaluation of their influence on stereoscopic depth constancy while performing a ‘pure’ stereoscopic task.

### Observers

Eight observers with normal stereopsis participated. All observers had normal or corrected to normal vision except for one observer who had reduced visual acuity (20/25) in one eye due to early cataract. Additional scrutiny was paid to this observer’s data that indicated the observer performed at a similar performance level to the other observers.

### Task and procedure

The observer sat at a table with head supported on a chin rest. Depth estimates were obtained at two viewing distances, 4.5 and 9.0 m. At each viewing distance, separate blocks of trials were presented under binocular and monocular viewing conditions and with room lights on versus room lights off. Monocular viewing was obtained by occluding the non-dominant eye with a black eye patch. With room lights on, a rich visual environment was visible with many cues to the layout of the room; with lights off only the illuminated LEDs were visible.

Each combination of viewing condition and illumination (Light-Monocular, Light-Binocular, Dark-Monocular, Dark-Binocular) was presented in a separate block of trials. All combinations were presented to each observer in a factorial repeated measures design. Order of the binocular and monocular blocks was counterbalanced across observers. We were concerned that exposure to the light condition and hence the environmental layout would bias the observers on subsequent dark conditions. Therefore observers were not exposed to the room prior to the experiment. Before the session they were blindfolded and led about the room several times before being seated at the chinrest effectively disorienting them about their location in the room. In each session, a pair of dark blocks was run (one monocular and one binocular) followed by a pair of light and finally another pair of dark blocks (intended to evaluate the effect of exposure to the environment on the dark settings).

On each trial, a pair of test and reference lights was illuminated. Depth between the target and reference LEDs was 0.05, 0.31, 0.53, 0.73, 1.05, 1.31, 1.52, or 1.71 m. Each depth was repeated three times per block with lateral offset (gap) jittered trial to trial by using three different lateral offsets—4.5, 6.75 or 9.0 cm—for the reference LED.

Observers were required to estimate the distance in depth between the LEDs in centimeters. Observers held a 30 cm ruler and were informed of its length to help ground the scale they used for the estimates. Although the reference was always in front of the test and at the distance of the screen observers were also required to indicate which LED appeared in front since depth was often reversed under monocular viewing. Each pair of LEDs was illuminated until the observer responded with her estimate. Between trials the LEDs were extinguished for 500 ms.

### Results and discussion

[Figure 8](#) plots mean reported depth as a function of true depth for the various lighting-binocularity conditions at each distance. Observation of the figure shows that mean reported depth increased monotonically with true depth (Pearson  $r(94) = 0.55$ ,  $p = 0.001$ ) over all viewing conditions. However, the gain (proportion increase in



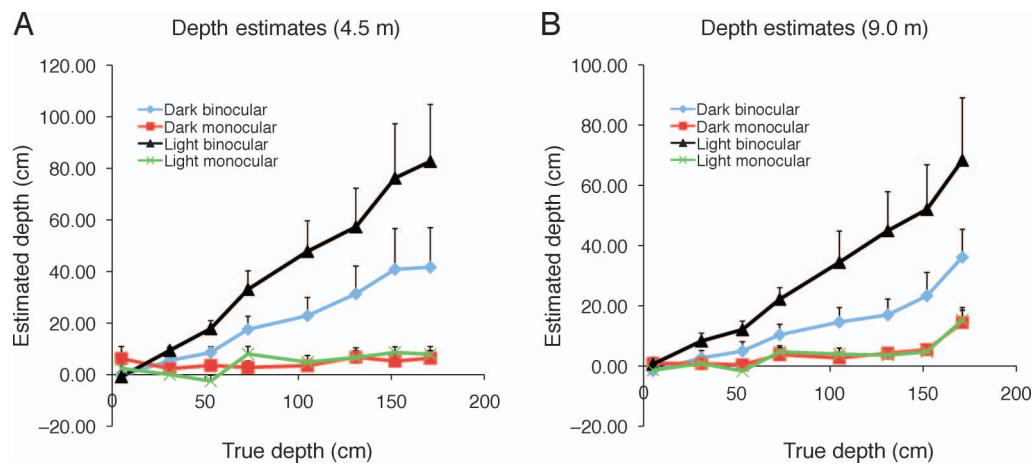


Figure 8. Mean (+SEM) estimated depth ( $N = 8$ ) for the (A) 4.5 m and (B) 9.0 m viewing distance.

reported depth per unit increase in true depth) varied with lighting-binocularity condition. Under binocular viewing compared to monocular viewing, reported depth was greater on average and gain was larger. Gain between perceived depth and true depth increased when presented in a full cue environment under binocular but not monocular viewing.

The light box configuration effectively isolated binocular disparity cues to depth between the target LEDs. Monocular depth was zero under most conditions and occasionally of the wrong sign. This indicates that the observers were confused as to the depth of the configuration under monocular viewing in both the light and dark conditions—the dark interior of the box and the lights within appeared to be of indeterminate depth. In contrast, in the binocular conditions observers reported more depth that increased approximately proportionally to the true depth.

The stimulus arrangement avoided confounding monocular cues to the absolute distance of the configuration (needed for scaling) with stereoscopic cues to relative depth (distance between the two objects of interest). Depth between the lights was given only by stereopsis.

Repeated measures ANOVA (with Greenhouse-Geisser corrections) and multiple regression analyses were performed to analyze and quantify these trends. We hypothesized that the gain would be much larger binocularly due to use of a stereoscopic stimulus and that stereoscopic depth constancy would be enhanced in the lit environments. Thus we expected and found a significant three-way interaction between lighting condition, binocularity and true depth ( $F(1.51, 10.55) = 6.59, p = 0.019$ ). Observation of the interaction plots showed that this interaction was ordinal with the gain (reported depth relative to true depth) increasing with both binocular viewing and in lit environments (albeit weakly for monocular conditions). Simple effect analysis of the interaction term for fixed levels of lighting showed that binocular viewing had a significant and positive modulating

influence on the effect of depth (i.e. gain—as indicated by the linear trend for the polynomial contrast for depth—was increased with binocular compared to monocular viewing) in both the dark ( $F(1,7) = 6.18, p = 0.042$ ) and in the light ( $F(1,7) = 7.990, p = 0.026$ ). Simple effect analysis for fixed levels of binocular viewing indicated a positive moderating influence of lighting (increased gain with depth in the light) that was significant for binocular viewing ( $F(1,7) = 12.577, p = 0.009$ ) but not for monocular viewing ( $F(1,7) = 2.387, p = 0.166$ ). The lack of significant influence of lighting on the monocular estimates is not surprising since subjects reported little depth under any monocular condition. Thus, we interpret this three-way interaction as evidence for an increase in perceived depth as a function of true depth in the lit conditions under binocular viewing. This is supported by pairwise post-hoc comparisons of the effect of lighting across this interaction. Mean binocular depth estimates were significantly larger ( $p < 0.05$ , Bonferroni corrected) in the light compared to the dark at all depth intervals except at the smallest depth interval (where the sign of the difference was still consistent but not significantly so). In no depth condition was the mean monocular estimate significantly different between the light and the dark.

A second significant three-way interaction was between distance, binocularity and true depth ( $F(1.98, 13.829) = 6.255, p = 0.012$ ). Observation of the interaction plots showed that this interaction was dis-ordinal. Simple effect analysis of the interaction term for fixed levels of distance showed that binocular viewing had a significant and positive moderating influence on the effect of depth (i.e. gain increased with binocular compared to monocular viewing) at 4.5 m ( $F(1,7) = 8.586, p = 0.022$ ) and 9.0 m ( $F(1,7) = 5.856, p = 0.046$ ). Simple effect analysis for fixed levels of binocular viewing indicated a dis-ordinal modulating influence of distance; negative (increased distance decreased reported depth) for binocular conditions ( $F(1,7) = 6.104, p = 0.043$ ) but positive for the monocular conditions ( $F(1,7) = 6.697, p = 0.036$ ). The

moderating effects in the monocular case appeared to be spurious and be mainly due to the increase at 9.0 m compared to 4.5 m in monocular reported depth only at the largest true depth. Mean monocular estimates at other true depths were similar (typically smaller rather than larger) at 9.0 m compared to 4.5 m (Bonferroni adjusted post-hoc comparisons indicated a significant difference between the 9.0 and 4.5 m monocular estimates only at the largest depth interval). Thus gain between reported and true depth decreased with viewing distance under binocular conditions whereas distance had little effect under monocular viewing (presumably since little or no depth was perceived). No other three- or four-way interactions were significant.

There was no significant difference between depth estimates in the pre and post dark conditions ( $F(1, 7) = 2.49, p = 0.16$ ). On average estimates in dark conditions before exposure to the lit conditions were  $1.10 \pm 1.37$  cm larger than estimates in the post conditions. There was no significant pre versus post difference in mean settings for any binocularity-depth condition (multiple post-hoc comparisons with Bonferroni adjustment and  $\alpha = 0.05$ ). This indicates that observers were not biased by exposure or knowledge of the spatial configuration of the room.

Gain between perceived depth and true depth was largest with binocular viewing in the illuminated environment. However, even under these conditions depth was still underestimated. Depth underestimation may be partly due to use of verbal depth/distance estimates (Andre & Rogers, 2006; Philbeck & Loomis, 1997). While depth and distance underestimation is common in studies of stereoscopic vision it has been reported that distance perception is relatively accurate when measured with distance production tasks such as blind walking (Fukushima, Loomis, & Da Silva, 1997).

Another possibility for the underestimation of perceived depth is that distance or a sensory correlate is likewise underestimated. We calculated the equivalent distance that the target would need to be located at in order to predict the depth estimates obtained (Glennerster, Rogers, & Bradshaw, 1996). These equivalent viewing distances averaged 72% and 63% of the actual viewing distance for the full cue, binocular conditions at 4.5 and 9.0 m, respectively. Interestingly, when asked to estimate the distance to the curtain in the two conditions following the sessions, observers typically reported smaller values than the true distance, typically about 75% of the true distance.

## Discussion

### Binocular advantage

We have addressed the proposition that stereoscopic depth perception is ineffective beyond very near distances.

Contrary to this proposal, we demonstrated in three experiments that stereopsis supports reliable depth discriminations beyond typical laboratory distances. Furthermore, binocular vision can significantly improve both the accuracy and precision of depth estimation to at least 18 m. We propose that these advantages are due to the stereopsis provided by binocular vision. Binocular vision confers other benefits to an observer but these are unlikely to result in the increased precision we observed. The degree of increased sensitivity was larger than could be expected based on binocular/probability summation. Similarly depth estimation based upon vergence changes is less precise than stereopsis and ineffective beyond about 2.0 m (Tresilian, Mon-Williams, & Kelly, 1999). Other binocular depth or distance cues such as vertical disparities or monocular occlusions were absent or minimal in our stimuli. Finally, depth discrimination thresholds obtained in the first experiment are very similar to near stereoacuties when expressed in angular disparity terms. Given this similarity and that stereopsis is the only binocular cue known to provide this level of precision strongly indicates the binocular improvement is due to stereopsis.

Under monocular conditions, perceived depth was significantly compressed. Binocular depth estimates were much nearer to veridical although also compressed. It is informative to compare monocular performance in [Experiments 2](#) and [3](#), which used similar tasks with very different stimulus configurations. [Experiment 2](#) used rod and edge stimuli. Observers presumably used trial-to-trial variations in monocularly visible features, such as small variations in projected rod width, which is also a hyperacuity (McKee, Welch, Taylor, & Bowne, 1990). These depend on memory and judgements of very small feature changes (based on [Experiment 1](#), at 9.0 m the difference in angular subtense for the rod at a threshold offset compared to the rod placed at zero depth is approximately 0.3% for the best binocular threshold and 3.2% for the best monocular threshold) and hence limited observers to imprecise estimates of depth. In contrast with the small stimuli and jittered dot spacing in the third experiment monocular cues were unreliable and observers saw little or no depth. Interestingly, in both [Experiments 2](#) and [3](#) some observers spontaneously reported that they saw little compelling depth monocularly, even when they could perform the task (as in [Experiment 2](#)). Hence it is possible that observers used a correlate of depth interval such as rod width directly.

### Stereoscopic depth perception at a distance

At longer distances, suprathreshold studies of binocular vision have concentrated mostly on the binocular perception of absolute distances (e.g., Crannell & Peters, 1970; Morrison & Whiteside, 1984) or have studied distance perception with both monocular and stereoscopic

information available (e.g., Hecht, van Doorn, & Koenderink, 1999; Loomis et al., 1992; Philbeck & Loomis, 1997). The typical finding is that viewing an isolated target, with only accommodation, vergence and vertical disparity available as absolute distance cues, produces poor estimates of target distance. However in a full cue situation absolute distance perception is found to be good at least up to around 20 meters (Fukushima et al., 1997).

Any claim that stereopsis cannot work at modest to large distances is easily put to rest. Anyone who has experienced stereoscopic cinema knows that stereopsis can produce depth percepts at considerable distances (from any seat in the theatre). Similarly, many investigators have used haploscopic projection to place a stereogram at a vergence distance of optical infinity; stereopsis is normally obtained if accommodative conflicts can be eliminated or overcome. Thus, it is clear that stereopsis can operate at considerable distances with artificial stereoscopic displays. However, in these situations designers have the ability to display independent images to the left and right eyes and can arrange the disparities for compelling depth percepts.

## Depth and distance cue relationships

A more convincing argument is based on the binocular geometry of natural viewing and the relative utility of depth cues (e.g., Cutting & Vishton, 1996). In this argument, it is asserted that the decline in stereoacuity makes absolute or relative stereoscopic performance insufficient to be useful beyond relatively short distances. In making depth estimates observers rely on a variety of cues. The relative utility of these cues depends on intrinsic and extrinsic factors that vary (typically degrading) with distance. Depth can depend on a variety of interactions between these cues. For instance, height in the field (or declination from the horizon) is a powerful cue but depends on assumptions of attachment to a flat ground plane (Sedgwick, 1986). Cues such as stereopsis may be especially important in validating such assumptions (and hence whether the monocular cue is reliable).

We also found that monocular cues can significantly influence depth from stereopsis at moderate distances. In [Experiment 3](#), we used a novel paradigm that allowed the presentation of real binocular disparity stimuli in the presence of rich environmental cues to distance. We found that presence of monocular and binocular cues to distance such as a ground plane promoted stereoscopic depth constancy at distances of 4.5 and 9.0 m. In addition to the ground plane there are several other long-range distance cues that could be used for scaling depth from stereopsis.

There have been few previous investigations of the effect of non-stereoscopic cues, especially ground plane information and familiar size on disparity scaling even at relatively close distances. Although Frisby et al. (1995) concluded that slant from texture was not used to calibrate

stereopsis in near space, they did not consider the general effects of monocular distance cues and their experiments were performed in the presence of binocular and oculomotor cues to distance. Similar to our findings, O’Leary and Wallach (1980) claimed that the monocular cue of familiar size could be used to scale disparity for distance although their study was limited to close distances and Predebon (1993) has argued that the scaling was based on cognitive rather than perceptual processes. The study of Durgin et al. (1995) is most comparable with the present study (see Glennerster et al., 1996 for a similar study using stereoscopic displays). Their task involved judging the depth to base ratio of real cones in a structured environment. They found depth constancy under binocular but not monocular conditions between 1 and 3 m. Thus, in normal environments, interaction between stereopsis and other depth cues is not limited to cue combination to improve precision but distance information from other sources, such as perspective, can be effective in scaling depth from disparity.

## Depth constancy

The results of [Experiments 2](#) and [3](#) can also be compared in terms of the degree of stereoscopic depth constancy observed. In the lit conditions of [Experiment 3](#) observers had a wide range of distance cues to the location of the curtain. Not surprisingly depth constancy was high under these conditions. However, appreciable binocular depth was still reported under the reduced conditions of [Experiment 2](#) and the dark conditions of [Experiment 3](#). Furthermore, there was evidence of depth constancy in these conditions since depth estimates across distances followed true depth rather than following disparity as would be expected in the absence of depth scaling. For example, in [Experiment 2](#) mean regression slopes of estimated versus true depth were nearly identical at 4.5 and 9.0 m falling to half this value at 18.0 m. This demonstrates substantial, although not complete constancy, given that disparity for a given depth decreases sixteen-fold over this distance range. How was this accomplished beyond the range normally ascribed for useful distance estimates from oculomotor cues? We propose that observers were likely using monocular cues to scale depth from disparity. In [Experiment 2](#), observers were familiar with the laboratory and were exposed to the stimulus at several distances due to the repeated measures design. Hence they could have learned to use reliable, suprathreshold monocular cues to the absolute distance of the configuration such as the angular width of the gap between the rod and the edge of the reference plane. The observer could use such cues to scale his/her responses, either perceptually or even cognitively in the response production.

Similarly, depth estimates in the dark conditions of [Experiment 3](#) were only slightly smaller at 9.0 than 4.5 m



and nowhere near that expected from the four-fold decrease in disparity. In this experiment observers were not familiarized with the room and were led blindfolded into it. Monocular measures suggest that there were few non-stereoscopic cues to the depth of the targets themselves. It is possible that some weak distance cues could be used such as change in the angular size of the lights although these should be below or near threshold for these small LEDs. Jitter of the lateral separation between test and reference lights reduced the reliability of the gap as a distance cue although it is possible but unlikely that observers estimated the average angular separation of the test and reference over the block as an indicator of distance. Finally, they were exposed to the lit environment. However, comparison of responses under dark conditions before and after this exposure gave no indication that exposure influenced depth judgements.

Cognitive influences may have a different role if observers have a presumed or preferred range of responses and adjust their estimates to cover the range. If subjects used the same response range in both [Experiments 2](#) and [3](#), even though there was a larger range of true depths in [Experiment 3](#), then this mapping may explain the unexpectedly larger depth estimates in [Experiment 2](#) compared to [Experiment 3](#). Alternative techniques such as magnitude estimation or depth interval production may shed light on this question and we will be following up this surprising constancy under reduced conditions in future work.

Binocular and oculomotor information has been proposed to mediate depth constancy in near space. Most investigators have found that the precision of these cues degrades rapidly with distance. One advantage of using oculomotor correlates of distance such as vergence or accommodation is that depth constancy could be obtained from direct use of these cues without need of an explicit intermediate representation of the target distance (Gillam, Chambers, & Lawergren, 1988). This idea has been championed as a way of avoiding complications and apparent paradoxes in size-distance perception without the need for constructs such as ‘registered distance’ (for review, see Gillam, 1995; Sedgwick, 1986). Our finding of depth constancy at distances beyond those purportedly used by these cues indicates that other distance cues such as perspective can be used to scale disparity. Given that it is unlikely that such pictorial cues could have a direct influence these results seem to support mediation of depth constancy by an explicit representation of target distance.

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