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Depth interval estimates from motion parallax and binocular disparity beyond interaction space

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Abstract

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Depth interval estimates from motion parallax and binocular disparity beyond interaction space

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Abstract. Static and dynamic observers provided binocular and monocular estimates of the depths between real objects lying well beyond interaction space. On each trial, pairs of LEDs were presented inside a dark railway tunnel. The nearest LED was always 40 m from the observer, with the depth separation between LED pairs ranging from 0 up to 248 m. Dynamic binocular viewing was found to produce the greatest (ie most veridical) estimates of depth magnitude, followed next by static binocular viewing, and then by dynamic monocular viewing. (No significant depth was seen with static monocular viewing.) We found evidence that both binocular and monocular dynamic estimates of depth were scaled for the observation distance when the ground plane and walls of the tunnel were visible up to the nearest LED. We conclude that both motion parallax and stereopsis provide useful long-distance depth information and that motion-parallax information can enhance the degree of stereoscopic depth seen.

1 Introduction

Differences between the optic arrays on the left and right eyes (binocular disparity) allow objects and surfaces to be seen in depth (Wheatstone 1838). Similarly, with head movement, changes in the velocities and/or positions of points within the optic array of a single eye (motion parallax) can provide depth information (Bourdon 1902; Helmholtz 1867/1962). Ono and Wade (2005) provide an excellent review of other early accounts of motion parallax. Gillam (2007) tried to sort out frequent confusions in the literature on parallax between optic array and retinal properties. Critically, stereopsis requires different simultaneous views, whereas motion parallax requires different successive views. Consider the situation where an observer views two objects placed at different distances directly in front of him/her. Horizontal angular disparity, δ, can be approximated by the following equation:

$$\delta \approx \frac{\Delta d \times I}{D^2 + \Delta d \times D}, \tag{1}$$

where Δd is the physical depth between the two objects, I is interocular distance, and D is the distance between the observer and the nearest object (the observation distance). For motion parallax with lateral head motion, the relative angular velocity of the two points is equivalent to disparity (δ) in binocular vision and head velocity is equivalent to interocular distance.[1] However, to accurately recover depth magnitude, angular disparities (in the case of stereopsis) and relative velocities (in the case of motion parallax) must also be scaled for the observation distance, as equation (1) shows.

There have been a number of studies comparing depth for motion parallax alone, binocular disparity alone, and a combination of the two. Classical research by Rogers and Graham (1982, 1983), with computer-generated displays of sinusoidally modulated random dots, found that motion parallax had a higher depth threshold than disparity, and showed less perceived depth but had a similar sensitivity function with variations

[1] Motion parallax could alternatively be characterised by relative angular displacement of two points with the equivalent of interocular distance then being the angular head displacement.

in spatial frequency. Ono et al (1986) have shown that computer-generated sinusoidally modulated depth stimuli show some scaling with observation distance up to about 0.8 m "in a normal indoor environment". These studies differed from ours in using computer displays and continuously modulated depth surfaces, whereas we used discrete real objects. Thus, the discussion below of studies that have used real discrete targets in depth is more relevant as a background to our work. Bradshaw et al (2006) showed that depth magnitude based on disparity and motion parallax cues was not predictable from depth thresholds; thus we concentrate on studies that measured metric depth.

Using discrete LEDs, Bradshaw et al (1998) found that reliance on monocular motion-parallax cues led to depth underestimation, while reliance on binocular disparity resulted in overestimation. When the two cues were presented together, their outputs appeared to be averaged. Bradshaw et al (2000), on the other hand, found that judgments of depth based on motion parallax were as accurate as those based on stereopsis, and did not find an advantage of adding the two cues. Since both studies presented stimuli in dark surroundings, distance scaling was attributed to vergence (see Foley 1980). Vertical disparity could also be a distance scaling factor when targets have a vertical extent (Mayhew and Longuet-Higgins 1982; Gillam and Lawergren 1983), which these LED stimuli did not. Several other studies (Durgin et al 1995; McKee and Taylor 2010) have, like ours, used conditions in which the room was lit. Both studies found that depth from disparity was far more veridical in a geometric sense than depth from motion parallax, with the Durgin et al study showing good distance scaling of the former as observation distance varied. However, they did not vary the observation distance in motion-parallax conditions. The McKee and Taylor study, using two vertical rods in depth as targets, was designed to see how effective these cues were under natural viewing conditions with context placed next to and behind the targets. Thus, perspective information concerning the absolute distance to the targets was not provided as in our study. The report of the Durgin et al study did not make it clear just what contextual information was present. They used real cones in which the base was always 10 cm and the depth varied. Width may have provided a distance cue as well as the context.(2) In neither study with lit conditions was a comparison made with conditions where the foreground and surroundings of the depth-separated stimuli were in complete darkness.

All the studies described above have been conducted with observation distances of 3 m or less, the outer limit for use of vergence/vertical disparity cues to absolute distance. However, both stereopsis and motion parallax are thought to provide useful depth information at much larger observation distances. Recently, Allison et al (2009) and Palmisano et al (2010) have shown that stereoscopic estimates of the depth between two LEDs are still scaled for 10, 20, and 40 m observation distances. However, depth estimates for the same binocular disparity only increased with the observation distance when the ground plane and walls of the surrounding environment were visible up to the nearest LED, not when these LEDs were viewed in darkness—indicating that perspective-based cues arising from these scene features must have been responsible for scaling disparity at these larger distances. (There was no perspective information available about the depth between the targets.) The present study extends this investigation to motion parallax.

To our knowledge our study is the first to compare estimates of real depths based on motion parallax and binocular disparity at a very large observation distance (40 m), well beyond interaction space and beyond the distance at which oculomotor cues or vertical disparity could be useful in providing the distance factor necessary for scaling. On different trials, pairs of depth-separated LEDs were presented inside a dark railway tunnel. The nearest LED was always 40 m from the observer and the depth separation

(2) Durgin has informed us that viewing distance was varied between subjects in his 1995 study in order to avoid absolute retinal size and memory acting as confounding influences for range.

between the two LEDs ranged from zero up to 248 m. While the region between the two LEDs was always dark (providing only binocular disparity and/or motion-parallax information about depth), in half of the trials the foreground of the tunnel was lit (as opposed to dark). Thus, we tested motion-parallax- and stereopsis-based cues to depth either in isolation or in combination, and either with or without available information about the observation distance.

2 Methods

2.1 *Observers*

There were nine observers with normal stereoacuity [minimum Titmus Circle Stereotest score of 8 (50 s of arc)] and visual acuity (minimum of 6/7.5 or 20/30 in both eyes). They were graduate students from the University of New South Wales and the University of Wollongong from a variety of disciplines. Six of these observers were naive to the layout of the experimental apparatus and environment. Each observer was tested for eye dominance with a sighting test, and the dominant eye was then used in all monocular conditions.

2.2 *Apparatus and stimuli*

This experiment was conducted within a 381 m long disused railway tunnel at Helensburgh, New South Wales, Australia. The tunnel was 5.05 m high and 4.5 m wide and its floor was slightly sloping upward (by 1.43° in the direction of the observer's gaze). Pairs of light-proof tarpaulins were attached inside each end of this tunnel, blocking all external light, allowing us to completely control the ambient lighting within the tunnel. LEDs were used as targets; they were viewed through a slit in a black polythene screen, which was located at a distance of 39.6 m from the observer (see figure 1).

The nearest LED target was always located just beyond the screen at the observation distance of 40 m. The observer sat either in complete darkness or with the foreground of the tunnel (ie the region from the observer up to the screen) fully lit. This screen blocked the LED mounting hardware from the observer's view and prevented the light (when present) from spreading beyond the tunnel's foreground.

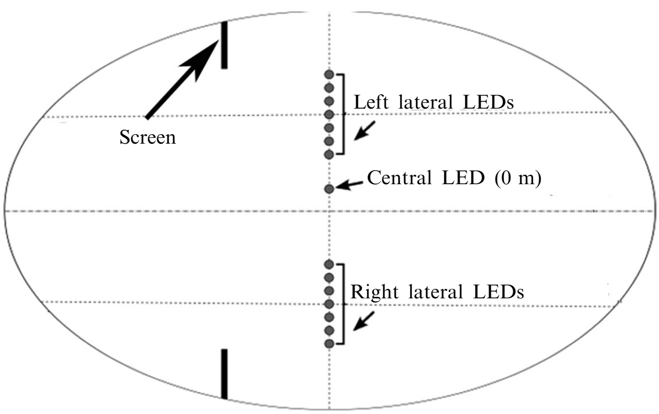

Figure 1. Bird's eye view of the LED arrangement near the occluding screen. The locations of all fourteen lateral LEDs (including seven left lateral LEDs and seven right lateral LEDs) and one of the seven central LEDs (which represented a 0 m depth separation relative to the lateral LEDs) are indicated. As can be seen, the lateral LEDs were all located just beyond the screen at the observation distance of 40 m. Only one lateral LED and one central LED were turned on in any given trial. This lateral LED was one of the fourteen lateral LED targets (shown in the figure). The central LED target for the trial was located either 0.0 m (shown in the figure), 7.8 m, 15.5 m, 31.0 m, 62.1 m, 124.1 m, and 248.2 m beyond the lateral LEDs.

In dark-foreground conditions, the observer was only able to see the LEDs which were red (Super Bright LEDs product code RL5-R5015, 5000 mcd, 631 nm peak emission wavelength, 15° half-power angle, and 5 mm diameter clear lens). They were mounted on matte-black-painted vertical poles attached to wide wooden bases at various distances along the tunnel. All LEDs could be switched on and off in any pattern under computer control with Bluetooth-controlled switching hardware (Allison et al 2009). The LEDs were arranged to avoid occlusions when viewed from the observer's vantage point (strict linearity was achieved by using both a laser and a taut string line that ran from the observer following the centreline of the tunnel). LEDs were illuminated in pairs. The nearest LED of the pair (the 'lateral LED') was always located at the observation distance, and was positioned either to the left or right of the centreline of the tunnel (as can be seen in figure 1, this was one of fourteen possible lateral LEDs). The farther LED of the pair was always a 'central LED', and this one varied in distance to create a variety of depth separations between the pair. The maximum depth separation between near/lateral and far/central LEDs was 248.2 m, with each of the five smaller depths being exactly half of the next largest one (the smallest depth was zero; to achieve a very large range of depths with only seven central LEDs). The seven true depths examined were, therefore, 0.0, 7.8, 15.5, 31.0, 62.1, 124.1, and 248.2 m. When equation (1) was applied to these depths, binocular disparity was calculated to be 0.0, 53.6, 92.2, 144.2, 200.7, 249.6, 284.2 s of arc (based on an assumed interocular distance of 64 mm). In addition to being located at different depths relative to the lateral LEDs, each of the seven central LEDs also had a unique horizontal position so as to avoid occlusions (central LEDs were displaced by small, randomly chosen, amounts to either the left or the right of the centreline). Importantly, the horizontal separation between each pair of lateral and central LEDs was always 0.5 deg (achieved by turning on a different set of lateral LEDs with each of the seven central LEDs; each central LED was paired with one specific left lateral, and one specific right lateral, LED). All LEDs were placed at the observer's eye-height (1.25 m above the tunnel floor). Because the LEDs were effectively point-light sources, our experimental setup provided no usable relative size information that could indicate depth. In addition, the intensity of each LED was set so that it was directly proportional to the square of the distance from the observer. LED intensity could also be adjusted over 240 steps between fully off and fully on; when illuminated, the most distant LED shone at maximum intensity. Pilot testing confirmed that luminance and other monocular depth cues had indeed been equated, and did not serve as a reliable cue to either distance or depth. In lit-foreground conditions (otherwise identical to the dark-foreground conditions) the portion of the tunnel that lay between the observer and the screen was lit by twelve evenly spaced linear halogen lamps (Fairway DCWLT1000 twin-head quartz halogen work lights, each with a single 150 W bulb). These lamps, which lined the left and right walls of the tunnel, were equally spaced at distances of 5.7, 11.4, 17.1, 22.9, 28.6, and 34.3 m from the observer (measured parallel to the tunnel's centreline). Each lamp was mounted on a stand with the bulb at a height of 1.25 m above the tunnel floor. All lamps were aimed at the opposite wall of the tunnel. Three rectangular bin lids were spaced evenly along the centreline of the floor of the tunnel (at distances of 10, 20, and 30 m from the observer). These acted as additional aids to distance perception and depth estimation during the lit-foreground conditions. The lit-foreground conditions not only provided strong static (monocular and/or binocular) cues to the distance to the screen and the nearest LED target (including the perspective of the earthen floor, the bricks of the walls, and the ceiling of the tunnel, as well as cues arising from the size and position of the bin lids and the lamps), but they also provided powerful motion perspective and kinetic occlusion cues when the observer moved his/her head from left to right. Figure 2 shows an elevated view of the layout of the apparatus.

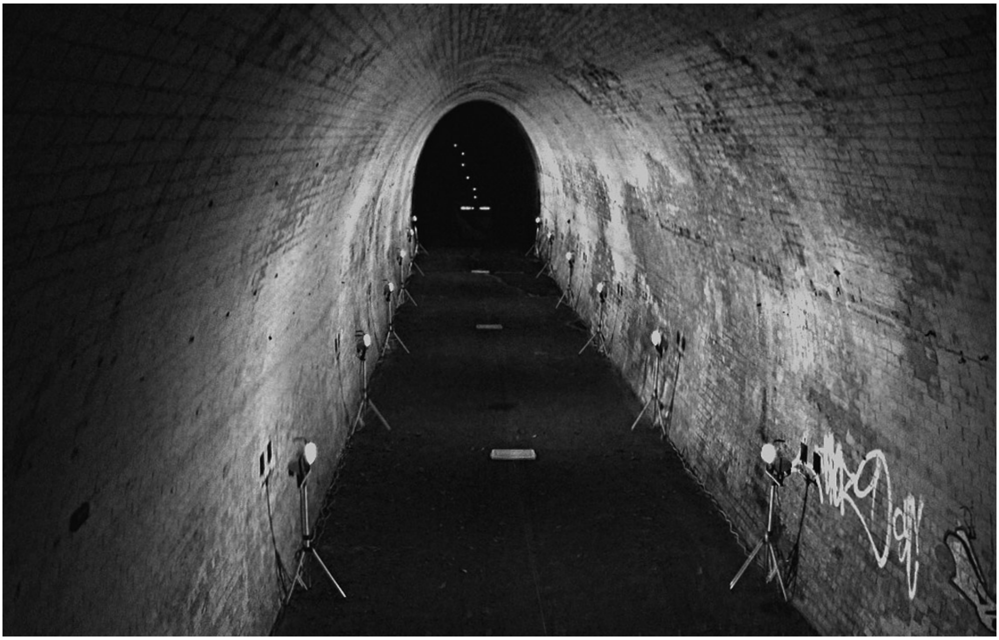

Figure 2. A photo taken from an elevated viewpoint of the setup showing the entire LED arrangement. The occluding screen, which was always present during the experiment, was removed for this photograph. During a trial, only one lateral LED and one central LED were turned on. Here all fourteen lateral LEDs and all seven central LEDs are turned on. The fourteen lateral LEDs appear as two horizontal lines—one located to the left and the other located to the right of the tunnel's centreline. All seven central LEDs can be seen quite clearly at depths of 0.0, 7.8, 15.5, 31.0, 62.1, 124.1, and 248.2 m (relative to the lateral LEDs). The horizontal positions of these central LEDs were jittered to the left/right of the centreline by different amounts so as to avoid occlusions. During the experiment, a different set of lateral LEDs was turned on with each of the seven central LEDs, which always kept the horizontal separation between them constant at 0.5 deg.

In static viewing conditions, the observers kept their heads perfectly still with the aid of a chin-rest. However, in dynamic viewing conditions, observers moved their heads laterally (about the centre of the chin-rest) with horizontal peak-to-peak amplitude of 1.5 interocular distances. Amplitude was limited to 96 mm by adjustable paddle stops, and eye height was kept constant with a horizontal chin-guide. Head oscillation frequency was approximately 0.75 Hz (ie with a period of 1.5 s; observers were trained in the proper technique before beginning the experiment). In these dynamic viewing conditions, observers were required to begin head oscillation when a pair of LEDs first appeared, halting only when a final depth judgment had been made. They were required to make at least three complete cycles before a judgment was made.

2.3 *Procedure*

Each trial began with the presentation of a single fixation LED in isolation. This fixation LED was either a lateral (nearer) or the central (farther) LED of a depth pair. When the observer had fixated this LED, he/she then pressed a button which turned off the fixation LED. The lit depth pair (consisting of one lateral LED and one central LED separated in depth by between 0 and 248 m) was presented 1 s later. The observer then provided a verbal estimate of the depth separation between the two LEDs (in millimetres, centimetres, or metres), which was manually recorded on the computer by the experimenter prior to initiating the next trial. Each block consisted of 56 trials.

There were two replications of each condition, which were a factorial combination of the two types of fixation LED (central or lateral), the two locations of the lateral LED (left or right), and the seven different true depth separations between the pairs of LEDs. Trials were presented in a different pseudorandom order for each block. Each participant ran eight blocks of trials. In each block, viewing was either: (i) monocular or binocular; (ii) static or dynamic; or (iii) in complete darkness (ie with only the LED pair visible) or with the foreground of the tunnel fully lit. The order of the factorial combination of the eight blocks was counterbalanced for viewing condition, motion condition, and illumination condition.

3 Results

3.1 *Estimates of depth between LEDs*

The depth estimates for each of the two illumination conditions (dark and lit foreground), for each of the four viewing conditions (static monocular, dynamic monocular, static binocular, and dynamic binocular), and for each of the seven true depth separations are shown in figure 3. Where depth was seen, these curves were strikingly nonlinear. By contrast, the depth estimates for all four viewing conditions were quite linear with respect to binocular disparity, confirmed by significant linear (but not quadratic or cubic) trend contrasts (see figure 4). We decided to analyse the slopes of these curves (ie the gain of binocularly/monocularly perceived depth as a function of the angular disparity) as a way of comparing the distance scaling between conditions. The horizontal axis in figure 4 represents the binocular disparity for the true depths shown in figure 3. Since the lateral head motion was 1.5 times the interocular distance, the differential velocity would be somewhat more than the disparity shown on this axis.

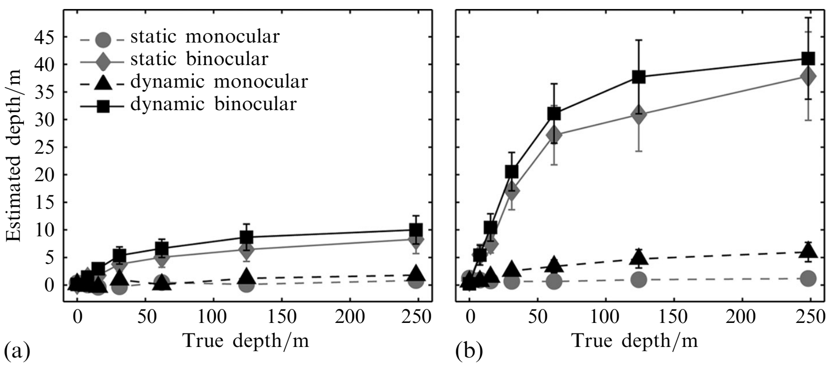

Figure 3. Binocular and monocular estimates of LED depth magnitude at an observation distance of 40 m, with and without lateral head motion, plotted as a function of true depth. (a) Magnitude estimates of LED depth in complete darkness; (b) performance with a lit foreground (in both cases averaged across observers). Error bars show ±1 SEM.

After confirming that the fixation LED position (central or lateral) and the location of the lateral LED (left or right) did not have significant effects on depth estimation, we collapsed the data across these conditions. The slopes of the eight curves shown in figure 4 are given in table 1. In the static-monocular control conditions, neither the dark nor the lit foreground slopes differed from zero ($t_8 = 0.89$ and -0.25, both $p\text{s} > 0.05$). To assess the relative effect of motion parallax and stereopsis (both in isolation and in combination, as well as with/without environmental scaling cues available) on estimated depth, these gain data were subjected to a within-subjects planned contrast analysis, which controlled the family-wise error rate at 0.05 (via Bonferroni correction for six contrasts).

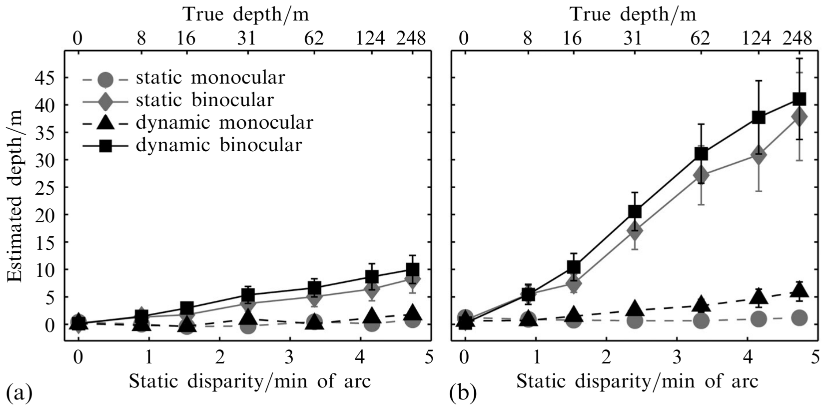

Figure 4. Binocular and monocular estimates of LED depth magnitude at an observation distance of 40 m, with and without lateral head motion, plotted as a function of static-binocular disparity (bottom horizontal axis). The true depths for all conditions are also provided (top horizontal axis). (a) Magnitude estimates of LED depth in complete darkness; (b) performance with a lit foreground (in both cases averaged across observers). Error bars show ±1 SEM.

Table 1. Mean slopes of the linear regression of perceived depth against static binocular disparity [m (min of arc)$^{-1}$] for each of the eight possible combinations of motion condition, viewing condition, and illumination condition.

Foreground illumination	Monocular disparity		Binocular disparity	
	static	dynamic	static	dynamic
Dark	0.10	0.35	1.67	2.11
Lit	−0.01	1.15	8.07	9.24

With a lit foreground, the gains of the observers' depth estimates were significantly greater with dynamic-monocular than with static-monocular viewing ($F_{1,8} = 14.08$, $p < 0.05$), which shows that motion parallax can provide useful depth information when objects lie beyond interaction space. However, in darkness, the gains of the observers' depth estimates were not significantly different during dynamic-monocular and static-monocular viewing ($F_{1,8} = 8.28$, $p > 0.05$), indicating that environmental scaling cues (from the lit foreground) were necessary for successful depth perception based on motion parallax.

With a lit foreground, depth estimates made with static-binocular viewing were significantly greater (ie closer to veridical) than those made with dynamic-monocular viewing ($F_{1,8} = 15.90$, $p < 0.05$). This indicates a superiority of stereopsis over motion parallax when scaling cues are available and binocular/angular disparity is similar. In darkness, binocular-static was not significantly different from monocular-dynamic viewing ($F_{1,8} = 5.44$, $p > 0.05$).

With a lit foreground, the gains of the observers' depth estimates were also significantly greater with dynamic-binocular than with static-binocular viewing ($F_{1,8} = 13.04$, $p < 0.05$). This indicates that motion parallax can enhance stereoscopic depth estimates when environmental scaling cues are available. Again, in darkness, the gains of the observers' depth estimates were not significantly different during dynamic-binocular and static-binocular viewing ($F_{1,8} = 3.22$, $p > 0.05$), indicating that motion-parallax-based information has little effect on stereoscopic depth estimates when environmental scaling cues are not available.

3.2 *Estimates of distance to nearest LED*

To evaluate how observers saw the observation distance, at the end of each block of trials we had them verbally estimate the distance to the nearest LED (see table 2; the nearest LED was always located at the observation distance of 40 m from the observer). Both lit foreground conditions and binocular viewing were found to increase observer estimates of the observation distance (ie they became closer to the veridical distance of 40 m). However, head motion appeared to have little or no effect on these estimates of the observation distance. Of interest, inter-observer error appeared to consistently decrease in the presence of a lit foreground.

Table 2. Mean estimated observation distance in metres for each of the eight possible combinations of motion condition, viewing condition, and illumination condition. Standard errors are shown in parentheses.

Foreground illumination	Monocular disparity		Binocular disparity	
	static	dynamic	static	dynamic
Dark	19.50 (6.97)	20.78 (7.01)	24.00 (6.18)	26.33 (7.09)
Lit	37.12 (5.08)	38.67 (5.92)	40.23 (4.76)	42.45 (6.04)

3.3 *Calculations of implicit distance used in depth estimates*

An implicit observation distance can be estimated by fitting equation (1) to our data with observation distance as the only free parameter. These equation-based estimates of the observation distance are shown in table 3. There was, of course, no equivalent to angular disparity for static-monocular conditions. We calculated the implicit observation distances for dynamic-binocular, static-binocular, and dynamic-monocular viewing conditions using binocular disparities and dynamic angular disparities, respectively. Note that the 95% confidence intervals represent the goodness of fit of the curve to the data, and have very little dependence on the inter-observer variability. Overall, these implicit observation distances were more deviant from the actual observation distance (40 m) than were the verbal estimates of observation distances (they were lower than the verbal estimates). Under binocular viewing, the pattern was the same for implicit and for estimated distances, with fits being closer to the actual observation distance (40 m) during lit-foreground conditions, with a negligible difference when motion cues were added. Under monocular viewing, fits were also closer to the actual distances during lit-foreground conditions. However, the fact that observation distances obtained by fitting equation (1) to the depth data were lower than the observers' verbal estimates of the observation distance suggests a weak relationship between perceived observation distance and perceived depth.

Table 3. Best fitting observation distance in metres when using equation (1) and the estimated depth data for each of the six meaningful combinations of motion condition, viewing condition, and illumination condition against static binocular disparity (using nonlinear least squares, with observation distance as the only free parameter). Fits using dynamic horizontal angular disparity (1.5 times binocular disparity) are shown in parentheses where appropriate. 95% confidence intervals are shown.

Foreground illumination	Monocular disparity	Binocular disparity	
	dynamic	static	dynamic
Dark	7.11 ± 2.10 (5.73 ± 1.64)	15.84 ± 0.37	17.53 ± 0.66
Lit	13.76 ± 0.47 (10.87 ± 0.35)	27.83 ± 1.41	28.91 ± 1.80

By looking at the sign of the estimated depth magnitudes it is possible to evaluate the accuracy of the observers' depth sign judgments. The lateral 'near' judgment proportions, excluding those where true depth was zero, were averaged together resulting in the mean percentage-correct depth signs shown in table 4.

It is clear that under monocular conditions a lit foreground greatly increased the accuracy of detection for depth sign despite the fact that the relative motion signals were the same in lit and unlit conditions. The sign was almost always correct for stereopsis even in the dark.

Table 4. Mean percentage-correct depth sign for each of the six meaningful combinations of motion condition, viewing condition, and illumination condition (excludes depth signs when true depth was zero).

Foreground illumination	Monocular disparity	Binocular disparity	
	dynamic	static	dynamic
Dark	68	96	94
Lit	93	99	99

4 Discussion

Monocularly, estimated depth was only found to increase with true depth during dynamic (as opposed to static) conditions with a lit (as opposed to a dark) foreground. This is evidence that motion parallax was scaled by foreground distance cues, such as linear perspective, compression, and implicit horizon. The fact that the slope of estimated depths increased much more under lit conditions for stereopsis alone than motion-parallax alone, indicates that motion parallax was not scaled as effectively as stereopsis. We used lateral head motions that were 1.5 times the interocular distance. It is possible that motion parallax would have been more effective if we had used larger lateral head motions, such as those used, for example, by Durgin et al (1995) which were 4 times the interocular distance. However, the difference between motion-parallax-alone and stereopsis-alone conditions in the current experiment was very large and unlikely to be eliminated, even if we had used larger lateral head motions. We wished to compare the two cues under somewhat similar conditions of array change. Motion parallax already has the advantage that the change is continuous while stereopsis has only two discrete views to work with.

It is clear from the poor performance of motion parallax in the dark, including the poor detection of depth sign, that our observers were not basing their depth judgments on the relative two-dimensional motion of the targets in the motion-parallax conditions. This is particularly a danger in threshold studies, such as the classic study by Graham et al (1948), in which observers merely have to discriminate between motion conditions.

Estimated depth in lit-foreground conditions was greater under dynamic-binocular conditions than under either static-binocular or dynamic-monocular conditions, suggesting that motion parallax contributed to depth perception even when stereopsis was present with a summation of their effectiveness. It is possible that the two sources of depth information reduced uncertainty in the final depth estimate. Richards (1985) developed a model to account for the superiority of the joint processing of motion parallax and stereopsis in structure-from-motion tasks (eg Tittle and Braunstein 1993). However, it is based on an intersection of constraints which does not apply in the present case. It should also be noted that, since motion perspective (Gibson 1966) was added to static perspective as a distance cue under dynamic conditions, it is possible that the greater slope found for dynamic-monocular, as opposed to static-monocular, conditions was at least partly the result of superior distance information (it should be noted, however, that estimated distance was very similar for static and dynamic lit conditions; table 2). Likewise the superiority of binocular conditions over monocular conditions could be partially attributable to the superiority of binocular-perspective cues to absolute distance and not merely to the superiority of disparity per se. Again, however, the distance estimates in table 2 do not support this view.

The most important aspect of our findings is that both stereopsis and motion parallax are available as depth cues at much greater distances than commonly believed, and that for similar stimulus conditions there is a marked superiority in favour of stereopsis. The effectiveness of these cues at such large distances clearly depends on perspective information providing the distance factor that allows scaling. In the current experiment, the mean estimated depths were far short of veridical but still substantial; the mean maximum depths in the light being around 41 m for dynamic-binocular conditions (stereopsis and motion parallax) and 6 m in dynamic-monocular conditions (with the true depth in both cases actually being 248.2 m). This information appears not to be mediated by conscious estimates of the observation distance, which were close to accurate under lit conditions, while the implicit distance estimates (based on the depth-estimate data) were much less accurate.

Given that conditions were randomised in blocks, observers may (despite instructions to use current impressions of distance) have been influenced by previous conditions, even when there was no current visual information available. One aspect of the data to which this point may be relevant was that stereoscopic conditions (both static and dynamic) showed a gain of greater than zero even in the dark. It could be that, after seeing lit trials, some residual sense of distance entered into the scaling of disparity during subsequent dark trials.

In summary, both motion parallax and stereopsis can add to the impression of depth at great distances, far beyond those at which vergence and vertical disparity can operate. While both cues appear to be useful at the observation distance tested (40 m), the contribution of motion parallax to estimated depth appears to be considerably less than that of stereopsis (at least under similar conditions of array change). We show that perspective-based distance cues provided by a lit foreground clearly play a role in the scaling of both motion parallax and stereopsis. It is possible that other cues, such as contextual size in static viewing conditions, and motion perspective in dynamic viewing conditions, also play a role.

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