Stereoscopic perception of real depths at large distances

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There has been no direct examination of stereoscopic depth perception at very large observation distances and depths. We measured perceptions of depth magnitude at distances where it is frequently reported without evidence that stereopsis is non-functional. We adapted methods pioneered at distances up to 9 m by R. S. Allison, B. J. Gillam, and E. Vecellio (2009) for use in a 381-m-long railway tunnel. Pairs of Light Emitting Diode (LED) targets were presented either in complete darkness or with the environment lit as far as the nearest LED (the observation distance). We found that binocular, but not monocular, estimates of the depth between pairs of LEDs increased with their physical depths up to the maximum depth separation tested (248 m). Binocular estimates of depth were much larger with a lit foreground than in darkness and increased as the observation distance increased from 20 to 40 m, indicating that binocular disparity can be scaled for much larger distances than previously realized. Since these observation distances were well beyond the range of vertical disparity and oculomotor cues, this scaling must rely on perspective cues. We also ran control experiments at smaller distances, which showed that estimates of depth and distance correlate poorly and that our metric estimation method gives similar results to a comparison method under the same conditions.

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

Introduction

The left and right eyes receive different perspective views of the same scene. Image differences between these two views, or binocular disparities, are known to generate compelling stereoscopic impressions of relative distance or depth (Wheatstone, 1838). The horizontal angular disparity between pairs of points is the simplest stereoscopic cue to depth and the one that has received the most study. Consider the following situation, where a binocular observer views two objects lying at different egocentric distances. The horizontal angular disparity (δ) in this situation can be approximated using the following equation:

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

where Δd is the physical depth between the two objects, I is the distance between the two eyes, and D is the observation distance (or the distance of the observer from the nearest object). As can be seen from the above equation, the binocular disparity produced by the same depth separation generally decreases with the square of the observation distance. This means that binocular disparity for a given depth will be much greater when the observation distance is small; a fact that has led many researchers to conclude that stereopsis is only useful in near/personal or interaction/action space (e.g., Arsenault & Ware, 2004; Cutting & Vishton, 1995; Palmer, 1999). For example, Gregory (1966, p. 53) has stated that we are "effectively one-eyed for distances greater than about twenty feet" (approximately 6m). However, these claims appear to be inconsistent with findings that humans are exquisitely sensitive to binocular disparity. For example, Howard (1919) showed that good stereoscopic observers are capable of detecting depth differences corresponding to binocular disparities of only a few seconds of arc. Based on such findings, geometrical analysis predicts that we should be able to obtain useful information from

stereopsis at very large observation distances. Using a conservative estimate of stereoacuity of about 10 s of arc, we can calculate that the maximum useful range of stereopsis should exceed 1 km. Based on Equation 1, the minimum depth separation detectable from binocular disparity should increase strongly with the observation distance. However, this stereoscopic information should still be useful, given that at larger distances only large depths are likely to be ecologically important.

The stereoscopic perception of depth magnitude at large distances

At near observation distances (e.g., 1–2 m), not only can depth differences based on binocular disparity be discriminated but the magnitude of the depth separation can be perceived. Previous research has shown evidence of stereoscopic improvements in discriminating real depths at much larger distances (17 m and beyond—e.g., Hirsch & Weymouth, 1948; Jameson & Hurvich, 1959; Teichner, Kobrick, & Wehrkamp, 1955). However stereopsis cannot be understood on the basis of depth discrimination data alone. Perceived depth magnitude, about which little is known at larger distances, is also important. The veridical perception of depth magnitude, across changes in observation distance and despite variations in binocular disparity, is known as stereoscopic depth constancy. As Equation 1 shows, this would require that horizontal angular disparity be scaled for the observation distance. It has been established that stereoscopic depth constancy does occur for observation distances of 2 m or less (Cormack, 1984; Ono & Comerford, 1977; Wallach & Zuckermann, 1963) but is not perfect (e.g., Johnston, 1991). At these near distances, the cues of vertical disparity, accommodation, and convergence could all be used to scale binocular disparity information and derive depth (Foley, 1985; Foley & Richards, 1972; Gillam, Chambers, & Lawergren, 1988; Gillam & Lawergren, 1983; Gogel, 1977; Mayhew & Longuet-Higgins, 1982; Rogers & Bradshaw, 1993; Wallach & Zuckermann, 1963). O'Leary and Wallach (1980) have also claimed that perspective and familiar size cues are used to scale depth from binocular disparity at near observation distances (0.4–0.8 m). While larger observation distances will be beyond the range of vertical disparity and oculomotor cues, perspective (and potentially also familiar size)-based information about distance should still be available for disparity scaling. For example, it has been shown that blindfolded people can walk accurately to previously viewed targets (in full cue conditions) located at distances as far away as 12 m (Loomis, Da Silva, Fujita, & Fukusima, 1992). Levin and Haber (1993) also appear to show that absolute distances can be estimated quite accurately as far away as 20 m. Linear perspective from the ground plane (possibly used in conjunction with eye height) is likely to be an important perspective-based

source of information that could provide this absolute distance (Sedgwick, 1986; Thompson, Dilda, & Creem-Regehr, 2007; Wu, He, & Ooi, 2007). However, there are a variety of other perspective-based cues that should also be available in well-lit real-world environments (e.g., texture gradients, relative size, aspect ratio—see Gillam, 1995; Sedgwick, 1986 for a review). The current study examined whether perspective and familiar size-based distance cues could be used to scale binocular disparities ranging from 0 to 5 arcmin between a pair of target points, when the closer of these target points was located at a distance of either 20 or 40 m. Throughout this paper, we will refer to the distance of the closest target point as the *observation distance*.

Previous studies

Only a handful of studies have attempted to examine the stereoscopic perception of depth magnitude at observation distances beyond a few meters. In one of these studies, Cormack (1984) examined the binocular perception of depth and distance when disparate afterimages (either 16.3 or 4.5 arcmin) were viewed from a variety of observation distances. He examined performance with: (i) 5-, 10-, and 20-m observation distances inside a lit hallway that was rich in depth cues (a textured floor, cement block walls, ceiling tiles, and so on); and (ii) 250-m, 6-km, and 7.8-km observation distances outside across an open field at night, which would have severely limited the available distance information for disparity scaling. Unfortunately, Cormack only measured relative depth (rather indirectly) for the three shorter observation distances. Observers had to report what the distance was between themselves and the crossed disparity afterimage as a percentage of the observation distance (he defined this as the egocentric distance of the real-world fixation object). At the three larger observation distances, he simply had observers set a probe so that it appeared to be in the plane of the afterimage, which is not informative about perceived depth magnitude. Despite these methodological limitations and lighting issues, Cormack concluded from his results that apparent stereoscopic depth continues to grow with increasing observation distances, up to at least 7.8 km (the maximum distance that he tested).

In a more recent study by Allison, Gillam, and Vecellio (2009), subjects were binocularly and monocularly exposed to pairs of light emitting diode (LED) targets, either in complete darkness or when the foreground of the laboratory was lit (i.e., up to the nearer of the two LED targets). The region between the two LEDs was always dark and provided only binocular disparity information about depth. On different trials, the near LED was located either 4.5 m or 9 m from the observer. The far LED was located a further 0, 0.05, 0.31, 0.53, 0.73, 1.05, 1.31, 1.52, or 1.71 m beyond its mate and the observer's task was to verbally estimate the absolute depth separation between

these pairs of LEDs (in metric units). They found that while binocular estimates of depth increased in a fairly linear fashion with increasing disparity, monocular estimates were independent of the physical LED separation. There was also evidence of depth scaling, with much larger depth estimates produced in binocular viewing conditions with a lit foreground (compared to binocular viewing in the dark). There was no effect of having a lit foreground with monocular vision.

The current study extended and developed the work of Allison et al. (2009), utilizing a similar experimental setup. However, we examined the stereoscopic perceptions of a much wider range of depths (from 0 to 248 m), which were presented at larger observation distances (20 or 40 m). Stereoscopic depth perception had not been previously explored for these distances and depth magnitudes, presumably because of logistical difficulties in stimulus control at these distances, and because of the almost universal assumption that stereopsis is not useful at these distances. At observation distances of 20 and 40 m, our largest target depth separations generated binocular disparities that were close to the maximum levels physically possible for natural viewing. We wanted to determine whether the binocular advantage for perceived depth persists at these large observation distances and large target depths, when perspective and familiar size-based information was available for scaling. We also extended Allison et al.'s study by systematically exploring the relationship of the perceived depth between the two remote targets to the perceived observation distance (i.e., the perceived distance to the closest target). This factor may perhaps account for the large individual differences in responding in the earlier study of Allison et al.

Experiment 1: Perceived depth magnitude at large observation distances

In this experiment, observers made monocular and binocular estimates of the depth separation between pairs of LEDs, either in complete darkness or with the foreground lit up to the nearest LED. *The region between the two LEDs was always dark and provided only binocular disparity information about depth* (The intensities of these LEDs and their heights in the visual field were equated so as not to provide additional depth cues). As noted above, accurate stereoscopic perception of depth would require scaling for the observation distance. However, the 20- and 40-m observation distances used were well beyond the range where vertical disparity and oculomotor cues could be used for disparity scaling. Thus, the main sources of absolute distance information in this situation were the perspective-based cues provided by the

lit foreground of tunnel, including linear perspective and size gradients.

Methods

Apparatus and stimuli

The observers were seated inside a disused steam railway tunnel (located in Helensburgh, NSW, Australia) measuring 5.05 m high, 4.5 m wide, and 381 m long. The floor of this tunnel was flat but slightly upsloping (by 1.43°) in the direction of the observer's gaze. Pairs of lightproof tarpaulins were attached at each end of this tunnel, which blocked all outside light. The tunnel not only allowed us to examine large target depths and large observation distances, but it also allowed us to carefully control the ambient lighting conditions. The red LED targets used (Super Bright LEDs product code RL5-R5015, AlGaInP, 5000 mcd, 631-nm peak emission wavelength, 15° half-power angle, 5-mm diameter package) were viewed through slits in two black polyethylene screens (see Figure 1). The location of the near LED target was designated as the observation distance (either 20 or 40 m from the observer). The second LED target

Figure 1. Elevated view of the setup for Experiment 1 (much of the foreground has been cropped to aid in viewing the apparatus). Two spatially separate arrays of LEDs can be seen (one for the 20-m observation distance and the other for the 40-m observation distance). The screen for the 20-m observation distance trials has been removed (although the canopy remains). While only two LEDs were turned on in each experimental trial (one central LED and one lateral LED), all of the LEDs were turned on for this demonstration. The lateral LEDs in each case were located exactly at the observation distance. The central LEDs could be at one of 7 different depths relative to these lateral LEDs. Several LEDs are occluded by the polyethylene screen or canopy in this view, but all were visible from the observer's vantage point.

was at a variable depth behind the first. These LEDs were all located close to the observer's eye height. Different pairs of LEDs were switched on and off by computer control using Bluetooth interfaced switching hardware (Allison et al., 2009). The observer sat either in complete darkness or with the foreground region of the tunnel fully lit. The black polyethylene screens (placed 0.4 m in front of the near LED) prevented light from spreading beyond the foreground region of the tunnel (and also served to block the LED mounting equipment from the observer's view). *They effectively isolated the binocular disparity cues about LED target depths* (i.e., they avoided confounding perspective information about the observation distance and binocular disparity information about target depth). The screen for the 20-m observation distance was attached to the frame of a large canopy, which was also covered in black polyethylene (this screen, but not the canopy, was removed when the observer ran in the 40-m observation distance conditions). For the larger 40-m observation distance, observers could see through the canopy to the more distant LEDs and could also see the ground plane despite the presence of the canopy.

In dark conditions, the observer was only able to see the two LED targets (these were mounted on stands consisting of a matte black vertical pole attached to a wide wooden base). The nearest LED of the pair (the "lateral LED")

was always located exactly at the observation distance (positioned to either the left or right of the tunnel centerline). The farther LED was always a "central LED". The seven levels of physical depth separation between these LED pairs depended on which observation distance was being tested. The maximum depth was 31.02 m at the 40-m observation distance, and 7.76 m at the 20-m observation distance. The six smaller depths were recursively chosen to be exactly half of the next largest one at each observation distance (so as to achieve a wide range of depths with only seven central LEDs). When Equation 1 was applied to these depths, binocular disparity was calculated to be 0.0, 7.9, 15.6, 30.5, 58.3, 107.2, and 184.5 arcsec at the 20-m observation distance, and 0.0, 7.8, 15.3, 29.2, 53.6, 92.2, and 144.2 arcsec at the 40-m observation distance (based on an assumed interocular distance of 64 mm). Figure 2 shows how these LEDs were arranged to avoid occlusions from the observer's vantage point (strict alignment was achieved using both a laser and a string line that ran from the observer, along the centerline of the tunnel, up to the position of the furthest LED). In order to avoid occlusions: (i) LED pairs were randomly displaced to the left or right by increments of 256 arcsec. The actual horizontal separation between each pair of lateral and central LEDs was held constant at 0.5°; and (ii) LEDs viewed at 20- and 40-m observation distances
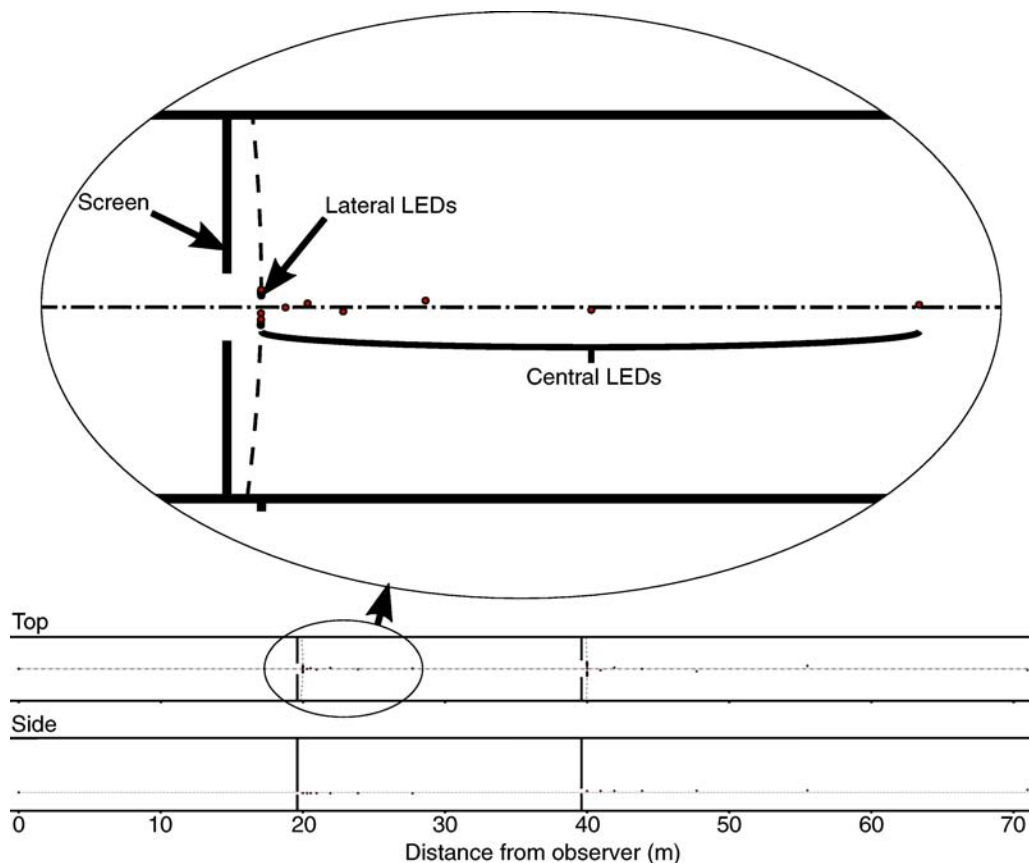

Figure 2. Top (plan) and side (elevation) views of the LED arrangement in the tunnel. The pairs of central and lateral LEDs were viewed through slits in two polyethylene screens (one located 19.6 m and the other 39.6 m from the observer).

were displaced below and above the observer's eye height (also by 256 arcsec), respectively. As these LEDs were effectively point light sources, our experimental setup provided little/no relative size information about their depth separation. 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). Pilot testing confirmed that luminance had indeed been equated and did not serve as a reliable cue to depth/distance.

Lit foreground conditions were identical to the dark conditions described above, except that the region of the tunnel that lay between the observer and the screen was lit by either 6 or 12 evenly spaced halogen lamps (Fairway DCWLT1000 twin-head quartz halogen work lights with 150-W bulbs). The 6 nearest lamps were turned on during the 20-m observation distance trials, and all 12 lamps were turned on during the 40-m observation distance trials. These lamps, which lined the left and right sides of the tunnel, were placed in pairs at distances of 6, 12, 18, 26, 32, and 38 m from the observer (measured along the tunnel's centerline). Each lamp was mounted on a stand, so that its bulb was 1.25 m above the tunnel floor. Both the 18- and 32-m pairs of lights were aimed perpendicularly to the wall of the tunnel, while the pairs at the remaining four distances were rotated a further 30° (i.e., from this perpendicular orientation) away from the observer, to avoid dazzling him/her. These lit foreground conditions provided strong cues to the distance of the screen (including the perspective of the dirt-covered ground and bricks in the tunnel wall and ceiling, the graffiti on the tunnel walls, the converging lines of the opposite edges of the tunnel, as well as cues arising from the size and position of the lamps themselves). Binocular viewing in these lit foreground conditions provided both monocular and binocular cues to the observation distance (perspective and perspective differences). However, only monocular distance cues were available from the lit foreground during monocular viewing. Importantly, there was no useful monocular information about the depth of the LED targets, and (given the large distances involved) the dominant cues to observation distance must have always been based on perspective and familiar size (during both binocular and monocular viewing).

Observers

Eight volunteers were brought to the tunnel. All had normal stereoacuity (minimum Titmus Circle Stereotest score of 50 arcsec) and visual acuity (minimum of 20/20 in both eyes). Three of these observers were naive concerning the layout of the experimental apparatus.

Task

Each trial began with the presentation of a single fixation LED in isolation. This fixation LED was either the nearer (i.e., lateral) or the farther (i.e., central) LED of the depth pair. When the observer had fixated this LED, he/she then pressed a button, which triggered the following events: (i) first, the fixation LED was turned off briefly (for 1 s); and (ii) then the fixation LED and the other LED in the depth pair were turned on together. The observer then provided a verbal estimate of the absolute depth separation between the two LEDs in metric units, which the experimenter manually recorded on the computer prior to initiating the next trial (the observer had previously been shown a meter rule to provide them with a frame of reference). Each observer ran eight blocks of trials. In these blocks, viewing was either: (i) monocular or binocular; (ii) from a 20-m or 40-m observation distance; and (iii) in complete darkness (i.e., with only the LED pairs visible) or with the foreground of the tunnel fully lit. Each block consisted of 56 trials, which were presented in a random order. Specifically, there were two replications of each condition, which were factorial combinations of the two types of fixation LED (central or lateral), the two locations of the lateral LED (left or right), and the seven different physical depth separations between the pairs of LEDs. As can be seen in Figure 1, the mounting equipment for the LEDs at the 20-m observation distance was visible during the 40-m observation distance trials when the tunnel foreground was lit. For this reason, we always ran the 40-m trials after the 20-m trails. In addition, we always ran the lit foreground trials after the dark trials. If the order of the lit foreground and dark blocks had been randomized, observers might have used remembered distance information from a previous lit foreground block to scale their disparity estimates in dark conditions.

Results and discussion

As can be seen from Figure 3, binocular estimates of depth made at both observation distances increased in a linear fashion with binocular disparity (confirmed by linear contrast analysis—$F(1,7) = 14.70$, $p < 0.001$ at 20 m; $F(1,7) = 12.81$, $p < 0.01$ at 40 m). These patterns of gain were not surprising. Although Equation 1 predicts a non-linear relationship between disparity and physical depth separation, Figure 4 shows that, for the observation distances and depths examined in this experiment, the relationship is well approximated by a linear function. Using linear regression, we calculated the gain of perceived depth (in meters) as a function of binocular disparity (in arc minutes) for each observer in each of the 8 experimental conditions (Binocular-Light, Binocular-Dark, Monocular-Light, and Monocular-Dark at both the 20- and 40-m observation distances) and then subjected these gain data to a within-subjects planned contrast analysis. Prior to running this analysis (and the analyses in subsequent experiments), we confirmed that there were no significant effects of either the location of the fixation
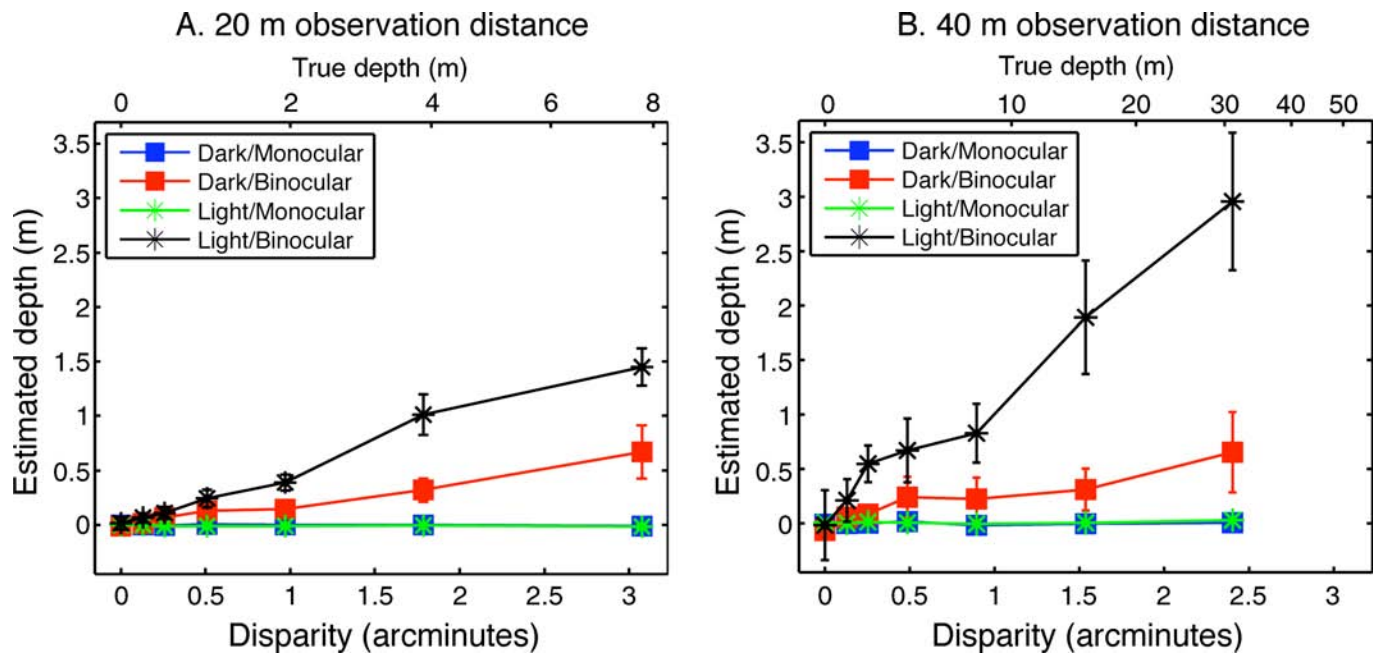
Figure 3. Binocular and monocular estimates of LED depth magnitude, in complete darkness and with a lit foreground, plotted as a function of binocular disparity (0–3 arcmin; bottom horizontal axis). The physical depths for these binocular disparities are also provided (top horizontal axis). The left plot shows magnitude estimates of LED depth with a 20-m observation distance, whereas the right plot shows performance with a 40-m observation distance. Error bars (*SEM*s) are provided to show the variability in observers' depth estimates but should not be used to make statistical comparisons as this experiment had a repeated measures design (see Cumming & Finch, 2005).
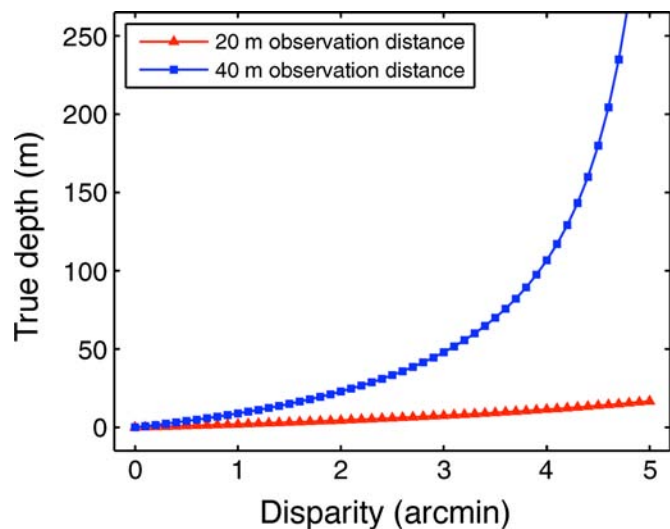

Figure 4. The physical relationship between depth (in meters) and horizontal angular disparity (in arc minutes) for the 20- and 40-m observation distances. For the depths examined in Experiment 1, which ranged from 0 up to 31 m, the relationship between physical depth and horizontal angular disparity appears quite linear. However, this relationship becomes non-linear as the physical depth increases further (up to 248 m, the largest target depth separation examined in Experiment 4).

LED (near or far fixation LED) or the side of the lateral LED (lateral LED on the left or right of the central LED) on our observers' depth estimates. We also confirmed that only stereoscopic information about depth was available in the current experiment. Monocular estimates of depth typically remained at, or near, zero for all of the levels of disparity (i.e., physical depth) examined (see Figure 3). Monocular gains were found not to be significantly different from zero at either the 20- (monocular-dark $t(7) = -1.03$, $p > 0.05$; monocular-light $t(7) = -1.44$, $p > 0.05$) or the 40-m observation distance (monocular-dark $t(7) = 0.48$, $p > 0.05$; monocular-light $t(7) = 1.00$, $p > 0.05$).

As expected, the gains of our observers' depth estimates were significantly greater during binocular viewing compared to monocular viewing ($F(1,7) = 16.65$, $p < 0.01$). In these binocular viewing conditions, the gains of the observers' depth estimates were significantly greater during lit foreground conditions compared to viewing these LEDs in darkness ($F(1,7) = 38.38$, $p < 0.001$). We had also predicted that depth from disparity would be scaled according to the observation distance in the lit foreground conditions, with greater depths being seen at the larger of the two observation distances. Consistent with this prediction, we found that in lit binocular conditions, the gain was significantly larger for the 40- compared to the 20-m observation distance ($F(1,7) = 32.386$, $p < 0.001$). In fact, in these lit binocular conditions, the mean gain was almost twice as large for the 40-m observation distance trials (0.84 compared to

0.44 for the 20-m observation distance trials). As expected, gain was not found to vary significantly with the observation distance in the dark binocular conditions ($F(1,7) = 5.69$, $p = 0.05$). Overall, the above findings are consistent with partial stereoscopic depth constancy, as they show that as the observation distance increases, so too does the magnitude of the binocular depth estimate for the same level of disparity. However, binocular estimates of depth were far from veridical in the current experiment, even when the lit foreground of the tunnel provided rich cues to the observation distance. Binocular depth estimates in the light were, on average, 19% and 12% of their physical depths at the 20- and 40-m observation distances, respectively. However, they were considerably better than binocular depth estimates in the dark, which were only 5% and 2% of their physical depths at the 20- and 40-m observation distances, respectively.

As can be seen from Figure 3, binocular depth estimates were found to increase with disparity in both the lit foreground and dark conditions. In addition to the above analyses, we also fitted our depth data for the binocular conditions using Equation 1, with the observation distance as a free parameter. In binocular-lit conditions, the effective scaling distances obtained from these non-linear fits were significantly larger for 40-m observation distance conditions (12.9 ± 0.9 m) than for 20-m observation distance conditions (9.4 ± 0.3 m; 95% confidence intervals reported). This provides further evidence of observation distance-based differences in disparity scaling in the lit foreground conditions. By contrast, in binocular-dark conditions, the effective scaling distances were not significantly different for 40- (5.8 ± 0.5 m) and 20-m (5.5 ± 0.3 m) observation distance conditions. Since no useful information was available about the observation distance in these binocular-dark conditions, it seems likely that the visual system assumed a particular observation distance as the scale factor (e.g., similar to Gogel's notion of a specific distance tendency). Consistent with this notion, the effective scaling distances found for both observation distances in these binocular-dark conditions were very similar and quite close to Gogel's (1965) estimated specific distance tendency (of around 2–4 m).

The findings of the current experiment confirm that stereopsis can provide useful information about relative distance/depth at observation distances as large as 40 m. These findings also support the notion that stereoscopic depth perception is still scaled for large observation distances. When the foreground of the tunnel was lit, binocular estimates of depth were found to become more veridical (than in darkness) and to increase in magnitude with the observation distance (for the same level of binocular disparity). Since the 20- and 40-m observation distances used were well beyond the range of vertical disparity and oculomotor cues, any scaling of depth from binocular disparity must have been based on perspective (and possibly familiar size)-based information about the observation distance. However, even with this scaling, binocular estimates of depth were always underestimated and the level of this underestimation was found to increase with the observation distance.

Experiment 2: Effect of perceived observation distance on perceived depth magnitude

Experiment 1 found evidence of large individual differences in the scaling of the observers' depth estimates. On closer inspection of these data, we discovered that two of our eight observers (one naive and one non-naive) had produced absolute depth estimates that were much smaller than the others (while their maximum depth estimates were only 0.11 m and 0.14 m, respectively, the six other observers' maximum depth estimates ranged from 1.04 m to 3.56 m). Experiment 2 examined possible reasons for "small depth", as opposed to "large depth", responding. Individual differences in responding are not unusual when using the method of magnitude estimation, which is why such data are often grouped using geometric means (Corso, 1967). However, it was possible that these individual differences were produced by our observers scaling their binocular disparity information about depth very differently. According to this notion, the two "small depth" responders in Experiment 1 might have: (i) consistently perceived that the observation distances were smaller than our "large depth" responders (in both lit and dark foreground conditions); and (ii) as a result, their disparity-based depth estimates might have received far less scaling. It was even possible that systematic differences in disparity scaling occurred because some of the observers were aware of the true observation distances and depths of the LEDs themselves (in Experiment 1, only 3 of the total 8 observers were completely naive to the setup). Experiment 2 reexamined binocular and monocular perceptions of depth in lit foreground conditions from a 20-m observation distance. Importantly, all 9 of these observers were naive and carefully kept ignorant of both the observation distance and the physical depths under examination. The purpose of this experiment was to examine the correlation across observers between perceived distance and perceived depth magnitudes. To this end, we collected binocular and monocular estimates of the observation distance, as well as binocular and monocular estimates of the perceived depths.

Methods
Apparatus and stimuli

The setup was similar to the 20-m observation distance conditions examined in Experiment 1, with the following

differences: (i) this experiment was run in a main hallway located inside the Mathews Building at the University of New South Wales over the summer break; and (ii) only lit foreground conditions were used. The lit foreground of the hallway was rich in distance and depth cues, which were generated by its regularly spaced doors, ceiling tiles, lights, cement brick walls, and so on (see Figure 5, left). The seven levels of physical depth tested were 0.0, 0.24, 0.48, 0.97, 1.93, 3.88, and 7.76 m (which should have produced binocular disparities of 0.0, 7.9, 15.6, 30.5, 58.3, 107.2, and 184.5 arcsec based on Equation 1). As in Experiment 1, these LEDs were viewed through a horizontal slit in a black polyethylene screen located just in front of the nearest LED. The ceiling lights beyond the screen were turned off. The screen was attached to the floor, walls, and ceiling, which prevented light from spreading beyond the foreground of the hallway.

Observers

Nine completely naive volunteers served as observers. All had normal stereoacuity (minimum Titmus Circle Stereotest score of 50 arcsec) and visual acuity (minimum of 20/20 in both eyes).

Task

Our naive observers were walked blindfolded to their seat and were only exposed to the view of the lit hallway and the LEDs during testing. They did not know how far the hallway extended beyond the black polyethylene screen. We ran both binocular and monocular blocks of trials. The order of block presentation was randomized across observers. Each block consisted of 56 trials (2 replications of 2 types of fixation LED × 2 types of lateral LED × 7 different levels of depths), which were presented in a random order. As in Experiment 1, observers verbally estimated the absolute LED depth separation for each trial. In this experiment, they were also asked to estimate the distance from their eye to the nearest LED (i.e., the 20-m observation distance) on the second last trial of each binocular and monocular block.

Figure 5. The left picture shows the observer's view in Experiment 2. The right picture shows the observer's view in a depth matching control experiment outlined in Appendix B, where colored sticks were placed on the floor at various distances in front of him/her.
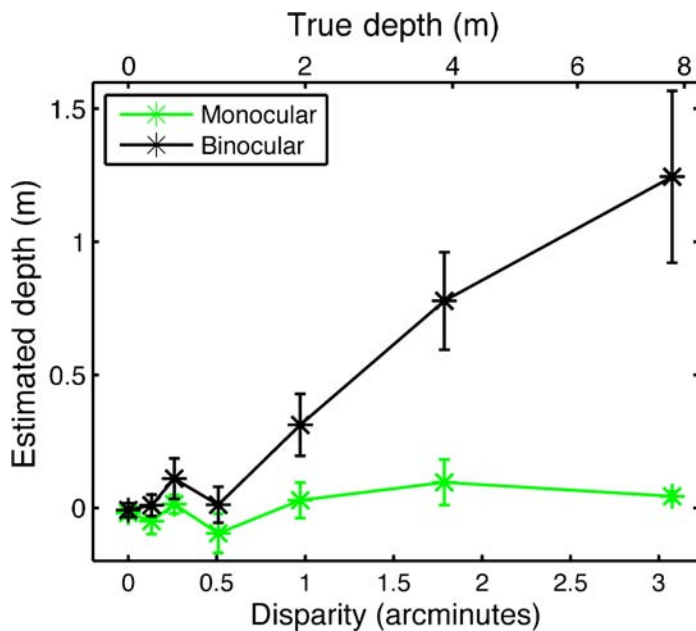
Figure 6. This plot presents binocular and monocular estimates of depth (averaged across observers) as a function of binocular disparity (bottom horizontal axis). The physical depths corresponding to these binocular disparities are also provided (top horizontal axis). Error bars (*SEM*s) show the variability in observers' depth estimates.

Results and discussion

Using linear regression, we calculated the gain of perceived depth (in meters) as a function of binocular disparity (in arc minutes) for each observer in both experimental conditions (Binocular-Light versus Monocular-Light). As in Experiment 1, we found that the gains of our observers' depth estimates were significantly greater during binocular viewing compared to monocular viewing ($F(1,8) = 9.74$, $p = 0.01$—see Figure 6). Monocular gains were found not to be significantly different from zero ($t(8) = 1.66$, $p > 0.05$). Thus, we were able to replicate the binocular advantage for perceived depth with a group of completely naive observers. However, the main purpose of this experiment was to determine whether variations in the magnitude of perceived depth were systematically related to differences in the perceived observation distance. For this analysis, we only looked at the binocular viewing conditions. We correlated observers' estimates of the seven target depth separations with their estimates of the 20-m observation distance ($M = 15.3$ m; $SD = 3.9$ m). We found that the relationship between perceived depth and perceived observation distance was negative and not significant (Pearson $r(7) = -0.35$, $p > 0.05$).

This result provides no support for the hypothesis that disparity scaling was based on perceived observation distance. It seems that the distance estimates used by the visual system to scale binocular disparity were different

from those that were consciously reported. Thus, since scaling is obviously occurring, it must be based directly on the available perspective (and possibly familiar size)-based information provided by the lit hallway. This issue is taken up in the General discussion section.

Experiment 3: Stereoscopic perception of very large depths (40-m observation distance)

How accurate is the stereoscopic perception of very large depths at large observation distances? This has never been examined. For this experiment, we returned to the same disused steam railway tunnel used in Experiment 1. However, this time we utilized the entire length of the tunnel, which allowed us to test a maximum depth separation of 248.2 m at the 40-m observation distance (the distance between the observer and the nearest LED). This maximum depth separation, which corresponded to a binocular disparity of 4.7 arcmin, was close to the maximum possible binocular disparity based on geometry (as can be seen in Figure 4). In order to facilitate disparity scaling in this experiment, we aimed to provide more useful distance information in the lit foreground conditions. In the earlier tunnel experiment, the LED mounting equipment used for the nearer 20-m observation distance was always visible when observers viewed the LEDs at the 40-m observation distance in the light. These LED support poles were randomly, as opposed to regularly, positioned in depth. When the screen for the nearer observation distance was removed for these 40-m observation distance trials, the canopy that it was attached to remained and this obscured some details of the lit foreground (see Figure 1). Experiment 3 provided a fairer test of disparity scaling at a 40-m observation distance, since the texture of the lit foreground was fully visible all the way up to the black polyethylene screen.

Methods

The method was identical to Experiment 1, with the following exceptions: (i) only a 40-m observation distance was used; (ii) three identical rectangular storage container lids were placed in front of the observer—they were evenly spaced along the centerline of the floor of the tunnel (at distances of 10, 20, and 30 m from the observer) and served as additional aids for depth estimation during lit foreground conditions; (iii) the seven levels of physical depth tested were chosen to have a minimum of 0 m and a maximum of 248.2 m. These depths were: 0.0, 7.8, 15.5, 31.0, 62.1, 124.1, 248.2 m (which corresponded to binocular disparities of 0.0, 53.6, 92.2, 144.2, 200.7,

249.6, and 284.2 arcsec based on Equation 1); and (iv) the order of the four experimental blocks (Binocular-Light, Binocular-Dark, Monocular-Light, and Monocular-Dark) was fully randomized for each observer.

Observers

Eleven observers participated in this experiment. All had normal stereoacuity (minimum Titmus Circle Stereotest score of 50 arcsec) and visual acuity (minimum of 20/20 in both eyes). Nine of these observers were naive to the layout of the experimental apparatus.

Results and discussion

Based on Figure 4, we had expected to see clear evidence of response expansion in binocular depth estimates for the two largest binocular disparities (since these disparities were generated by very large 124- and 248-m depth separations). However, to our surprise, binocular estimates of depth continued to increase in a linear fashion with disparity (see Figure 7). This observation was confirmed by carrying out linear contrast analysis
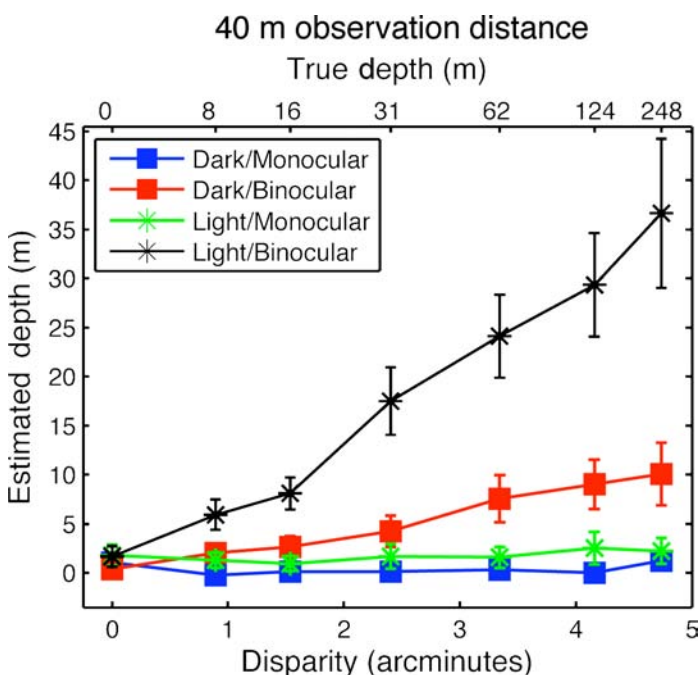

Figure 7. Binocular and monocular estimates of depth magnitude (in the dark and with a lit foreground) as a function of binocular disparity (0–5 arcmin) at a 40-m observation distance. The physical depths for these binocular disparities are also provided (top horizontal axis). Error bars (*SEM*s) show the variability in observers' depth estimates.

on the depth estimates (for each level of disparity) in the binocular-lit conditions ($F(1,10) = 24.05$, $p < 0.001$)—the quadratic and cubic contrasts were both non-significant ($F(1,10) = 1.55$, $p > 0.05$; $F(1,10) = 2.68$, $p > 0.05$). Thus, again using linear regression, we calculated the gain of perceived depth (in meters) as a function of binocular disparity (in arc minutes) for each observer in each of the four experimental conditions. These gain data were then subjected to a within-subjects planned contrast analysis. As in Experiment 1, we found that the gains of the observers' depth estimates were significantly greater during binocular viewing compared to monocular viewing ($F(1,10) = 53.33$, $p < 0.0001$). The gains of these binocular depth estimates were again significantly greater in lit foreground conditions than in darkness ($F(1,10) = 28.52$, $p < 0.001$). As expected, monocular gains were found not to be significantly different from zero in either the lit foreground ($t(8) = -0.25$, $p > 0.05$) or dark ($t(8) = 0.89$, $p > 0.05$) conditions.

As can be seen in Figure 7, binocular viewing conditions with a lit foreground produced the largest depth estimates. In these conditions, depth estimates were on average 44% of the physical depth, which is a substantial improvement on performance at the same 40-m observation distance in Experiment 1. When the depth data for these binocular-lit conditions was fitted using Equation 1, the effective observation distance was estimated as being 25.7 ± 1.3 m (which was greater than the 12.9 ± 0.9 m scale factor estimate for Experiment 1). This improvement may have arisen because the lit foreground of the tunnel was fully (as opposed to partially) visible in the current experiment. As noted above, the lit foreground also contained more regularly (as opposed to randomly) positioned scene features (lamps, lamp stands, and storage container lids) that could be seen clearly all the way up to the black polyethylene screen.

However, as in Experiment 1, binocular depth estimates were found to increase with disparity in both the lit foreground and dark conditions. In these latter dark conditions, since no useful information was immediately available about the observation distance, it was possible that the visual system assumed a particular observation distance as the scale factor (e.g., similar to Gogel's (1965) notion of a specific distance tendency). However, unlike Experiment 1, this estimated scaling distance would have to have been considerably greater than Gogel's estimate of 2 to 4 m in order to account for the binocular depth magnitudes obtained in the dark (when the depth data for these binocular-dark conditions were fitted using Equation 1, the effective observation distance was estimated as being 17.7 ± 0.7 m). It is more likely that this result arose because, unlike Experiment 1, the order of the light and dark experimental blocks was randomized in this experiment. On closer observation of the data, we found that observers who were first exposed to lit foreground conditions tended to rate depths as being larger in the later

dark conditions, which suggests that their verbal depth estimates were biased by remembered information about the observation distance.

Experiment 4: Stereoscopic perception of very large depths (20-m observation distance)

In the first tunnel experiment, we used a slightly different range of disparities at the 20- (0–3.1 arcmin) and 40-m (0–2.4 arcmin) observation distances. In order to examine how larger/identical disparities are scaled for different observation distances, we halved the observation distance used in Experiment 3 (from 40 m to 20 m) and tested depths that produced the same range of disparity (0–4.7 arcmin). Unfortunately, due to time restrictions, we were only able to test four observers (one naive and three non-naive) in this fourth and final experiment (entry to the tunnel used for testing was gained via an active rail corridor. We only had 12 weeks approved access along this corridor, 4 of which had been required to survey and then light proof the tunnel).

Methods

The method was identical to that of Experiment 3, except that the observation distance was reduced to 20 m.

The seven levels of physical depth examined were 0.0, 1.77, 3.25, 5.59, 8.74, 12.16, and 15.13 m. Only six of the twelve lamps used in Experiment 3 were turned on during the lit foreground conditions. Three lamps were placed on each side of tunnel (5 m apart). One rectangular bin lid was placed on the ground in front of the observer at a distance of 10 m (which bisected the 20-m observation distance).

Observers

All four observers had previously run in Experiment 3. Only one of these observers was naive as to the layout of the experimental apparatus (compared to the 9 naive observers in Experiment 3).

Results and discussion

Using linear regression, we calculated the gain of perceived depth (in meters) as a function of binocular disparity (in arc minutes) for each observer in each of the four experimental conditions (Binocular-Light, Binocular-Dark, Monocular-Light, and Monocular-Dark). After combining this gain data with the corresponding data for the same four observers in Experiment 3, we then carried out a within-subjects planned contrast analysis. Despite our small sample size, the expected effects were all found to reach significance: (i) binocular gains were still significantly greater with a lit foreground than in darkness ($F(1,3) = 19.62$, $p < 0.05$); (ii) there was no significant
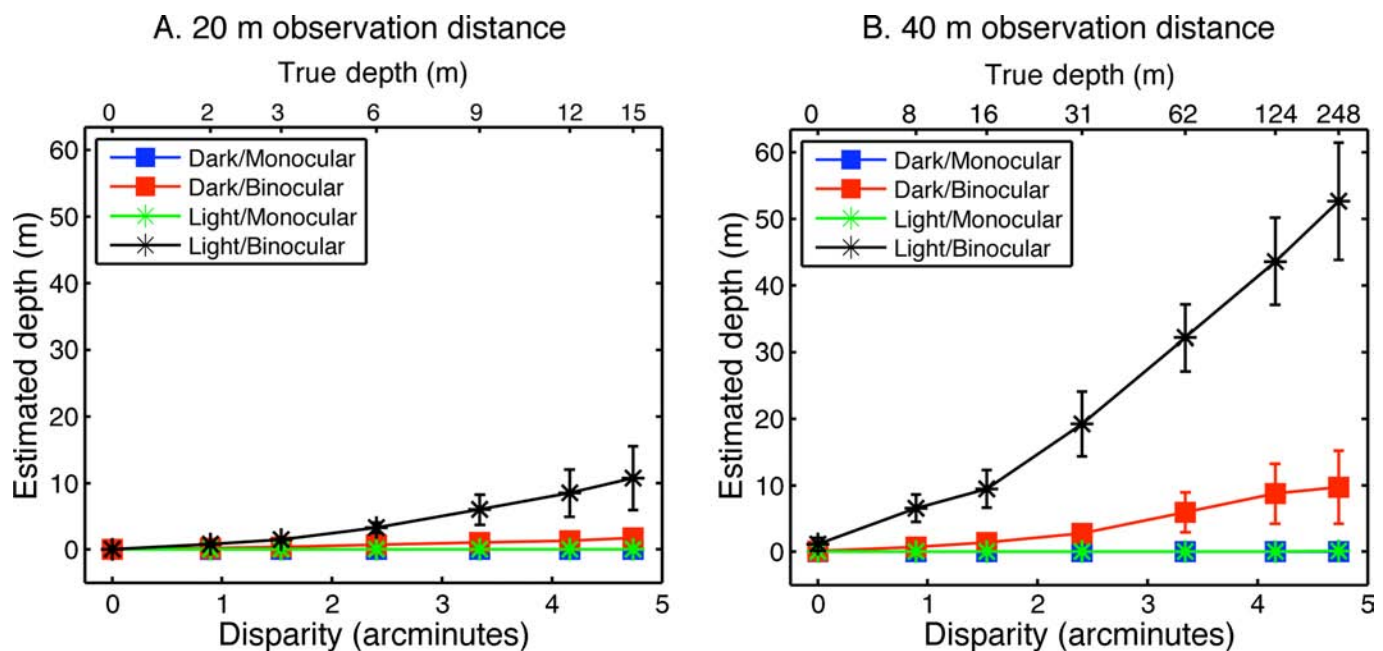

Figure 8. Binocular and monocular estimates of depth magnitude (in the dark and with a lit foreground) as a function of both binocular disparity (0–5 arcmin; bottom horizontal axis) and the observation distance. The physical depths for these binocular disparities are also provided (top horizontal axis). The left plot shows magnitude estimates of LED depth in Experiment 4, which had a 20-m observation distance. The right plot shows the performance of the same 4 observers in Experiment 3, which had a 40-m observation distance. Error bars (*SEM*s) show the variability in observers' depth estimates.

difference between monocular gains with a lit foreground or in darkness ($F(1,3) = 0.34$, $p > 0.05$); and (iii) binocular gains in lit foreground conditions at the 40-m observation distance were significantly larger than those obtained at the 20-m observation distance ($F(1,3) = 15.62$, $p < 0.05$). Thus, as can be seen from Figure 8, the depth estimates for the same level of binocular disparity did increase with the observation distance during binocular viewing with a lit foreground. We also fitted the depth data for these binocular-lit conditions using Equation 1, with observation distance as a free parameter. The effective scaling distances obtained from the resulting non-linear fits were: (i) 17.3 ± 0.6 m at the true 20-m observation distance; and (ii) 30.4 ± 1.1 m at the true 40-m observation distance (95% confidence intervals reported). This provides further evidence that disparity scaling was based on the observation distance.

General discussion

Our experiments clearly demonstrate a binocular enhancement of apparent depth magnitude, even at large observation distances. This binocular advantage was evident for both observation distances (20 and 40 m) and for almost all of the target depth separations tested (including the largest depth separation of 248 m). We also found that binocular estimates of depth that were made with a lit foreground: (i) were closer to veridical than those made in the dark (which in turn were superior to monocular estimates made in both lit and dark conditions); and (ii) increased with the observation distance. Thus, it is clear that stereopsis supports some perception of metric depth (albeit compressed) at large observation distances (i.e., it provides more than a simple "closer further" discrimination). Since the observation distances tested were all well beyond the range of vertical disparity, convergence, and accommodation cues, it appears that perceptions of depth from disparity were scaled for distance using cues such as perspective and possibly familiar size. An alternative explanation of these results, based on the possibility that the aperture of the screen may have provided additional disparity cues in the lit foreground (but not in the dark) conditions, was ruled out by a control experiment outlined in Appendix A.

Although *the above trends held true for all of our observers*, there were often large individual differences in the magnitudes of their depth estimates. We hypothesized that "small depth" responders may have seen the targets at closer distances while "larger depth" responders may have seen these same targets as being more distant. However, in Experiment 2, we showed that perceived depth magnitudes were not predictable from the observers' own estimates of the observation distance. We concluded from this finding that disparity scaling was based on an automatic/direct response to distance cues rather than being mediated by consciously available distance estimates based on these cues. This is analogous to the failure of the size–distance invariance hypothesis to explain size constancy, despite the dependence of perceived size on the presence of distance cues (for a discussion of these issues, see Berkeley, 1709; Gillam, 1995; Sedgwick, 1986). Another possible explanation for the large individual differences in depth estimates was that there was a problem with our task/measure. A control experiment outlined in Appendix B showed that observers made very similar estimates of depth with a novel relative depth matching task (compared to the absolute depth estimation task used in the rest of our experiments). However, while our data suggest that binocularly perceived depths were based on direct scaling, it appears that our verbal measures were not immune to indirect influences. In particular, in the later experiments, where the order of lit foreground and dark trials was randomized, we found evidence that remembered distance did have some influence on our observers' absolute depth estimates.

Experiment 3 was run to examine binocular and monocular perceptions of very large target depths (up to 248 m). At a 40-m observation distance, binocular estimates of depth continued to increase linearly with disparity even though the physical relationship between physical depth and disparity becomes highly non-linear with such large depth separations. Based on threshold data alone, Cutting and Vishton (1995, see Figure 1, pp. 80) had previously estimated the limit of stereoscopic depth perception as 44.1 m. However, this limit was the mean egocentric distance of the two depth separated objects, rather than the distance to the nearest of the two objects (which we have defined here as the observation distance). Our stereoscopic depth magnitude data clearly show that stereopsis is useful for objects whose mean egocentric distance is much greater (up to 164 m). Using Cutting and Vishton's terminology, this means that stereopsis is useful not only in personal and action space but also in vista space.

Experiment 4 measured binocular and monocular estimates of depths at 20 m, which produced the same disparities as those tested in Experiment 3 at 40 m. Taken together, Experiments 3 and 4 appear to provide the best evidence of disparity scaling and stereoscopic depth constancy, with binocular estimates of depth in the lit foreground conditions being, on average, 59% and 52% of the physical depths at the 20- and 40-m observation distances, respectively. As in previous experiments, binocular estimates in the dark were less veridical (only 12% and 8% of the physical depth on average for the 20- and 40-m observation distances, respectively). It is possible that the more veridical depth estimates in Experiments 3 and 4 (compared to our earlier experiments) were simply the result of differences in intersubject variability that arose due to sampling (although it should be noted that these differences in scaling still appear to be

present if one looks only at the common observers in all three experiments). Alternatively, it is possible that this improvement was artificially produced by randomizing the order of the light and dark blocks in Experiments 3 and 4 (as opposed to always presenting the dark blocks before the light blocks in Experiment 1). Consistent with this notion, the subset of observers who were first exposed to lit foreground conditions generally produced larger depth estimates than those who were first exposed to dark foreground conditions. A final possibility was that the greater scaling displayed in these later experiments was the result of the superior perspective information available from the lit foreground—due to the uninterrupted view of the foreground scene (there was no occluding canopy as in Experiment 1) and the addition of the storage container bin lids.

It is worth asking whether the rather inaccurate depth percepts that we have obtained at these very large distances and depths are useful. We would argue that they are. The distances that we have tested are beyond the normal range of direct and immediate visually guided motor action (even throwing), where accurate perceptions of depth would be most useful. The sense one has when looking at our stereoscopic stimuli is of very large depths rather than precise metric depths. This sense of space and depth enhances the phenomenology of distant spatial layouts under circumstances in which there are no real behavioral consequences of rather coarse approximations. It is also possible that these binocularly perceived depths would have been even more accurate in the presence of other scaling factors (additional size cues, height in the visual field, the horizon, and so on). These could be used directly to signal the relative depth or to provide contextual cues to interpret the depth from disparity. For example, just as size can be scaled relative to a surrounding context of sizes, it may be the case that depth can be scaled by a context of sizes in the same way. Familiar size may also play a role so that for example a context of buildings will produce larger depth estimates for a given disparity than a context of furniture. These issues remain to be explored.

Appendix A

Visible aperture control experiment

Binocular estimates of depth may have been larger in lit foreground conditions than in darkness, because they provided perspective-based cues to the observation distance, which were used to scale disparity information about depth. However, there was another stimulus difference that could have contributed to this finding in Experiments 1, 3, and 4. It was possible that the visible aperture in the polyethylene screens contributed to the superiority of the lit foreground conditions (as it provided a relative disparity with each of the LEDs). By contrast, in the dark, only the LEDs were visible. Accordingly, we carried out a control experiment, which examined whether the availability of additional disparity information from a lit/visible screen aperture increased binocular estimates of depth in an otherwise dark environment.

Methods

Apparatus and stimuli

The design of this experiment was similar to that of Experiment 2, with the following exceptions: (i) viewing of the LED pairs was always binocular and in the dark; and (ii) the slit in the screen (through which the observer viewed the LEDs) was made visible in the dark under half the conditions (it was previously invisible when the environment was dark). This was achieved by fitting a removable 256-arcsec-wide rectangular cardboard aperture to the outside of the slit (the slit extended 128 arcsec above and below the LEDs and equally to the left and right of the left- and rightmost LEDs in the configuration). The aperture was painted with a yellow-green fluorescent paint. This painted aperture could be illuminated by a pair of ultraviolet LEDs, which were switched on and off from the experimenter's position. Their intensity was adjusted so that the UV light only illuminated the aperture and not the surrounding environment (note that black polyethylene is not fluorescent under ultraviolet light). Blocks of trials were counterbalanced for the visibility of the aperture. The counterbalanced set of two blocks was repeated twice per observer, to produce a total of four blocks.

Observers

Ten volunteers participated in this experiment. All had normal stereoacuity (minimum Titmus Circle Stereotest score of 50 arcsec) and visual acuity (minimum of 20/20 in both eyes). Nine of these ten observers were naive to the layout of the experimental apparatus.

Results and discussion

Using linear regression, we calculated the gain of perceived depth (in meters) as a function of binocular disparity (in arc minutes) for each observer in both experimental conditions (binocular viewing in the dark with either a visible or an invisible aperture). We found that the gains of our observers' binocular depth estimates were not significantly different when they viewed the LEDs through a visible, as opposed to an invisible, aperture ($F(1,9) = 0.174$, $p > 0.05$). This result did not support the hypothesis that lit foreground conditions

produce larger depth estimates (than dark conditions) because they provide additional binocular disparity information about depth (i.e., between the slit in nearer screen and the two LEDs).

Appendix B

Relative depth matching task

This control experiment examined whether large individual differences in responding would persist when a different depth task was used. Instead of providing a verbal estimate of the absolute depth between the two LED targets in metric units, observers matched the perceived depth between the two distant LEDs to a depth scale arrayed on the floor in front of them. We examined the performance of ten completely naive observers on this relative depth matching task. By necessity, this experiment had to be run in a shorter internal laboratory hallway, and as a result, we were forced to reduce the observation distance to only 10 m. We also ran eight additional observers (seven naive and one non-naive) on the same experimental conditions using the absolute depth estimation task (after we had removed the colored sticks from the floor), which allowed us to directly compare the effectiveness of the relative depth matching task to this task.

Methods

Pairs of LEDs with various depth separations were viewed through a horizontal slit in a black polyethylene screen (located 0.4 m in front of the nearest LED). As in Experiment 1, the lit foreground of the hallway was rich in distance and depth cues, which were provided by its cupboards, bookcases, computer monitors, ceiling lights, and the window frames. We examined six different levels of physical depth: 0.0, 0.12, 0.24, 0.049, 0.97, and 1.94 m (which corresponded to binocular disparities of 0.0, 15.8, 31.2, 61.0, 116.7, and 214.4 arcsec based on Equation 1). In the new relative depth matching task, the observer had to match the perceived magnitudes of each of these physical depths to the separation between the nearest and another series of uniquely colored sticks (see Figure 5, right). Because these sticks had to be visible for the observer to make his/her judgments, only lit foreground conditions were tested. The first stick in the scale was located on the ground at a distance of 2.4 m directly in front of the observer. Subsequent sticks were located at 0.01, 0.015, 0.02, 0.03, 0.04, 0.06, 0.09, 0.12, 0.17, 0.24, 0.34, 0.49, 0.69, 0.97, 1.37, 1.94, 2.74, and 3.88 m.

Observers

Seventeen naive volunteers and one non-naive volunteer served as observers. All had normal stereoacuity (minimum Titmus Circle Stereotest score of 50 arcsec) and visual acuity (minimum of 20/20 in both eyes). Ten
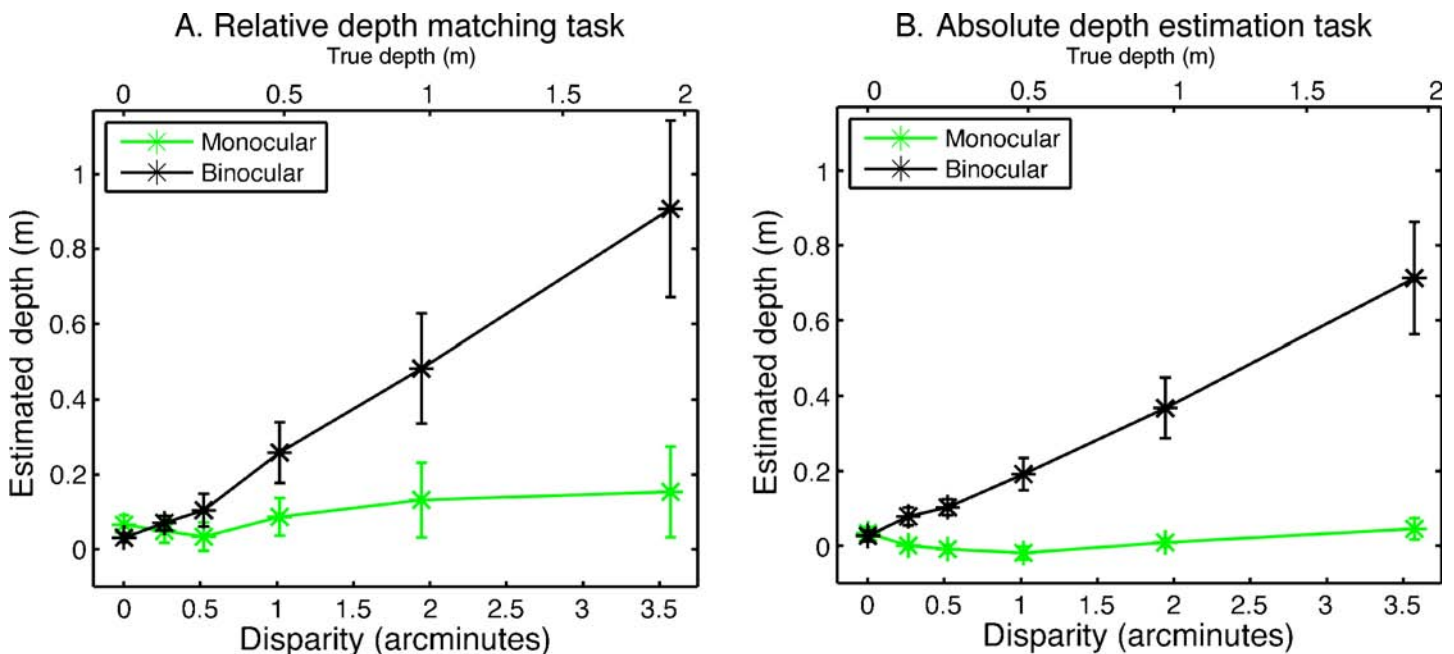

Figure B1. Binocular and monocular relative depth matches (on the left) and absolute depth estimates (on the right) plotted as a function of binocular disparity (0–3.5 arcmin; bottom horizontal axis). The physical depths for these binocular disparities are also provided (top horizontal axis). Error bars (*SEM*s) show the variability in observers' depth estimates.

observers (all naive) participated in the relative depth matching task. The remaining observers participated in the absolute depth estimation task.

Results and discussion

Large individual differences in responding continued to be found with the relative depth matching task. In fact, the relative depth matching and absolute depth estimation tasks produced very similar estimates of depth (see Figure B1). The gain in responding was somewhat larger with the matching task than with the estimation task— either due to individual differences in responding or because there was less distance information available on the ground during the estimation task. We calculated the gain of perceived depth (in meters) as a function of binocular disparity (in arc minutes) for both experimental tasks and then subjected this gain data to a split plot ANOVA. We found that the gains of our observers' depth estimates were significantly greater during binocular viewing compared to monocular viewing ($F(1,15) = 7.67$, $p = 0.01$). However, neither the main effect of task type ($F(1,15) = 0.745$, $p > 0.05$), nor the interaction between task type and view type ($F(1,15) = 0.607$, $p > 0.05$), were found to reach significance. Thus, we can conclude that the binocularly estimated depths increased in a very similar linear fashion with disparity using both experimental tasks.

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