

OBSERVATION

Fast Perception of Binocular Disparity

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Is depth perception from binocular disparities—stereopsis—slow or fast? Many of the temporal properties of stereopsis are known. For example, rapidly changing disparities are perceptually difficult to track, which suggests that stereopsis is generally slow. But, remarkably, this basic question has not yet been addressed. We compared speed–accuracy trade-off functions between 2 forced-choice discriminations: 1 based on stereoscopic depth and 1 based on luminance. Unexpectedly, both speed–accuracy trade-off functions deviated from chance levels of accuracy at the same response time—approximately 200 ms—with stereo accuracy increasing, on average, more slowly than luminance accuracy after this initial delay. Thus, the initial processing of disparity for perceived depth took no longer than the initial processing of luminance for perceived brightness. This finding, that binocular disparities are available early during visual processing, means that depth is perceived quickly, and, intriguingly, that disparities may be more important for everyday visual function than previously thought.

Keywords: stereopsis, disparity, latency, response time, speed–accuracy trade-off

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Stereopsis is the perception of depth from differences in retinal projection in the two eyes, or disparities, resulting from the lateral shift between the eyes in the cranium (Wheatstone, 1838). It is a

highly potent cue for evoking a qualitative sense of depth (Howard & Rogers, 2002). But despite popular accounts (Barry, 2009), the importance of stereopsis for daily functioning remains unclear (Fielder & Moseley, 1996), in part because it is commonly believed to be slow (Tyler, 1991). On the one hand, the nervous system extracts disparity very quickly, with disparity-selective responses evident in cortical neurons at 60 ms after stimulus presentation in macaque monkeys, which is similar to other visual features such as orientation (Trotter, Celebrini, Stricanne, Thorpe, & Imbert, 1996). On the other hand, the temporal resolution of the stereoscopic system for stimuli that fluctuate in depth is about 10 Hz, as compared with 70 Hz for luminance modulation, which can be explained by the fact that binocular cells in visual cortex must cross-correlate temporally filtered inputs from the two eyes (Kane, Guan, & Banks, 2014; Nienborg, Bridge, Parker, & Cumming, 2005).

If stereopsis is slow, its use must be limited to conscious appreciation of depth, actions that can be planned ahead of time (e.g., Keefe, Hibbard, & Watt, 2011; Schlicht & Schrater, 2007), and slow tasks such as threading a needle (Brenner & Smeets, 2006; Sheedy, Bailey, Buri, & Bass, 1986; Valsecchi & Gegenfurtner, 2015). However, poor temporal sensitivity for disparity modulation, relative to luminance modulation, does not necessarily mean that luminance is used more quickly during perception. Here, we ask this question explicitly: When are disparity signals made available for perceptual decisions as compared with luminance signals?

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Baptiste Caziot developed the study concept after discussions among all four authors. Baptiste Caziot and Benjamin T. Backus designed the study. Testing and data collection were performed by Baptiste Caziot. Baptiste Caziot and Benjamin T. Backus performed the data analysis and interpretation and wrote the manuscript. Matteo Valsecchi and Karl R. Gegenfurtner provided critical revisions. All authors approved the final version of the manuscript for submission. Preliminary results were reported at the annual meetings of the Vision Sciences Society in Naples, Florida, May 2012, and the Optical Society of America in Philadelphia, Pennsylvania, October 2014. This work was supported by National Eye Institute/National Institutes of Health Grant R01 EY 013988. We thank Frédéric Chavane for suggesting direct comparison of stereo and luminance tasks, Suzanne McKee for discussion, and Saul Sternberg for discussion and comments on a draft of the manuscript.

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A simple theoretical framework for making this comparison is shown in Figure 1. We define *visual processing latency* as the time between the presentation of a visual stimulus and the time at which a signal within the stimulus starts to be used for perceptually mediated decisions. In a behavioral study, the visual processing latency cannot be measured directly because response times also include decisional and motor components (Luce, 1986; Sternberg, 1969). However, these additional components can be controlled. To keep the distribution of durations for the motor component constant across the stereo and luminance conditions, we used the same highly stereotyped response—namely, a simple button press—in both of our conditions.

Controlling the duration of the decisional component is more intricate. The decisional component begins immediately after the visual processing latency, when the processed signal first takes form as a representation that helps to make the decision. Signal and noise accumulate together in a decision variable, and the decision on a given trial is correct or incorrect depending on the contents of the accumulator when a decision threshold is reached (Bogacz, Brown, Moehlis, Holmes, & Cohen, 2006; Carpenter & Williams, 1995; Gold & Shadlen, 2001; Luce, 1986; Ratcliff & Rouder, 1998).

Importantly, the accumulation period can be made longer or shorter by giving the observer more or less time to respond through the use of a deadline procedure (Pachella, 1974; Schouten & Bekker, 1967; Wickelgren, 1977). When given less time, the observer uses a lower, less conservative threshold and thus makes more errors (Bogacz, Wagenmakers, Forstmann, & Nieuwenhuis, 2010; Heitz, 2014). By varying the deadline, one can determine the full speed–accuracy trade-off function (SATF) and, in particular, the mean response time at which performance starts to increase above chance. We call this special response time the *residual latency* (Luce, 1986), and we estimate it from the data as the *delay* parameter in a fitted curve for the SATF. (The other fitted parameter of the SATF is the *time constant* parameter, which reflects the rate at which signal accumulates against noise once accumulation has begun.) If the residual latency is the same for two tasks that use comparable responses, then their visual processing latencies are the same (Carrasco, McElree, Denisova, & Giordano, 2003; Rousset, Fabre-Thorpe, & Thorpe, 2002).

To compare the visual processing latencies for disparity- and luminance-based stimuli, we measured SATFs for stereo-depth

and brightness tasks, respectively. Because stereopsis requires an interocular comparison of luminance-defined images, one might expect visual processing latency to be longer for it than for a comparable monocular luminance-defined stimulus. However, we found not only that stereopsis was fast but that the visual processing latency for stereopsis was close to identical to that for brightness.

Method

Observers

Observers were 10 students and faculty at the State University of New York College of Optometry. Two observers were authors (Baptiste Caziot and Benjamin T. Backus). All observers had normal or corrected-to-normal vision and stereoacuity of 20 arcsec or better as measured with the Randot stereoacuity test (Precision Vision, La Salle, IL).

Stimulus and Procedure

Stimuli were displayed on a stereoscopic LCD computer screen ($27^\circ \times 15^\circ$ of visual angle; Asus VG248QE; Taipei, Taiwan) at a viewing distance of 114 cm. Active shutter glasses (3D Vision P854; NVIDIA, Santa Clara, CA) were used to create a 120-Hz stereoscopic display (60 Hz in each eye). Each trial started with a 1,000-ms fixation period, followed by a 50-ms stimulus, followed by a blank screen (see Figure 2). There were two conditions in the experiment: stereo (see Figure 2A) and luminance (see Figure 2B). The stimulus background consisted of pixels with randomly chosen intensities (Gaussian white noise). In the stereo condition, the observer indicated which of two disks, one to the left and one to the right of fixation, was closer to him or her in depth. Both disks were darker than the background. The target disk had 6 arcmin of crossed disparity relative to the background, so it appeared closer. The other disk had 6 arcmin of uncrossed disparity, so it appeared farther away. Disks were 2° of visual angle in diameter and 5° from the fixation mark on average. The horizontal position of each disk was randomly jittered from trial to trial within an 18-arcmin range, so monocular position was not a reliable cue to perform the task. Accuracy was at chance in the stereo task when it was done monocularly (see the supplemental materials). Observers were

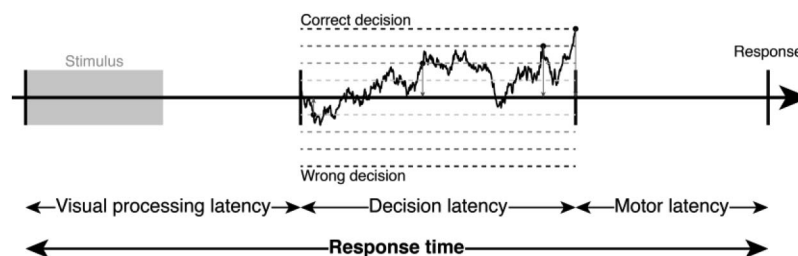


Figure 1. Components of response time. The visual processing latency starts at stimulus presentation and proceeds until the extracted signal first becomes available in the decision variable (jagged curve). This variable accumulates to a decision boundary (dashed lines), whereupon a motor response is initiated—either the correct one or the incorrect one. A liberal criterion (lighter gray dashed lines) reduces the mean accumulation time but also increases the error rate, because the signal-to-noise ratio is lower at the time of decision. In the present experiment, we used a deadline procedure to reduce the response time until accuracy in the task was at chance.

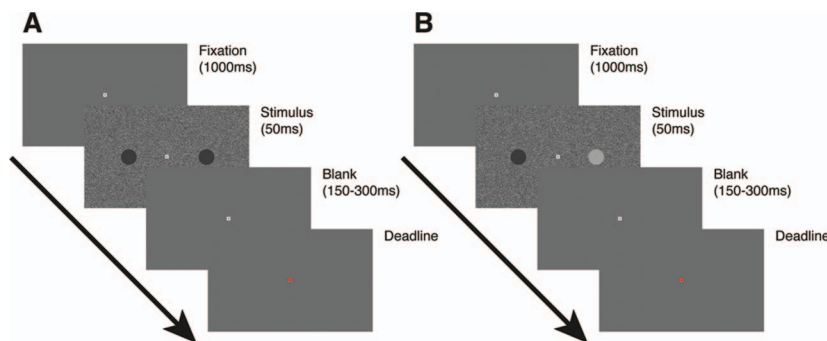


Figure 2. Time course of a trial. A blank screen with fixation mark was displayed for 1,000 ms, followed by a stimulus for 50 ms, followed by the blank screen again. The observer indicated which side of the stimulus contained the near stereo target, in the stereoscopic-detection task (A), or the dark target, in the luminance-detection task (B). When observers responded before the deadline, they received normal auditory feedback; otherwise, the fixation mark turned red at the deadline and an irritating sound was played.

given feedback after each trial, so in principle they could learn over time how to select the near disk on the basis of some unsigned disparity artifact within the binocularly fused image. However, observers were able to select the near disk at the start of the experiment; there was no evidence of diplopia; and, in any case, the target and foil had equal and opposite disparity, so they were indiscriminable within a fused image having the disparity of the background.

In the luminance task, one side of the display contained a dark target disk identical to that in the stereo condition, and the other side contained a light disk. The luminance task was run monocularly for proper comparison with the stereoscopic depth task.¹ The disks had high contrast to minimize variability in the visual processing latency (see the Discussion section); the dark disk, background, and light disk had effective luminances of 7.7, 15.2, and 30.6 cd/m² (including attenuation by the stereo glasses), respectively.

Observers indicated the target disk by pressing one of two keys on a keypad. After a deadline, the fixation square turned red. The deadline was 350, 300, 250, or 200 ms after stimulus onset within separate blocks of 75 trials. Blocks of the stereoscopic task alternated with blocks of the luminance task in an ABBA sequence, counterbalanced across observers. Each observer collected data in 32 blocks: 4 (repetitions) × 4 (deadline durations) × 2 (stimulus conditions), for a total of 2,400 trials per observer per single session.

Normal feedback was given when the observer respected the deadline: A high-pitched tone signaled a correct response, and a low-pitched tone signaled an incorrect response. When the observer responded after the deadline, a penalty sound composed of 10 disharmonic pure tones randomly chosen between 50 Hz and 2 kHz was played. All responses were recorded and analyzed regardless of whether the observer met the deadline.

Analysis

The top and bottom 2.5% of the response time data were trimmed to remove outliers that reduced the quality of the fits (Ratcliff, 1993). A separate SATF was fitted to the data for each observer using maximum-likelihood estimation. To ensure the

robustness of our conclusions, we fitted two different forms of the SATF, either fraction correct as an exponential function of response time (described later) or z score as a linear function of response time (see the supplemental materials; Lappin & Disch, 1972; Stanford, Shankar, Massoglia, Costello, & Salinas, 2010). The exponential SATF had two free parameters: delay and exponential time constant. The SATF was constant at 0.5 (chance accuracy) during the delay, then was an inverted exponential decay function with asymptote at 1.0. Statistics to estimate the difference between conditions were made using these fitted parameters. Statistics on the time constants were performed on their reciprocals.

We also bootstrapped these statistics for each observer separately: The 1,140 trials of a given condition were resampled with replacement and fitted with an SATF separately for luminance and stereo. We then took the difference between the delay parameters (or between the time constant parameters) for luminance and stereo to create one bootstrap estimate of the difference. This procedure was repeated 10,000 times. The p value for a two-sided test rejecting the hypothesis that the difference was 0 was twice the fraction of bootstrap estimates that were less than 0 (or greater than 0 when the mean difference was negative).

Results

Response times were longer and accuracy better as the deadline grew longer, as expected (see Figure 3). Observers were instructed to perform as well as possible while respecting the deadline, but they were unable to time their responses precisely. Thus, they often missed the deadline (the rate ranged from 6% of trials in the 350-ms deadline condition up to 29% of trials in the 200-ms condition). Figure 3A shows that as observers were given more time, they responded later in absolute terms but earlier relative to the upcoming deadline; thus, when accuracy was high, they chose to sacrifice some accuracy to meet the deadline more often.

Accuracy as a function of response time—the SATF—is plotted in Figure 4 to estimate the time at which responses started to

¹ In the stereo task, the two eyes do not supply redundant information streams to improve performance through probability summation, as would be the case for the luminance task if it were run binocularly.

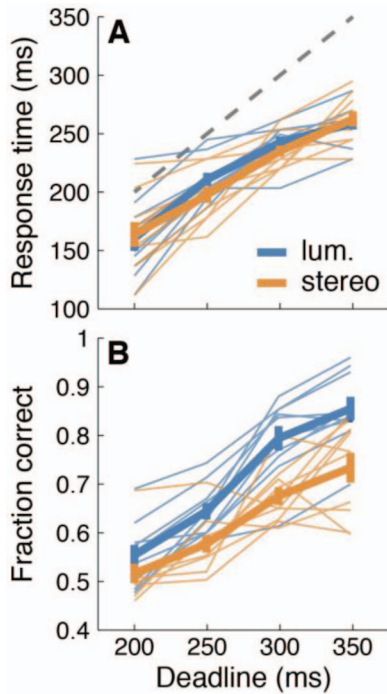


Figure 3. Median response times (A) and fractions correct (B) for each observer (thin lines) and averages for the population (thick lines) for the luminance (lum.; blue or dark gray) and stereo (orange or light gray) conditions as a function of deadline duration (dashed gray line), showing that speed and accuracy varied with the deadline, as expected. Bars represent standard errors. See the online article for the color version of this figure.

deviate from chance in both conditions for each individual. For some observers (1, 6, and 7), the SATFs were essentially identical in the two conditions. For other observers (2, 5, and 8), the slope of the SATF was clearly shallower in the stereo condition. However, the two SATFs deviated from chance at nearly the same time

for all observers. The average delay parameter among observers (see Figure 5A) was 203 ms for luminance and 209 ms for stereo (bootstrap of the individual differences: $p = .18$, confidence interval [CI] $[-16.6$ ms, 2.1 ms]). Alternatively, fitting SATFs as straight lines in z -score space (see the supplemental materials) gave similar delay values and the same conclusion: a mean difference between the two conditions of 9.9 ms (bootstrap of individual differences: $p = .14$, CI $[-22.0$ ms, 3.1 ms]). Thus, stereo started to affect observers' reports at about the same time as luminance.

The observer means of the time constants for the luminance and the stereo conditions (see Figure 5B) were 37 and 67 ms, respectively, and these are significantly different (bootstrap distribution of the mean of 10 individual differences: $p < .001$).

Within individuals, the delay was significantly different between the two conditions for only one observer (bootstrap estimates: $p < .05$, uncorrected for multiple comparisons). The slope was significantly shallower (higher exponential time constant) for four out of the 10 observers. Thus, most observers had similar delays in the luminance and stereo tasks, but most—though not all—observers required more time to achieve a given level of accuracy in the stereo task than in the luminance task.

In summary, responses deviated from chance at about the same time (200 ms) for discrimination of either stereo or luminance targets.

Discussion

Previous studies have looked at the dynamics of stereoscopic vision behaviorally and physiologically. These studies did not directly address the speed with which depth can be perceived from binocular disparities, but it is important to consider their implications.

Psychophysical studies relate physical characteristics of the stimulus to perception and behavior. In the 19th century, stereopsis was demonstrated using near-instantaneous displays, such as could be made using electrical sparks (Dove, 1841; Hering, 1865; Le Conte, 1897; Panum, 1858; Volkman, 1859; von Helmholtz, 1867). Since then, detailed studies have examined the effects on

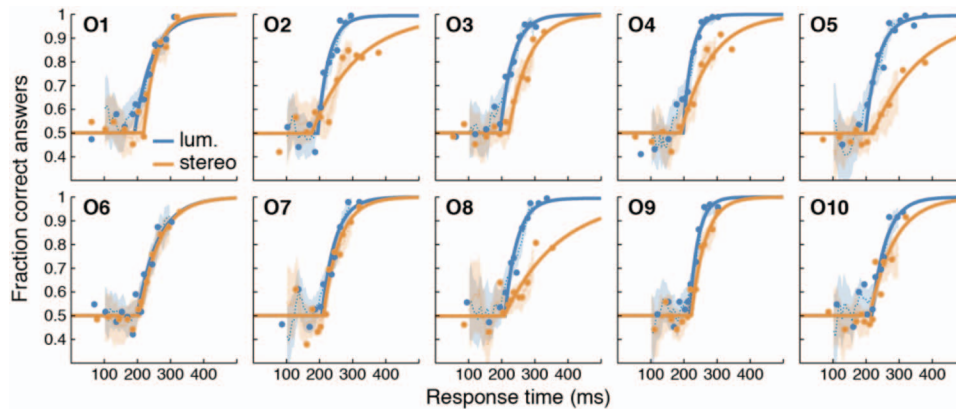


Figure 4. Individual data for the 10 observers (Os). Here, accuracy (fraction correct) is plotted as a function of actual response time. The thick lines are the fitted speed–accuracy trade-off functions for the luminance (lum.; blue or dark gray) and stereo (orange or light gray) conditions. The dashed lines and shaded areas are means and 95% binomial confidence intervals computed within a 20-ms sliding window. Points are mean performance as a function of median response time for binned data. O7 and O9 were authors. See the online article for the color version of this figure.

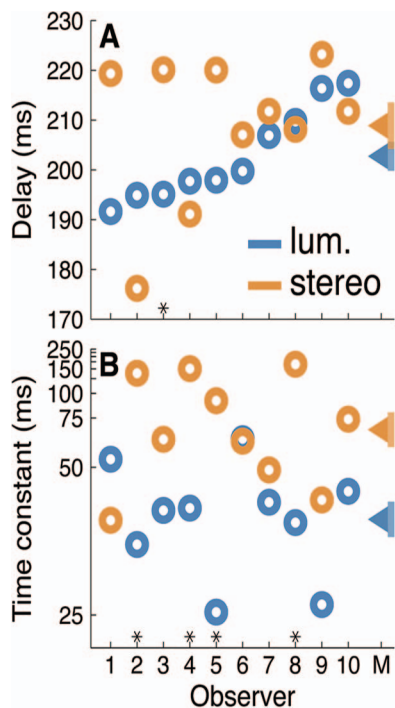


Figure 5. Delay (A) and time constant (B) parameters for each observer for the luminance (lum.; blue or dark gray) and stereo (orange or light gray) conditions. Stars show significant differences between conditions within individuals ($p < .05$, not corrected for multiple comparisons). M = the population mean with standard error. See the online article for the color version of this figure.

stereopsis of display duration (Dove, 1841; Geblewicz & Shen, 1936; Julesz, 1960, 1963; Langlands, 1926), masking (Uttal, Fitzgerald, & Eskin, 1975), interocular delay (Dodwell & Engel, 1963; Efron, 1957; Gheorghiu & Erkelens, 2005; Julesz & White, 1969), and the spatiotemporal properties of dynamic random-dot stereograms (Gheorghiu & Erkelens, 2005; Julesz & Payne, 1968; Julesz & White, 1969). These and subsequent studies showed that the visual system can extract stereoscopic information from transient visual stimuli within about 50 ms, similar to the system for luminance contrast (Breitmeyer & Ögmen, 2006). Electrophysiological evidence from nonhuman primates also shows that cells in primary visual cortex start to respond to disparity at the same time as other visual information (Gonzalez, Perez, Justo, & Bermudez, 2001; Trotter et al., 1996).

Vergence eye movements can be produced very quickly (in as little as 80 ms) in response to a disparity step (Busetini, Fitzgibbon, & Miles, 2001), and in fact they have a shorter initiation latency than saccades (Rashbass & Westheimer, 1961; Robinson, 1966). Reaching studies are mixed: Some show a longer latency for correcting movements when a visual target is perturbed in depth than in azimuth (Brenner & Smeets, 2006; Hu & Knill, 2011), whereas others show similar latencies for stereo and monocular information (Greenwald & Knill, 2009; Greenwald, Knill, & Saunders, 2005). In any case, the visual system could use binocular cues differently for perception and action (Knill, 2005); our focus here is perception.

There are some aspects of stereoscopic processing that are unquestionably slow. Humans cannot perceive depth variations at

frequencies higher than about 10 Hz, versus up to 70 Hz for changes in luminance (Beverley & Regan, 1974; Kane et al., 2014; Lankheet & Lennie, 1996; Norcia & Tyler, 1984; Regan & Beverley, 1973a, 1973b; Richards, 1951, 1972). Other measures of the integration window of the stereoscopic system also show it to be considerably longer than that of the luminance system (Harwerth & Boltz, 1979; Ogle & Weil, 1958; Shortess & Krauskopf, 1961; Tyler, 1991). These data are well explained by a simple cross-correlation model using monocular inputs that are filtered in space and time (Kane et al., 2014; Nienborg et al., 2005). The temporal resolution of the stereoscopic system is poor compared with that of the luminance system.

Neither the fast extraction of disparity nor the low temporal resolution of stereopsis reveals how long it takes to start using disparity for perception. Nor does the fact that apparent depth from disparity builds up over time (Bradshaw, Hibbard, & Gillam, 2002; Gillam, Chambers, & Russo, 1988; van Ee & Erkelens, 1996). Interestingly, Gillam et al. reported “instant” perceived depth in stimuli containing depth edges (disparity discontinuities), as our stimuli did and as most natural stimuli do. However, the stereo shape discrimination task in their study had a mean latency of 5 s or more, so it could not measure the time course of the perceptual response with precision. By measuring the SATF for comparable perceptual tasks on the basis of disparity or luminance, we found that responding begins to deviate from chance at about 200 ms for both tasks, with the majority of observers showing no delay parameter difference (see Figures 4 and 5A). Thus, during stereopsis, the visual system is obliged to integrate binocular-disparity information over relatively long time periods of 70 ms or more (Kane et al., 2014; Nienborg et al., 2005), but it is not required to wait until the end of this integration window to use what information it has.

This accumulation of perceptual evidence also causes responses to be more accurate for long deadlines than for short ones in both tasks. For some but not all of our observers, accumulation occurred more slowly for disparity than for luminance (see Figures 4 and 5B). Thus, for our stimuli, the stereoscopic system was often intrinsically noisier than the luminance system, consistent with prior literature (McKee, Levi, & Bowne, 1990). Our median observer required 291 ms to reach 95% correct in the luminance condition and 372 ms in the disparity condition. Without looking at the full SATFs, one would mistakenly conclude from the average data that a stereoscopic signal takes longer to become available for perception than does a brightness signal.

A different choice of values for the stimulus parameters—such as different disparity magnitudes, luminances, display durations, eccentricities, sizes, and so forth—would surely change the response time distributions. However, it seems unlikely to us that such changes could selectively cause a dramatic increase in the delay parameter for stereopsis, so long as the stimuli were still suprathreshold in both tasks, which would keep both response times short. In other words, we measured difficulty for two tasks using closely matched stimuli; our design does not require equating difficulty for the data to be interpreted as representing a surprisingly fast perceptual response to disparity. Does this fast response depend on using disparities of different signs? Disparity can make an object look near or far without a precise specification of apparent depth (Ogle, 1952; Wilcox & Allison, 2009), which

could be the basis for depth perception here. We cannot yet say how rapidly differences in disparities of the same sign are detected.

The physiological process for stereopsis starts when visual signals reach primary visual cortex (Barlow, Blakemore, & Pettigrew, 1967), where about 80% of cells have firing rates that are modulated by binocular disparity (Poggio & Fischer, 1977). Most areas in visual cortex contain at least some cells selective for binocular disparity (Gonzalez & Perez, 1998; Neri, Bridge, & Heeger, 2004; Parker, 2007), and stereoscopic processing requires many stages (Cumming & Parker, 1997; Janssen, Vogels, Liu, & Orban, 2003). This tremendous expenditure of neural resources is grounds for suspicion that disparity is important in vision. That stereopsis happens quickly means that stereoscopic depth perception can contribute widely during visual perception but also that binocular disparities could contribute to early visual processing more than has generally been appreciated. We have recently shown, for example, that disparity may enhance object recognition through spatial attention and image segmentation (Caziot & Backus, in press). The contribution of disparity to other basic visual abilities besides depth perception—such as image segmentation, contour integration and object recognition—deserves further study.

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