

Spatial scale of stereomotion speed processing

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To examine the spatial scale of the mechanisms supporting the perception of motion in depth defined by binocular cues, we measured stereomotion speed discrimination thresholds as a function of stimulus size using a two-interval speed comparison task. Stimuli were either random dot stereogram (RDS) bars featuring both the changing disparity (CD) and the interocular velocity difference (IOVD) cues to motion in depth or dynamic random dot stereogram (DRDS) bars featuring the CD cue alone. Monocular speed discrimination performance was also assessed, using half-images of the RDS stimulus. In addition, subjects' stereoacuity for stationary versions of the binocular stimuli was measured. Stimuli ranged in vertical extent from 1.25 to 40 min. Sensitivity to speed differences was strongly related to stimulus height for DRDS stimuli. Performance decreased rapidly as stimulus size was reduced, becoming nearly random for heights below 5 min. However, for RDS stimuli, speed discrimination performance declined with reductions in stimulus size at a far slower rate, providing superior performance at every stimulus size used. Monocular performance was superior still for the majority of subjects, yet showed a similar rate of decline to binocular RDS stimuli. We conclude that the spatial resolution of the CD mechanism and its static disparity inputs is, on average, nearly nine times more coarse than the IOVD system and its monocular motion inputs. Static stereoacuity controls show that this finding cannot be explained by differences in the disparity signals available in our RDS and DRDS stimuli.

Keywords: binocular vision, motion in depth, spatial summation, spatial integration

Introduction

In vision research, few topics have received as much research attention as the processing of motion information. Accurate and precise perception of the speed and direction of objects in a complex 3D environment is crucial to the survival of many organisms, particularly for objects that approach or recede from the observer. Though the majority of physiological and psychophysical research has focussed on the processing of frontoparallel motion, recent studies have begun to elucidate the mechanisms processing motion in depth. The visual cues to motion in depth available can be divided into two classes—monocular and binocular—either of which can create a vivid impression of motion in depth in isolation. Here, we focus our attention on binocular, or “stereomotion” cues.

It has been shown that as stimulus size decreases, stereomotion cues become relatively more effective compared to the monocular cue of isotropic expansion (Regan & Beverley, 1979; see also Gray & Regan, 1998). That this monocular cue for motion in depth dominates for larger objects might suggest that stereomotion information is not useful at such scales. Whatever physiological substrates are responsible for the processing of stereomotion might therefore be expected to operate at small spatial scales. However, the spatial scale of stereomotion processing itself has yet to be formally investigated.

To date, no physiological studies have unambiguously identified cells selective for stereomotion in primates. Though Poggio and Talbot (1981) have made such claims,

this finding should be viewed with caution. Maunsell and Van Essen (1983) pointed out that cells can misleadingly appear selective for motion in depth if tested with a family of motion in depth trajectories whose mean disparity was not at the preferred disparity of the cell concerned. Chen, Wang, and Qian (2001) recently formalized this prediction in a modelling study. When stimuli were appropriately controlled, Maunsell and Van Essen found no cells that were genuinely selective for motion in depth.

Studies in humans are necessarily limited to the non-invasive and so can provide little information on receptive field size. However, regional cerebral blood flow (Nagahama et al., 1996) and functional magnetic resonance imaging (Likova, Tyler, & Wade, 2003) studies suggest that the MT/MST complex is heavily involved. Receptive fields in analogous areas of primate cortex are known to have relatively large diameters that increase with eccentricity (e.g., typically 5 deg or more in MT, 30 deg or more in MST; Raiguel et al., 1997).

The recent psychophysical literature on stereomotion has not addressed the issue of spatial scale but has instead centred on a debate over which of two stereomotion cues for binocularly matchable stimuli may be used by the visual system. As a stimulus approaches an observer, its binocular disparity will change relative to other visible binocular features. This is the stereomotion cue of changing disparity (CD). In addition, for natural examples of stereomotion, the monocular images will move at different velocities (different directions and/or speeds) across the two retinæ. This has been referred to as the interocular velocity difference (IOVD) cue. It is now clear that both sources of information

can be used. There is evidence supporting the use of the IOVD cue (Fernandez & Farell, 2005, 2006; Shioiri, Saisho, & Yaguchi, 2000) and the CD cue (Cumming, 1995; Cumming & Parker, 1994) in stereomotion detection. There is also evidence supporting the use of the IOVD cue (Brooks, 2002b) and the CD cue (Portfors-Yeomans & Regan, 1997) in the context of stereomotion trajectory discrimination. For stereomotion speed discrimination tasks, several studies have indicated the importance of the IOVD cue (Brooks, 2001, 2002a; Brooks & Mather, 2000; Brooks & Stone, 2004; Harris & Watamaniuk, 1995), though it is clear that a motion in depth speed signal can still be derived even with the CD cue alone (Brooks & Stone, 2004; Harris & Watamaniuk, 1995).

One method commonly used to isolate the CD mechanism, and exclude the possibility of IOVD processing, is to use dynamic random dot stereograms (DRDSs). When a conventional random dot stereogram (RDS) simulates stereomotion, portions of each monocular image must move at different velocities in order to convey the necessary disparity change, as described above. However, if the elements of the stereogram are all redrawn in a new random configuration on each stereo frame, there will be no coherent monocular motion signals. The disparities still change as before, but with no monocular signals and hence no IOVD cue, stereomotion can only be sensed through the CD cue with this stimulus.

In this study, we systematically investigate the spatial scale of the CD and the IOVD systems using RDS and DRDS stimuli in a stereomotion speed discrimination paradigm. Just noticeable differences for speed were established for stimuli of various vertical dimensions, while holding their horizontal size at the maximum, to avoid the potential influence of half-occluded regions and their associated stereomotion signals (Brooks & Gillam, 2006) and the confound of proximity of such signals to the fovea. We believe that speed discrimination is a task better able to reveal the functioning of a stereomotion system per se, avoiding the possibility that performance is instead mediated by the exquisitely sensitive static disparity mechanisms that may signal a nonzero disparity at any time in a detection task. We used both RDS and DRDS stimuli to allow a comparison of performance using IOVD and CD cues versus the CD cue in isolation. Furthermore, any possibility that the results of these tests are influenced by differences in the visibility or the precision of the disparity signal between the two stimulus types is addressed in a static stereoacuity task using equivalent DRDS or RDS stimuli. We were able to span the entire relevant range of spatial extents from stimulus sizes sufficiently small as to produce performance at or near chance to sizes large enough to reveal asymptotic performance. We then fit the resulting spatial integration curves (i.e., plots of stereomotion sensitivity versus stimulus size) with an exponential function to quantify the spatial scale of the signals used to support the perception of speed in depth from different visual cues, independent

of absolute (asymptotic) performance. To anticipate, we find that the IOVD system provides a much finer resolution measure of speed in depth than the CD system but that speed discrimination was still possible down to stimulus sizes of about 10 min using the CD cue in isolation.

Methods

Stereomotion speed discrimination

Apparatus and stimuli

Stereoscopic stimuli were created by alternately displaying the monocular half-images on an Image Systems 240-Hz monitor (120 Hz per eye) using P46 fast phosphor, driven by a Matrox G400 video card. These were viewed through high-speed (switching time, 50 μ s), high-transmittance (30%) ferroelectric shutter glasses also running at 240 Hz synchronised to the vertical refresh of the monitor. Pilot tests confirmed that at the contrast levels used, there was no perceptible flicker or bleed-through of the unwanted monocular image.

The visible area of the screen subtended 7.3 (horizontal) \times 6.2 (vertical) deg at the viewing distance of 2.5 m. The mean luminance of the screen was 12.5 cd/m², and all tests took place in a room essentially devoid of extraneous light. Responses were recorded from a two-button mouse. Subjects wore their best optical corrections for all experimental sessions. In each stereo half-image, identical background patterns comprised 50% density bright/dark dots at a Michelson contrast of 99.97%, each subtending 1.24 \times 1.85 min (2 pixels square). Each background half-image filled the entire visible area of the screen. These features were in identical positions in each stereo half-image and, hence, were located binocularly in the fixation plane (see Figure 1). Target stimuli were also random dot patterns (same size, density, and contrast as the background), which were centred on the screen, occluding the background image, and extended horizontally to the edges of the image (width, 7.3 deg) in order to minimise and hold constant any effects of motion in depth signals from changing monocular half-occlusion (e.g., Brooks & Gillam, 2006), or stereo from motion-defined boundaries (e.g., Lee, 1970). The height of target stimuli varied between conditions. For RDS stimuli, the monocular half-images moved in opposite directions at a variety of speeds to simulate the appropriate IOVD and CD. The speed of the two monocular half-images in any single stimulus presentation was always equal in order to simulate directly receding motion in depth. Although moving RDS patterns remained unchanged throughout their duration, DRDS stimuli featured an entirely novel random array of binocularly correlated elements at the appropriate disparity in each stereo frame (i.e., at 120 Hz), in order to generate identical CD information without any IOVD. In a previous study (Brooks & Stone, 2004), we used such stimuli to

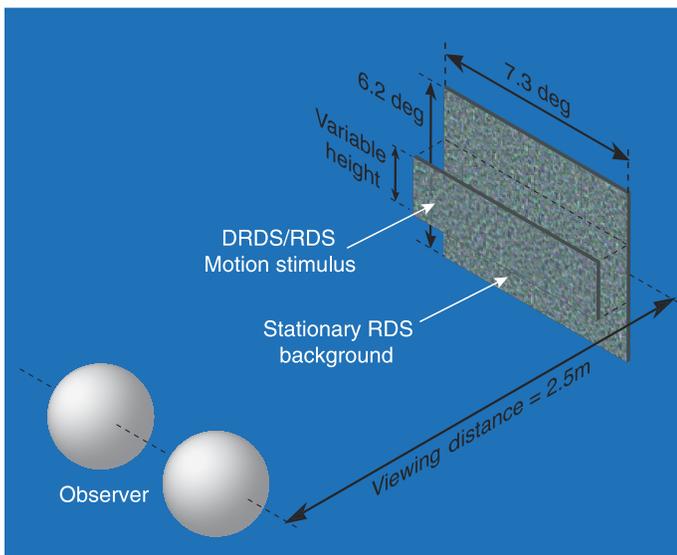


Figure 1. Stimulus presentation details. Figure not to scale. The stimulus configuration is similar to that used in earlier studies of stereomotion perception (see Brooks & Stone, 2004).

show that both CD and IOVD are available to support a true perception of speed in depth (independent of stimulus displacement or duration) and found little difference in performance between receding and approaching stimuli.

Observers

A total of four subjects contributed data, each of whom had normal or corrected-to-normal vision, and passed preliminary screening tests for stereo deficiencies. Except for one subject (the author LS), all subjects were naive as to the purpose of the experiment. Only one subject (DC) was not experienced at performing psychophysical tasks before beginning practice sessions.

Design and procedure

This experiment used an adaptive staircase method to determine the threshold for stereomotion speed discrimination in a two-factor repeated-measures design. The two factors were stimulus type (two levels: RDS or DRDS) and size (six levels: 1.25, 2.5, 5, 10, 20, and 40 min in height).

After extensive practice, subjects completed five or six sessions of testing for each stimulus type. These sessions consisted of three blocks, each of which lasted approximately 15 min. Each block of trials comprised six randomly interleaved up–down staircases (one representing each stimulus size), which were terminated after 12 reversals. We used a “yes–no” procedure, sequentially presenting the subject with a receding standard and test stimulus in random order, and requiring them to indicate in which interval (the first or the second) the stimulus appeared to be faster. The rate of change of disparity of

the standard stimulus was always 0.62 deg/s (for RDS stimuli, this is equal to the difference in monocular velocities). The staircase determined the speed of the test stimulus from a set of nine possible values: 0.25, 0.31, 0.41, 0.5, 0.62, 0.75, 0.83, 0.93, and 1 deg/s. These correspond to motion in depth speeds of 0.6 to 1.56 m/s at the viewing distance used. Test and standard stimuli lasted between 500 and 700 ms, and the midpoint of each stimulus motion in depth was located within a disparity range of ± 6.2 min (both randomised with a uniform probability distribution). The interstimulus interval was 1,500 ms. Though fixation was not formally constrained, subjects were instructed to view the centre of the screen before initiating each trial. Although vergence eye movements could affect the absolute disparity experienced by our observers, they would not alter the relative disparity of the target stimulus with respect to the stationary surround. It has been established that neither changes of absolute disparity nor vergence per se mediate stereoscopic motion in depth perception. Instead, a change of relative disparity appears to be the critical information for disparity-based motion in depth perception (Collewijn, Erkelens, & Regan, 1985; Erkelens & Collewijn, 1985; Regan, Erkelens, & Collewijn, 1986).

Data analysis

Data were analysed for each subject individually. Responses from trials in each of the three blocks within each session were combined, and a cumulative Gaussian curve was fitted to the data by probit analysis (Finney, 1971). This yielded a standard deviation of the underlying cumulative Gaussian distribution for each condition. Since stimuli within each individual trial comparison varied only in terms of their stereomotion speed, the point of subjective equality was assumed to be unbiased, leaving the threshold as the only free parameter in the curve fit. Threshold is defined here as the semi-interquartile difference of the psychometric function for each condition. This was repeated for each session of testing to allow mean thresholds and associated standard errors to be calculated. Sensitivities to differences in stimulus speed were derived, being the reciprocals of these thresholds measured in seconds per degree. Model-independent statistical significance was assessed for each observer using independent-samples ANOVAs and *t* tests (Bonferroni corrected as appropriate). When sensitivity was plotted against stimulus size, two-parameter exponential curves were fit to each data set using a least-squares error-minimisation routine, and differences between intersubject means of curve parameters were sought using paired *t* tests.

Stereoacuity

Methods for stereoacuity tasks were identical to those for stereomotion speed discrimination except in the

following respects. Each trial presented a pair of stationary RDS or DRDS stimuli sequentially. Observers were required to indicate in which of the two intervals the stimulus appeared closer to them. As in the stereomotion speed discrimination task, the disparity of the standard stimulus was displaced by up to ± 6.2 min (randomised with uniform distribution) to lessen the extent to which subjects could use the background dots as an omnipresent reference for the standard stimulus. The staircase determined the relative disparity of the test stimulus compared to the standard from a set of 11 possible values: -10 , -5 , -2.5 , -1.25 , -0.62 , 0 , 0.62 , 1.25 , 2.5 , 5 , and 10 min. After practice, subjects completed five sessions of data collection for each stimulus type.

Monocular/lateral motion speed discrimination

Methods for monocular speed discrimination tasks were identical to those for stereomotion speed discrimination except that subjects wore an eye-patch over their non-dominant eye and made their judgments based on the perceived lateral motion of one monocular half-image of an RDS stimulus.

Results

Stereomotion speed discrimination

The results of stereomotion speed discrimination tasks can be seen in Figure 2, which shows stereomotion speed sensitivity (in seconds per degree)—the reciprocal of threshold—plotted against stimulus size. For ease of

comparison, monocular speed discrimination results are also shown in this figure, with sensitivity expressed in terms of the equivalent stereomotion speeds, despite the fact that in these trials subjects saw only one stereo half-image.

For each subject, and in each condition, performance increases as a function of stimulus size, rising quickly at first, and then reaching relatively more stable values at the largest sizes. Considering the speed discrimination data, RDS sensitivity is always higher than that for DRDS stimuli, except for a single datum, in one subject (CN; size, 20 min). Performance on the monocular task was, in general, superior to that for RDS. For subjects LS, CN, and DC, all sensitivities were higher for monocular data except for a single datum (subject LS at the smallest size). In subject AK, sensitivity was very similar for RDS and monocular stimuli. The above observations from the data plots in Figure 2 are borne out by statistical analysis. A 3×6 independent-samples ANOVA showed a statistically significant effect of stimulus size for all subjects ($p < .0001$). Simple differences were assessed using Fisher's PLSD. RDS sensitivity was significantly higher than that for DRDS in all subjects ($p < .0001$). Performance for monocular stimuli was significantly better than that for RDS stimuli for three observers ($p < .0234$) but not for subject AK.

We observed an improvement in performance when observers were presented with isolated monocular half-images of a binocular motion in depth stimulus. This phenomenon, which has been noted before (Brooks & Stone, 2002; Brooks & Stone, 2006; Harris, McKee, & Watamaniuk, 1998; Harris & Rushton, 2003; Sumnall & Harris, 2000; Tyler, 1971), is referred to as stereomotion suppression. In addition, the superior speed discrimination performance with monocular stimuli over that with RDS

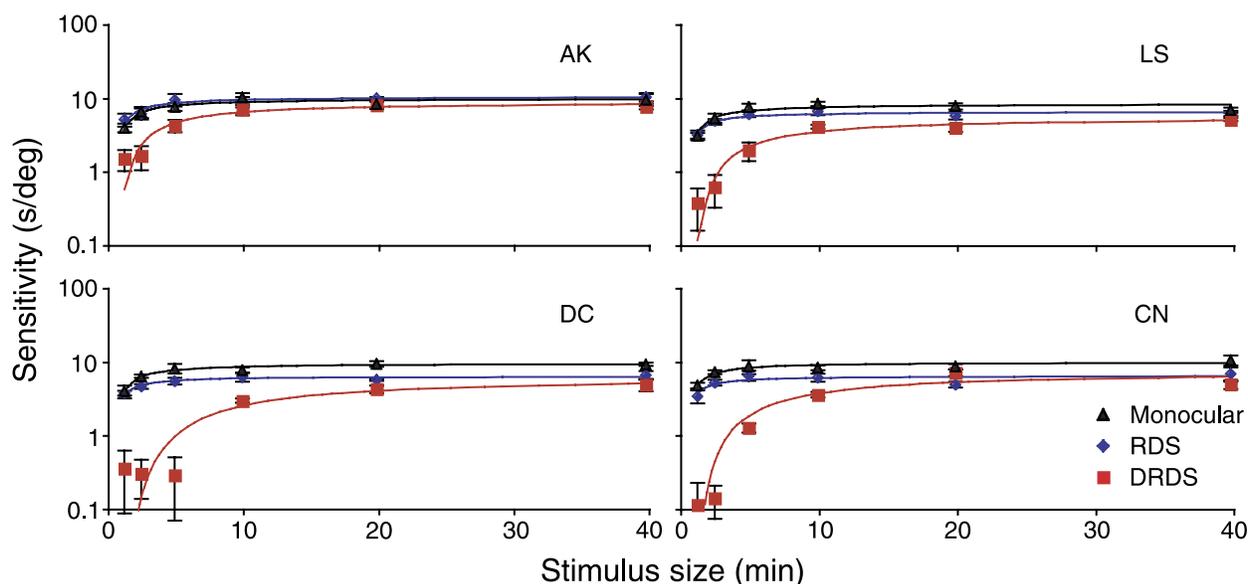


Figure 2. Stereomotion speed discrimination JNDs as a function of stimulus size for all four subjects. Lines show least-squares fits to the data points. Error bars represent ± 1 SEM.

stimuli, for three of our subjects, confirms that these individuals did not simply use the information in one half-image as the basis for their speed discrimination responses (for a detailed discussion of the potential role of monocular cues, see Brooks & Stone, 2004). Furthermore, all of our subjects reported a sensation of motion in depth even at the smallest stimulus sizes for RDS stimuli: a percept that cannot be explained by any monocular cue in our stimuli.

Stereoacuity

In this task, performance again rose as a function of stimulus size, as shown in Figure 3. For three of our subjects, performance for RDS and DRDS stimuli appeared similar, while for DC, a clear difference can be seen between plots, with superior performance for RDS stimuli. Differences in the data were assessed by a 2×6 independent-samples ANOVA. The main effect of stimulus size was again highly significant for all observers ($p \leq .0035$). Only subject DC showed a significant difference between performance for RDS and DRDS stimuli ($p = .0308$).

Curve fitting

Data for all stimuli in both tasks were fit with the following function:

$$\text{Sensitivity} = Ae^{-1/\lambda x},$$

where A represents asymptotic speed discrimination performance, x represents stimulus size, and λ represents

	Stereomotion					
	RDS		DRDS		Monocular	
	A	λ	A	λ	A	λ
AK	10.31	1.03	8.91	0.29	9.71	0.92
LS	6.52	1.25	5.59	0.21	8.23	0.94
CN	6.41	1.52	7.42	0.14	9.71	1.17
DC	6.41	1.42	6.49	0.10	9.38	0.96
Mean	7.41	1.30	7.10	0.19	9.26	1.00
SEM	0.97	0.11	0.71	0.04	0.35	0.06

Table 1. Stereomotion task: A and λ values for each subject.

the rate at which sensitivity rises toward its asymptotic value as size increases (in min^{-1}). Hence, λ (the inverse space constant) is independent of any absolute ordinate value. It is a measure of the spatial extent over which performance improves with increasing stimulus size and can be used to characterize the spatial scale of mechanisms driving performance in each of our tasks. More specifically, at the point where the stimulus extends across $3/\lambda$ (three space constants), performance reaches 72% of its asymptotic value.

For each stimulus type, the best-fitting values of A and λ , determined by a least-squares fit of each individual observer’s data, are shown in Table 1 for stereomotion and Table 2 for stereoacuity tasks, along with means and SEMs. Planned *a priori* significance testing using Bonferroni-corrected t tests was performed across observers to examine the effect of stimulus type on performance within each task and of task within each stimulus type. For stereomotion speed discrimination, t tests failed to find a statistically significant difference in A either between RDS

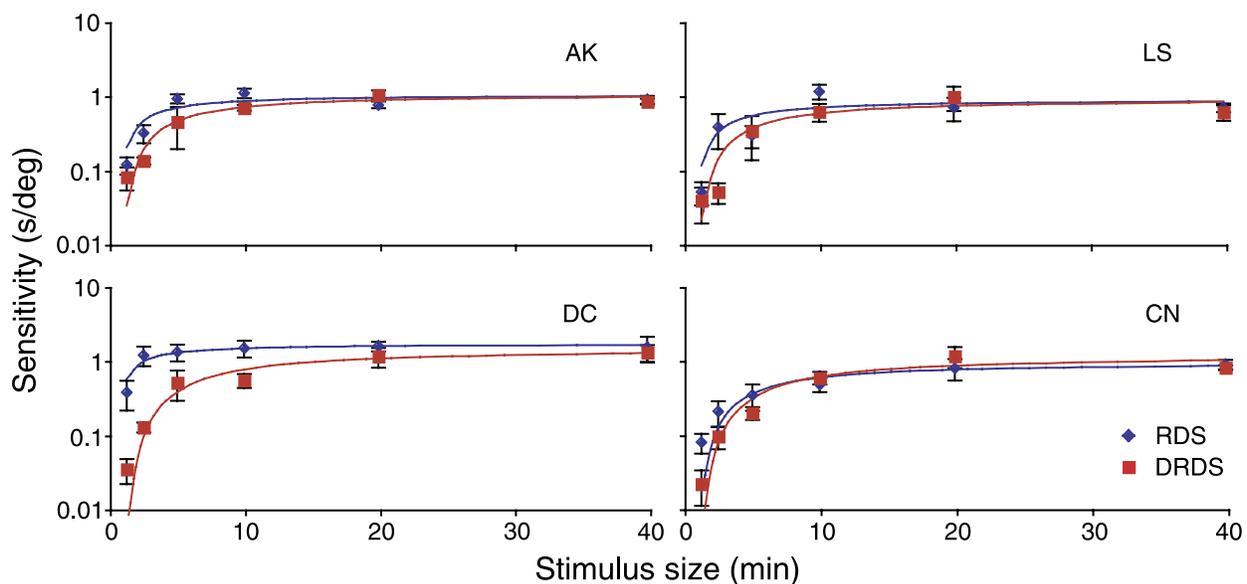


Figure 3. Stereoacuity as a function of stimulus size for all four subjects. Lines show least-squares fits to the data points. Error bars represent ± 1 SEM.

	Stereoaucuity			
	RDS		DRDS	
	A	λ	A	λ
AK	1.06	0.49	1.10	0.23
LS	0.92	0.39	0.94	0.21
CN	0.99	0.20	1.22	0.15
DC	1.70	0.75	1.54	0.06
<i>Mean</i>	1.17	0.46	1.20	0.16
<i>SEM</i>	0.18	0.11	0.13	0.04

Table 2. Stereoaucuity task: A and λ values for each subject.

and DRDS or between RDS and monocular stimuli. However, a significant difference in λ was found between RDS and DRDS ($p = .009$, Bonferroni corrected). Indeed, averaged across observers, the ratio of the DRDS-related λ to the RDS-related λ was 8.6. The difference in λ between RDS and monocular conditions was found to lack statistical significance ($p > .05$, Bonferroni corrected). For stereoaucuity, there was no significant difference in either A or λ between RDS and DRDS, despite the large difference in λ for one observer.

Though performance in the stereomotion and stereoaucuity tasks is necessarily measured in quite different units, preventing any meaningful comparison of absolute performance (including comparisons of A), it is however legitimate and informative to compare λ (the rate at which performance rises to asymptote) across tasks, since both are measured in min^{-1} and are independent of the absolute performance measure. For RDS stimuli, there was a statistically significant difference between the λ of stereoaucuity and of speed discrimination ($p = .016$). For DRDS stimuli, however, there was no significant difference.

Discussion

We found that speed discrimination sensitivity from stereomotion cues varied systematically as a function of stimulus size and that this variation with size was different for stimuli including or lacking the IOVD cue to stereomotion speed. Although speed discrimination performance for RDS stimuli suffers only moderately with a 32-fold decrease in stimulus size, performance for equivalent DRDS stimuli suffers a far more drastic decline. While the IOVD cue allows stimuli subtending only 1.25 min vertically to be perceived and discriminated with moderate precision, this task becomes near impossible for most subjects for stimuli devoid of this cue and smaller than 5 min. Alternatively, while RDS performance seems to asymptote at around 5 min, this does not occur for DRDS stimuli until around 20 min. These observations were confirmed and further quantified by the significantly

higher λ for RDS stimuli. Clearly, the spatial scale of the IOVD system is approximately 9-fold finer than that of the CD system. The finding that stereomotion speed discrimination performance is superior for stimuli that include the IOVD cue compared to stimuli whose motion in depth is signalled by the CD cue alone has been reported previously (Brooks & Stone, 2004; Harris & Watamaniuk, 1995). However, this is the first study to establish this difference over a range of stimulus sizes.

Cumming and Parker (1994) tested the spatial limits of perception using RDS stereomotion stimuli by asking subjects to discriminate between a test interval featuring a disparity-defined grating whose bars moved in opposite directions in depth and a field consisting of the same dots repositioned into random locations. They found a breakdown in performance for bar widths between 6 and 7.5 min. Their finding may appear at odds with ours, given that for our RDS stimuli, speed discrimination was possible even at the size of 1.25 min. However, we do not believe this to be the case. The limit shown by Cumming and Parker refers to the bar width at which subjects can no longer reliably discriminate the display with a regular spatial structure (a vertical square-wave arrangement, defined by differences in stereomotion signals) from one featuring randomly distributed stereomotion dots. In each of their displays, stereomotion could still be perceived, but at the highest spatial frequencies, the stimulus could not be segmented into strips of coherently moving dots. As such, Cumming and Parker's data refer to a spatial limit of scene segmentation based on motion in depth signals as has been described for lateral motion cues as well (e.g., Mestre, Masson, & Stone, 2001) rather than the spatial limit for the perception of stereomotion per se. The detection of stereomotion is clearly possible at even smaller stimulus sizes given that we have shown reasonable speed discrimination performance for RDS stimuli at spatial scales below 5 min of arc.

It would be convenient if a stimulus could be created that contained only a pure IOVD signal with no contribution from the CD mechanism. Attempts to create such stimuli have been made by presenting the subject with two completely independent noise patterns as stereo half-images, hence eliminating any coherent disparity signal for the target dots. The IOVD cue is preserved, since the two images drift horizontally at different velocities. One problem is that such an uncorrelated RDS stimulus can often appear as two rivalrous monocular dot patterns and does not effectively simulate motion in depth. Furthermore, though such a stimulus does not specify a coherent plane with a given disparity, random stereoscopic matches between dots can be made such that the stimulus represents a cloud of dots with various disparities. As the two half-images translate coherently in opposite directions, their various disparities change in unison to produce a CD cue. Shioiri et al. (2000) overcame this problem with the use of very low contrasts in conjunction with a vertical spatial offset, while Brooks

(2002a) introduced a temporal offset and used the stimulus for adaptation rather than as a stereomotion target. In order to avoid these complications, we elected simply to use RDS and DRDS stimuli and draw conclusions from the fact that while RDS stimuli contain two cues to motion in depth (IOVD and CD), DRDS stimuli contain the latter alone.

This raises the possibility that these two independent cues could both work on a similarly crude spatial scale but act in concert within RDS stimuli to allow for higher sensitivity at each stimulus size, compared with DRDS stimuli. Any increase in performance could theoretically be related to differences between the number of cues in RDS and DRDS stimuli as opposed to any inherent differences between the IOVD and CD mechanisms. However, the optimal combination of two equivalent IOVD and CD signals would simply act to reduce thresholds by as much as $\sqrt{2}$ at each stimulus size. This cannot account for the large differences in performance seen at the small stimulus sizes. Furthermore, this kind of simple cue summation would raise the entire curve, which would be reflected in an increase in the parameter A (the asymptote) from our curve fits while leaving λ (the rate at which performance rises toward asymptote) unaffected. We find the opposite pattern of results: a significant difference between λ for RDS and DRDS and no clear difference between A values. The observed data can only be explained by a difference in spatial scale between the IOVD and CD systems.

An observed difference in performance for RDS and DRDS stimuli at each stimulus size could reflect an inherent difference in the strength of the stereomotion signal in each stimulus and be unrelated to the spatial scale of the system processing them. However, a difference in signal strength cannot explain the clear difference in the rate at which the performance curves fall off dramatically for small sizes: a property captured by the difference in λ values. Any difference in signal strength between the stereomotion cues within DRDS and RDS stimuli would again predict different A values and no difference between λ values.

Spatial scale of the IOVD pathway

The fact that the λ for speed discrimination is on average the same for RDS and monocular stimuli suggests that the spatial scale of the IOVD mechanism is limited by monocular motion inputs shared with the lateral motion system. Though it remains possible that the IOVD system could use an entirely independent, specialised set of motion inputs, such a system would have to show fortuitously an identical spatial scale to that shown by the system processing stimuli not moving in depth. Parsimony would encourage us to prefer the former possibility. From our data, which show similar λ values for monocular and RDS stimuli in speed discrimination,

the computation of the IOVD signal does not appear to differentially affect performance for stimuli of different sizes. However, the observation that monocular speed discrimination thresholds are generally lower than their stereomotion counterparts at each stimulus size is consistent with the idea that the computation of an IOVD signal is a process that introduces additional noise (see Brooks & Stone, 2004; Brooks & Stone, 2006).

Consistent with previous studies comparing speed discrimination JNDs for RDS versus DRDS stimuli, all four observers exhibited significantly superior performance (i.e., higher sensitivity) with the RDS stimulus across the range of spatial scales tested confirming earlier studies that used relatively large stimulus sizes (e.g., Brooks & Stone, 2004: 1.3 deg height; Harris & Watamaniuk, 1995: 0.75 deg). It is however noteworthy that no statistically significant difference could be found between the asymptotic performance levels found by curve fitting (see parameter A in Table 1), although three of four observers did show larger values of A for RDS compared to DRDS stimuli. It seems likely that either a deviation in the data from the exponential model and/or the small sample size used here prevented the detection of a significant difference. It is also possible that our use of a smaller dot size than in our previous study (Brooks & Stone, 2004), necessary to accommodate the smaller stimulus sizes used here, also made the difference between speed discrimination performance with RDS and DRDS smaller.

Spatial scale of the CD pathway

The fact that λ is on average the same for DRDS stimuli whether performing a speed discrimination task or a stereoacuity task suggests that the spatial scale of the CD mechanism is limited by disparity inputs shared with the static disparity system. This finding is further reinforced by the fact that the DRDS λ values for stereoacuity and stereomotion tasks are highly correlated across observers ($r^2 = .8433$, $p < .025$). Though it remains possible that the CD system could use an entirely independent, specialised set of disparity inputs, such a system would have to show an identical spatial scale to that shown by the system processing stimuli not moving in depth. Again, parsimony would suggest that this is not the case and that, instead, the disparity inputs to the CD system are indeed those responsible for static disparity discrimination performance. Differentiation of the disparity signal does not appear to further limit performance in terms of scale, since there was no difference between λ values for DRDS stimuli in the stereomotion and stereoacuity tasks.

When considering differences between the performance of RDS and DRDS stimuli, it is important to control for the precision of the disparity signal available in each of these binocular stimuli. It is possible that the temporal modulation of the DRDS stimulus could place additional

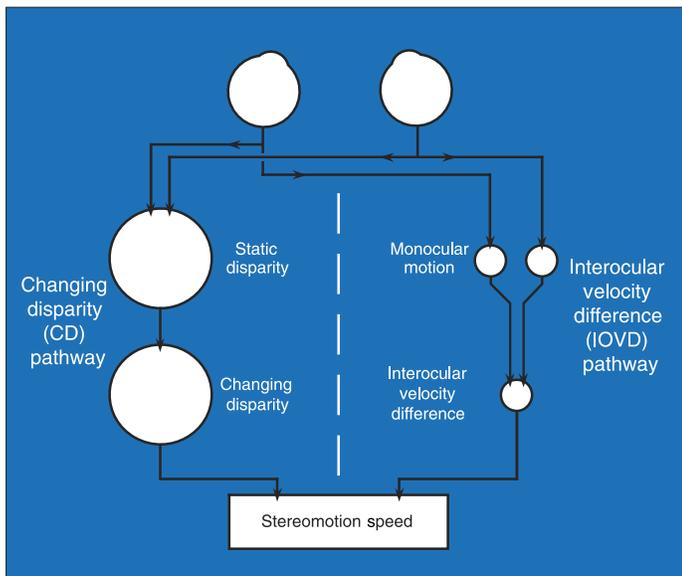


Figure 4. Two stereomotion systems. Processing stages in the changing disparity (CD) and interocular velocity difference (IOVD) pathways are shown, with sizes representing their approximate relative spatial scales. Mechanisms within the static disparity pathway integrate information over an area 8.6 times larger than those within the IOVD pathway. Within each pathway, higher stages of processing appear to be limited by the spatial scale of their input stage, suggesting little additional spatial pooling for the motion in depth computations in either the CD or IOVD pathway.

demands on the disparity estimation process, leading to an impoverished or less precise disparity signal as an input to the CD system. Though the RDS and DRDS stimuli objectively carry the same static disparity signal on any given frame, this signal may not be equally precise when processed by the human visual system. As such, any performance improvement for RDS compared to DRDS stimuli could theoretically be explained by an increase in the precision of the CD signal from an improvement in the underlying disparity signals (see Brooks & Stone, 2004). However, this is not the case in this study. For three of our subjects, no differences could be found when comparing static stereoacuity for RDS and DRDS stimuli across all spatial scales tested, allowing us to be confident in our conclusion that the addition of the IOVD cue was responsible for the performance improvement. For the remaining subject, DC, sensitivities to differences in static disparity were found to be higher for RDS stimuli and also led to a larger λ value for RDS stereoacuity (0.75) than for DRDS stereoacuity (0.06). As with our other subjects, this λ value for DRDS static disparity discrimination is similar to that for the stereomotion task (0.10), supporting the hypothesis that the two tasks use spatially limited information from the same source—a set of tuned relative disparity units. Though RDS and DRDS static disparity inputs may not have been identical for this observer, the

somewhat elevated value of λ for static RDS stimuli is still only approximately half that necessary to fully account for that in the RDS speed discrimination task (1.42). Hence, for all of our observers, the finer spatial scale of speed discrimination performance for RDS stimuli as opposed to DRDS stimuli cannot be explained simply as the result of an improved static disparity input to the CD system for RDS stimuli over that for DRDS stimuli. The finer scale must be due to the introduction of an IOVD cue that works at smaller spatial scales.

It is tempting to speculate that the receptive fields of neurons that limit the encoding of IOVD are much smaller than those that limit the encoding of CD at an equal eccentricity. Though this interpretation may be parsimonious, our data do not allow any firm conclusions about the receptive field sizes of the neurons involved in the processing of IOVD or CD. While we have clearly established that the overall neural mechanism responsible for processing IOVD works on a finer spatial scale than the neural mechanism that processes CD, these two mechanisms could theoretically employ ensembles of neurons with identical receptive field sizes (or indeed, almost any combination of sizes) that nonetheless interact to integrate information across space in different ways as captured by the observed differences in λ . This parameter quantifies the spatial scale of the functional mechanism, not necessarily of the individual neurons that interact to make up that mechanism.

Conclusions

The general findings of this study can be summarised by the model shown in Figure 4. This shows two stereomotion pathways: the CD system on the left and the IOVD system on the right, and is drawn to allow an approximate qualitative comparison of their respective spatial scales. In the IOVD pathway, small monocular (lateral) motion mechanisms feed their velocity signals into a similarly sized IOVD mechanism, where a small amount of additional noise appears to contaminate the signal. In the CD pathway, the processing of static disparity relies on a mechanism with a spatial resolution that is, on average, nearly nine times more coarse. The subsequent stage, where disparity signals are differentiated to reach a rate of change of disparity over time (CD), appears to have similar spatial properties. Thus, our data also show that the dramatically different spatial scales of the IOVD and CD pathways are set by the different spatial scales of their antecedent signals, related to lateral motion speed and disparity, respectively. A parsimonious explanation of our data is that receptive field sizes for foveal stimuli are larger for the neurons that limit performance within the CD system than for those within the IOVD system, though

other explanations remain possible. A more definitive picture can only come from direct single-unit investigations using both DRDS and RDS stimuli controlled appropriately as suggested by Maunsell and Van Essen (1983) in those cortical areas responsible for supporting the perception of motion in depth.

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