Poor visibility of motion in depth is due to early motion averaging

Julie M. Harris [a,*], Simon K. Rushton [b,c]

[a] *Department of Psychology, University of Newcastle upon Tyne, Henry Wellcome Building, Framlington Place, Newcastle NE2 4HH, UK*
[b] *Cambridge Basic Research, Nissan Research and Development Inc., Four Cambridge Center, Cambridge, MA 02142, USA*
[c] *Centre for Vision Research, Computer Science Building, York University, 4700 Keele Street, North York, ON, Canada M3J 1P3*

Abstract

Under a variety of conditions, motion in depth from binocular cues is harder to detect than lateral motion in the frontoparallel plane. This is surprising, as the nasal-temporal motion in the left eye associated with motion in depth is easily detectable, as is the nasal-temporal motion in the right eye. It is only when the two motions are combined in binocular viewing that detection can become difficult. We previously suggested that the visibility of motion-in-depth is low because early stereomotion detectors average left and right retinal motions. For motion in depth, a neural averaging process would produce a motion signal close to zero. Here we tested the averaging hypothesis further. Specifically we asked, could the reduced visibility observed in previous experiments be associated with depth and layout in the stimuli, rather than motion averaging? We used anti-correlated random dot stereograms to show that, despite no depth being perceived, it is still harder to detect motion when it is presented in opposite directions in the two eyes than when motion is presented in the same direction in the two eyes. This suggests that the motion in depth signal is lost due to early motion averaging, rather than due to the presence of noise from the perceived depth patterns in the stimulus.
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1. Introduction

When a distant object moves in a plane fronto-parallel to an observer, left and right eye image (or optic array) motion is identical. For close objects, object movement will result in identical left and right eye image motion when the object moves along the Vieth–Muller circle (a circle passing through the point of convergence and the two eyes, defining zero relative disparity). If an object moves along other trajectories, it generates different left and right eye image motion. The difference between (or ratio of) left and right image velocities provides potentially useful information about the trajectory of an object relative to an observer (Beverley & Regan, 1973).

A good example of the potential usefulness of left/right motion information is for the perception of motion trajectory. Beverley and Regan (1973, 1975) showed that the trajectory of a projectile—its direction of motion-in-depth—can be derived from the ratio of left to right eye object motion. For an object whose initial visual direction is head-centric straight ahead, the direction of its trajectory in depth, β, is given by:

$$\beta = \tan^{-1}\left[\frac{I[(\mathrm{d}\phi_R/\mathrm{d}t)/(\mathrm{d}\phi_L/\mathrm{d}t) + 1]}{2D[(\mathrm{d}\phi_R/\mathrm{d}t)/(\mathrm{d}\phi_L/\mathrm{d}t) - 1]}\right] \quad (1)$$

where $\mathrm{d}\phi_L/\mathrm{d}t$ and $\mathrm{d}\phi_R/\mathrm{d}t$ are the angular speeds of the image of object in the left and right eye respectively, D is the object distance, and I is the interpupillarly separation (Regan, 1993).

Let us consider the hypothesis that the brain has a specialised mechanism for detecting left/right image speed differences or ratios. Is there evidence that supports it? A cursory look at the literature indicates that, if binocular trajectory mechanisms exist, they have very different sensitivities for different trajectory directions. For example, oscillating motion directly towards and away from the nose (z-motion) has poorer temporal resolution than motion along the horizontal horopter (x-motion) (Regan & Beverley, 1973; Tyler, 1971). Correspondingly, measurements of the minimum amount of 3-D motion that can be detected (Dmin), indicate that the visual system is much less sensitive to z-motion than to x-motion (Sumnall & Harris, 2002). Further, when the eyes are presented with equal and opposite motion (as results from an object undergoing z-motion along the

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head's z-axis) detection is poor, but becomes progressively easier as the magnitude of the left and right eye motions begin to differ (Regan & Beverley, 1973; Sumnall & Harris, 2002; Tyler, 1971).

It may be possible to explain different sensitivities of binocular trajectory mechanisms based on different ways of combining monocular motions for x- and z-motion. However, an alternative explanation is that the visual system does not exploit the left/right motion differences to provide information about trajectory and so has no special sensitivity to them. In other words, the visual system may not have independent access to left and right eye motions (it has also been proposed that it does not have independent access to monocular information about visual direction (Ono, 1991; but see Erkelens, 2000)). If the difference between right and left eye motions were not available, z-motion would have to be detected through the use of other visual information.

Before moving on, let us look at what alternative information could be used for perceiving the direction of motion in depth. How can this be done without use of the left/right image motion ratio? An alternative strategy would be to rely on the detection of a different ratio: that of the x-component compared with the z-component of motion, with the change of binocular disparity providing information about the z-component of motion. Now, β can also be expressed as:

$$\beta = \tan^{-1}\left[\frac{I(\mathrm{d}\phi/\mathrm{d}t)}{D(\mathrm{d}\gamma/\mathrm{d}t)}\right] \tag{2}$$

where $\mathrm{d}\phi/\mathrm{d}t$ is the lateral speed of the Cyclopean image of the object (the average of left and right eye speeds) and $\mathrm{d}\gamma/\mathrm{d}t$ is the rate of change of binocular disparity (Cumming & Parker, 1994; Regan, 1993). Portfors and Regan (1997) presented results that favoured the use of Eq. (2) rather than Eq. (1).

So what happens to the left and right image motions? We recently advanced the hypothesis that the brain does not have independent access to right and left eye motions because they are simply averaged locally by binocular motion detectors (Harris, McKee, & Watamaniuk, 1998). Specifically, small motions at similar retinal coordinates in the left and right eye are averaged. What evidence is there in support of this averaging proposal? In a visual search task where a moving target dot is detected amidst a field of stationary distractors with random 3-D positions, z-motion of the target is harder to detect than x-motion (Harris et al., 1998; Sumnall & Harris, 2000), and performance falls as the number of distractors is increased. A mechanism that relied on a change in depth to detect z-motion could detect the target, but performance would fall as the number of distractors was increased, because their static depth would act as noise for the detector.

The results of these studies are incompatible with a sensitivity to left/right image motion differences because

a motion-specific detector should detect a moving target independent of the number of stationary distractors (because they are not moving they do not provide noise for a purely motion-sensitive system). If the left and right eye motions were still independently accessible, then detection for z-motion should be as good as, or better than, x-motion.

Could other effects account for the poor performance in z-motion detection tasks? Our explanation for why a z-motion target could be detected when moving through a plane of dots, but not when moving through a cloud, was that the dots in the cloud provide disparity noise, thus impairing the detection of the target's change of disparity (Harris et al., 1998). But it is possible that the perception of depth in the display could affect performance in other ways. For example, depth and scene layout can affect perceived distance and object location (Coello & Grealy, 1997). Therefore, it is critical to test whether the depth structure of the distractor array masks the change in disparity signal in the simple way that we hypothesised. Our aim here was to tackle this issue by creating a display that had no depth structure but in which we hypothesised that averaging would still occur. The logic was as follows. We created a stimulus in which perceived depth structure was removed. Although removing the depth structure gives no further information about the target dot, it does remove a source of noise in a putative depth detecting mechanism. If such mechanisms represent the limiting stage for the detection of the target motion, we would expect performance to improve when the noise is removed.

We made a binocularly anti-correlated version of our stimulus, in which each dot in the left eye was paired to a dot of opposite contrast polarity in the right eye. Depth is not perceived in dense anti-correlated random dot stereograms, in which each dot in the left eye is partnered by a dot of opposite contrast in the right eye (Cogan, Lomakin, & Rossi, 1993; Cumming, Shapiro, & Parker, 1998; Julesz, 1971). [1] Therefore, depth noise is removed from the stimulus when it is anti-correlated.

However, the stimulus does still in principle contain disparity noise. A disparity detector that responded to all possible disparities in a display, rather than the 'correct' depths would respond strongly to an anti-correlated stereo pair. We know that V1 binocular neurons respond to the disparity in anti-correlated displays and it has been suggested that these neurons do respond to all possible disparities (Cumming & Parker, 1997). Hence disparity noise will be present in early disparity

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[1] For the dot densities used here, our observers did not report any depth perception, despite previous research suggesting that such low densities might support depth perception in anti-correlated displays (Cogan et al., 1993). However, that study used much larger dots than ours. It is possible that dot size as well as density, plays a part in the extent to which anti-correlated displays support depth perception.

detectors. If motion averaging occurs early, perhaps in V1 disparity sensitive mechanisms, then we would expect an anti-correlated stereogram stimulus to continue to provide noise and that *z*-motion would still be harder to detect than *x*-motion.

In the first experiment we compared performance between *x*- and *z*-motion with anti-correlated stimuli. In the second, we tested whether the depth structure in the display had any influence on performance.

2. Experiment 1: Detection of motion in a 3-D cloud of stationary points

The aim of this experiment was to measure detection of a single target moving amidst stationary dots, each of which had a random disparity. We compared performance for motion in binocularly correlated and anti-correlated stereograms, for conditions in which the motion signals were the same in both eyes (*x*-motion perceived in a correlated display) and opposite in the two eyes (*z*-motion perceived in a correlated display).

2.1. Methods

2.1.1. Stimuli

The stimuli were sparse random dot stereograms, generated and presented using a Pentium 200 MHz PC with fast 24 bits/pixel graphics, running at 67 Hz. A pair of stereo half-images were displayed side-by-side on an Eizo 21 inch monochrome display monitor. A modified Wheatstone stereoscope was used to present each eye with a single half-image. Observations took place in a darkened laboratory.

The stimuli were composed of a variable number of stationary bright and dark dots (of luminance 96 cd/m² and 1 cd/m², respectively), presented on a mid grey background (48 cd/m²), each of which had an independent disparity sample added (from a rectangular distribution, ±6 min arc around fixation). In the correlated stimulus, each dot in the left eye was paired with a dot of the same luminance polarity in the right eye (see Fig. 1a). For the correlated stimulus, the stereograms could be fused so that the dots appeared as randomly distributed in depth throughout a notional end-on cylinder, centred on a small bright cross in the fixation plane. In the anti-correlated stimulus, each dot in the left eye was paired with one of opposite polarity in the right eye (see Fig. 1b). It was not possible to fuse the half images and no depth was seen. Observers were instructed to look at the fixation cross in the centre of the display (which was binocularly correlated). Stimuli were presented at 3m, with the half-images each subtending 2° and each bright or dark dot subtending 1 min arc.

On half the presentations, the stimulus also contained a single moving target dot, identical to the stationary
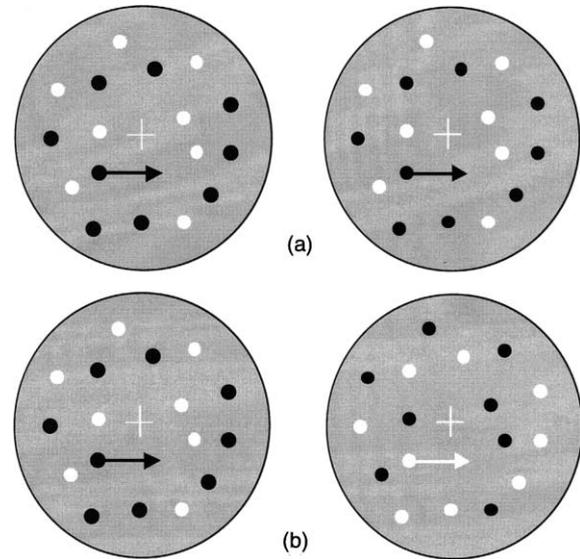

Fig. 1. Schematic showing the form of the visual stimuli. (a) Binocularly correlated displays contained a random pattern of static dots. Each bright (dark) dot in the left eyes image was paired with a bright (dark) dot in the right eye's image. The moving target dot could be bright or dark and was matched with a dot of the same contrast polarity in the other eye. (b) In binocularly anti-correlated displays each bright (dark) dot in the left eye's image was paired with one of opposite contrast polarity in the right eye's image. The moving target dot could be bright or dark and was matched with a dot of the opposite contrast polarity in the other eye.

dots in every way, except that it moved throughout the presentation. The target dot either had the same motion in the left and right eye (corresponding to lateral, or *x*-motion for the correlated stereogram) or opposite motion in the left and right eye (corresponding to motion in depth, or *z*-motion for the correlated stereogram). When anti-correlated stereograms were used the moving target was always of opposite contrast polarity in the two eyes. Note that for anti-correlated stereograms, *z*-motion was never seen. When motion was detected it was perceived as lateral motion.

2.1.2. Observers

Four observers performed the experiments, one of the authors (JMH) and three experienced psychophysical observers who were not aware of the experimental purpose. Observers had normal or corrected-to-normal vision and were experienced in binocular visual experiments.

2.1.3. Psychophysical procedure

A temporal two alternative forced choice procedure was used. On each trial the observer viewed two stimulus intervals (each lasting 1080 ms and separated by an inter-stimulus interval of 540 ms). In one (whose order was chosen at random from trial to trial), only the stationary distractor dots were present. In the other, the moving target dot was also present. The observer's task

was to decide which interval contained the target dot. Note that observers were not asked whether motion was in the x- or z-direction, their task was simply to detect the presence of motion.

Each experimental run consisted of 100 trials and for each run the target moved one of 5 distances over the duration of the trial. For each run we plotted percent correct for detection as a function of the extent of the target motion. We used Probit analysis to fit cumulative normal curves to the data and measured threshold as the 75% point on the fitted function. At least 4, but more usually 6, thresholds were measured for each stimulus condition. Data were collected for several different stimulus configurations, in which we used different numbers of stationary noise points, ranging from 1 to 500.

2.2. Results and discussion

We first measured detection thresholds for x- and z-motion for correlated random dot stereograms (in which depth was perceived) and anti-correlated stereograms (no depth was perceived) as a function of the number of stationary points. Fig. 2a shows data for four subjects using correlated stimuli. Note that the threshold axes are inverted in the data plots. Thus, small thresholds are presented as vertically higher on the graph than larger thresholds.

For all subjects, thresholds were lower for x-motion (black squares) than for z-motion (grey circles), consistent with our previous results (Harris et al., 1998). An analysis of variance conducted on the group data (Fig. 2b) revealed that the two conditions were significantly different ($F_{1,3} = 32.9$ $p < 0.01$).

Fig. 3a shows data for the anti-correlated stimuli. Subjects were more variable in their responses to these stimuli, but in general, thresholds were lower for x-motion (black squares) than for z-motion (grey circles),

despite no depth being perceived in the stimuli. An analysis of variance conducted on the group data (Fig. 3b) revealed that the two conditions were significantly different ($F_{1,3} = 41.1$ $p < 0.01$).

Thus, when the stimuli are binocularly anti-correlated, and no depth is perceived, there is a performance difference between the x- and z-motion conditions. It is harder to detect motion when each eye receives an equal and opposite signal, than when each eye receives the same signal, whether or not depth is perceived in the stimuli. Performance is as predicted from the averaging hypothesis. The absence of depth structure (anti-correlated display) does not change the relative performance difference between the x- and z-motion conditions.

What is responsible for the difference in performance between x- and z-motion? As discussed in the Introduction, the anti-correlated stereogram does not contain perceived depth, thus distractor dots do not act as a source of noise for high level depth detectors. The noise that limits z-motion performance is therefore not at the depth processing stage. Where could the limiting step be? Signals from the right and left eye are first combined in the brain in visual area V1. Disparity processing at this low level does not correspond with what an observer actually perceives (Cumming & Parker, 2000). V1 neurones do respond to anti-correlated stereograms, but with an inverted response to that found with correlated stereograms (Cumming & Parker, 1997). Thus, disparity noise will be present in the visual system at this early stage, when anti-correlated stimuli are used. If disparity noise is still present, and this limits performance in these neurons, our results suggest that z-motion may be detected as a change in disparity by these early disparity sensitive mechanisms.

Although suggestive, the data in this experiment do not prove that the limiting stage is early in depth processing. To check for a possible role for higher depth-sensitive mechanisms, we ran a second experiment in
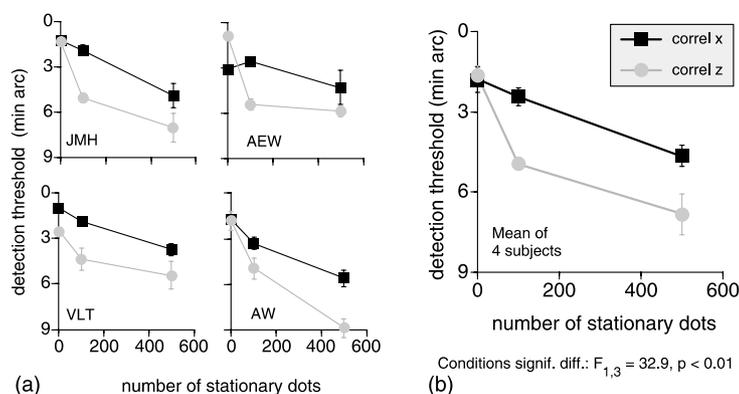

(a)   number of stationary dots

(b)

Conditions signif. diff.: $F_{1,3} = 32.9$, p < 0.01

Fig. 2. (a) Individual observer data plots for the binocularly correlated stimuli, for a comparison of x- and z-motion. Detection threshold was plotted as a function of the number of stationary points. Thresholds were consistently higher for z-motion (grey circles) than for x-motion (black squares). (b) Mean data across subjects for binocularly correlated stimuli. Thresholds for x-motion were significantly different than those for z-motion.
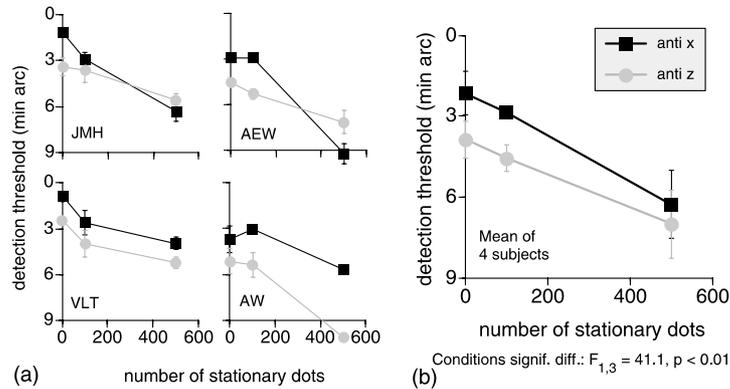
Fig. 3. (a) Individual observer data plots for the binocularly anti-correlated stimuli, for a comparison of *x*- and *z*-motion. Detection threshold was plotted as a function of the number of stationary points. Thresholds were consistently higher for *z*-motion (grey circles) than for *x*-motion (black squares). (b) Mean data across subjects for binocularly correlated stimuli. Thresholds for *x*-motion were significantly different than those for *z*-motion.

which we varied the physical depth structure added to the stimulus. We compared a 3-D anti-correlated cloud with an anti-correlated plane. If the anti-correlated stimulus produces some depth structure that may impair performance in depth mechanisms, then we should find a marked difference between the cloud (potential depth structure) and plane (no potential depth structure) conditions.

3. Experiment 2: Detection of motion for different arrangements of disparity noise

The aim here was to test whether the pattern of disparities of noise dots in the anti-correlated stimuli had any effect on detection of a moving target dot. For correlated stimuli, target *z*-motion is harder to detect when the target moves through noise dots arranged in a cloud than in a plane (Harris et al., 1998). We hypothesised that, in such a stimulus, the change of disparity of the target is masked by the arrangement of the distractors in depth (thus they provide disparity noise). In contrast, when a *z*-motion target moves through a plane, the target is defined by an additional cue, its disparity (it has moved to a position away from the plane of distractor dots). Would a similar performance difference occur when the observer did not perceive the depth structure, in an anti-correlated display? In other words, despite not being able to perceive the depth structure, is detection still more difficult when the dots are arranged in a cloud?

3.1. Methods

3.1.1. Stimuli

As in Experiment 1, the stimuli were sparse random dot stereograms, composed of a variable number of stationary bright and dark dots. Here, there were two possible arrangements of disparities for the noise dots. First, the cloud of dots with an independent disparity sample added from a rectangular distribution, as was used in Experiment 1. Second, all the noise dots were assigned zero disparity, thus they represented a flat surface in the fixation plane. As before we compared performance using binocularly correlated stereograms and anti-correlated stereograms.

In this experiment the target dot always underwent *z*-motion, in other words left and right eye motion signals were equal, but in opposite directions. As before, note that for anti-correlated stereograms, *z*-motion was never perceived, and no depth was seen in the display. It was not possible to perceptually distinguish between the two noise dot arrangements.

3.1.2. Observers and procedure

Three of the four observers who participated in Experiment 1 performed this experiment. The psychophysical procedure was the same as for Experiment 1.

3.2. Results and discussion

Fig. 4a shows detection thresholds for binocularly correlated displays, when the eyes were presented with equal and opposite motion, as a function of the number of stationary noise dots. As expected, for these correlated displays, when the noise dots were arranged in a flat plane (black squares) detection thresholds were very low. The target was easy to detect because it differed from the noise dots in both its motion and disparity during the duration of the trial (Harris et al., 1998). When the target differed from the noise in only its motion (cloud of noise dots, grey circles), detection thresholds were much higher. An analysis of variance performed on the group data (Fig. 4b) shows a significant difference between the conditions ($F_{1,2} = 39.1$ $p < 0.03$).
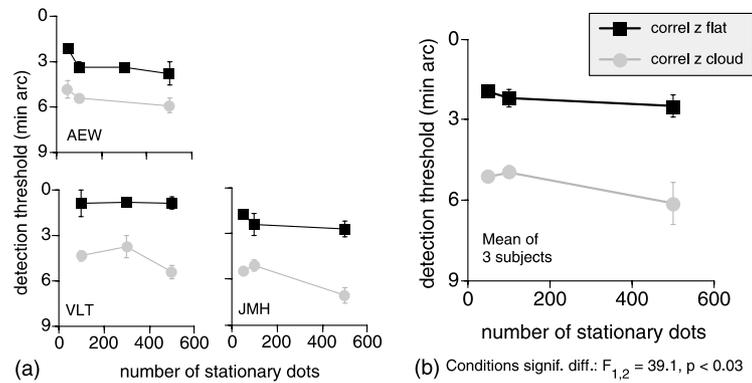
Fig. 4. (a) Individual observer data plots for the binocularly correlated stimuli, for the comparison of a flat plane and cloud of noise dots, with the target undergoing *z*-motion. Detection threshold was plotted as a function of the number of stationary points. Thresholds were consistently higher for the cloud of dots (grey circles) than for a flat plane (black squares). (b) Mean data across subjects for binocularly correlated stimuli. Thresholds for the flat plane and cloud of noise dots were significantly different.
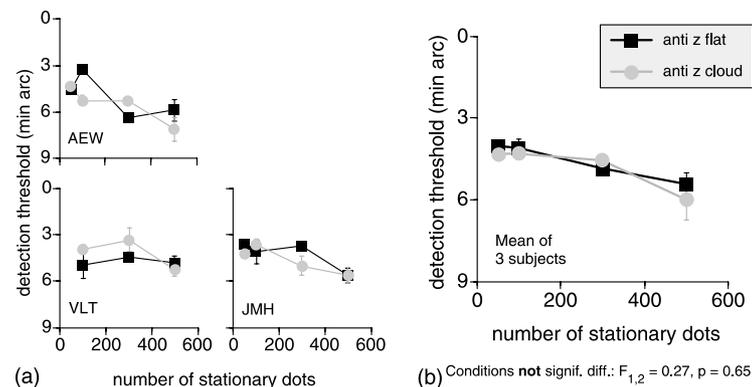

Fig. 5. (a) Individual observer data plots for the binocularly anti-correlated stimuli, for the comparison of a flat plane and cloud of noise dots, with the target undergoing *z*-motion. Detection threshold was plotted as a function of the number of stationary points. Thresholds were very similar for the cloud of dots (grey circles) and the flat plane (black squares). (b) Mean data across subjects for binocularly anti-correlated stimuli. Thresholds for the flat plane and cloud of noise dots were not significantly different.

In contrast, when we measured performance for the anti-correlated stereograms, we found no systematic performance difference between when the noise dots were given disparities specifying a flat plane (black squares), compared with when they specified a cloud (grey circles, Fig. 5a). An analysis of variance on the group data (Fig. 5b) revealed no significant difference between the conditions ($F_{1,2} = 0.27$ $p = 0.65$).

As we predicted, the pattern of physical disparities in the display had no effect on performance for the anti-correlated stimuli. Thus, there is no evidence to suggest that the particular disparities specifying the depth of the noise dots affect performance in any way.

4. General discussion

The first experiment showed that there is a consistent performance difference for detection of motion between a condition when the two eyes receive the same motion, and one where they are presented with equal and opposite motions. This performance difference is observed for both correlated and anti-correlated stereograms, in other words a performance difference is found, regardless of whether depth and motion in depth are perceived. The limiting source of noise for detection must still be present, and as described above, this implicates low level disparity detectors.

In the second experiment, we found that the pattern of binocular disparities had no effect on performance for anti-correlated stimuli, although there was a marked effect, as reported previously, for correlated displays. For these displays, when the pattern specified a flat plane with zero disparity, the target dot was very easy to detect because it differed in both disparity, and motion, from the stationary noise dots. That the physical depth structure was irrelevant in the anti-correlated displays, suggests that performance is limited by early mecha-

nisms that respond to all possible disparities, not by mechanisms that signal depth structure.

4.1. Mechanisms for processing binocular motion

What do these results suggest about the mechanisms responsible for processing binocular motion? Why is *z*-motion harder to detect than *x*-motion, even when no depth is perceived? Thes results are what would be expected if there were no useful mechanisms available to explicitly detect the motion. As we argued in the Introduction, the results are consistent with the idea that binocular motion mechanisms average input from the right and left eye. To reiterate, when opposite direction motion signals are presented to each eye (consistent with *z*-motion), the average is close to zero. Thus, *z*-motion is more likely to be detected by other processes, such as mechanisms that responds to changing disparity. Further, when we consider both experiments together, the results suggest that early binocular mechanisms provide the stage that limits performance for this task.

4.2. Why might averaging occur?

To detect the binocular disparities present in a scene, the visual system must measure the difference between left and right eye images. Averaging would render this difference information unavailable. For static or laterally moving objects, the visual system is extremely sensitive to even tiny binocular image differences. Why would it make sense to average left and right eye signals when an object is moving in depth, and thus lose a potential source of information about *z*-motion? Here we speculate on how motion averaging could be a useful visual adaptation.

The processing of stereoscopic information is thought to proceed in several stages. First, corresponding regions in the left and right eye images must be correctly matched (the correspondence problem, see Julesz, 1971), and then the differences between them are obtained and used to form an appreciation of depth. One way that the correspondence problem can be dealt with is to provisionally accept all possible matches (matching each point in the left eye with each in the right) and then reject those that are incorrect, using rules consistent with the structure of the outside world. For example, Marr and Poggio (1976) implemented the smoothness constraint in their stereo algorithm, which disallows matches that result in very jagged surfaces. Psychophysical data supports the use of this rule by the human visual system (e.g. Harris & Parker, 1994). Other sources of information have also been shown to aid stereomatching by reducing the number of potential matches, including contrast polarity (Harris & Parker, 1995), orientation (Mansfield & Parker, 1993) and importantly motion (Bradshaw & Cumming, 1997; van Ee & Anderson, 2001).

For motion to help solve the correspondence problem, one could imagine a matching rule where potential regions in the left and right eye are binocularly matched if their motions are the same. Thus, the motion of a region would be used as a label, or marker, for matching information from the left and right eyes. Now consider a case where the left and right eyes views are corresponding, but have different motions. When an object moves towards or away from the nose in depth (*z*-motion) there will be approximately equal and opposite motions in the two eyes. An explicit detector for such motion would essentially require very different characteristics to one that aids the correspondence problem. It would ideally be tuned to opposite directions of motion for the two eyes. Whilst there is evidence for neurons in V1 and V2 tuned to similar motions in the left and right eye, only a tiny handful of neurons have been found that have differential interocular motion tuning (Maunsell & van Essen, 1985; Poggio & Talbot, 1981; Spileers, Orban, Gulyas, & Maes, 1990). This suggests that very few of such single unit detectors are present. If disparity detection mechanisms are based on the responses of such neurons, or groups of neurons, this could explain why left and right eye motions are effectively averaged.

What does the visual system do when confronted by interocular motion differences? If disparity sensitive mechanisms are primarily tuned for seeing the *same* motion in the left and right eye, then none will optimally respond when the left and right eye contain different motion signals. The optimal binocular mechanism that will pick up both the left and right eye motion will be one whose direction tuning is close to both of them, in other words if it is tuned for the average of the left and right eye motion signals. In a sense, the population of such binocular units could be thought of as performing an averaging process on the input. Such a process would help reduce noise in the motion input by providing two motion samples, one for each eye's view of the scene. Therefore averaging could occur simply because image matching is a higher priority for the visual system.

This reasoning would suggest that matching for stereopsis is more important than picking up *z*-motion. Further, it infers that there is only one pool of neurons for the detection of motion, and that they are all binocular. Why cannot another population process *z*-motion? The ratio of left/right image motions is not very useful for perception of spatiotopic trajectory. As can be seen from Eq. (1), for a given trajectory, β, the left/right ratio varies as a function of the distance from the observer, and it also varies as a function of the head-centric direction. Thus in the natural world it is probably more efficient to exploit other cues to motion-in-depth such as looming (change in retinal size) and changing disparity.

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