Stereoscopic Motion in Depth

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Abstract

This chapter is a review of stereoscopic processes involved in the perception of motion in depth. We will first discuss mechanisms that could be used to process changing disparity signals to motion in depth. We will then review the evidence, some which has not been published previously, concerning which of these mechanisms is used by the visual system.

Keywords: motion in depth, stereopsis, inter-ocular velocity, dynamic disparity

1 Introduction

In 1997 we were designing experiments to assess the stability of correspondence between points in the two retinas and the phenomenon of stereoscopic hysteresis (Diner & Fender, 1987; Fender & Julesz, 1967). As part of these experiments we presented binocularly uncorrelated random-dot images to the two eyes in a stereoscope. Binocularly uncorrelated images produce a percept of noisy incoherent depth since there is no consistent disparity signal. However, when we moved the images in the two eyes laterally in opposing directions we obtained a compelling sense of coherent motion in depth. When the display was stopped, the stimulus again appeared as noisy depth. We quickly realized that the motion-in-depth percept was consistent with dichoptic motion cues in the stimulus. Thus, a compelling sense of changing depth can be supported by a stimulus that produces no coherent static depth. This was quite surprising since experiments several years earlier had suggested that motion-in-depth perception could be fully explained by changes in disparity between correlated images. Unknown to us, Shioiri and colleagues had made similar findings that they reported at the same ARVO meeting where we first presented our findings (Shioiri, Saisho, & Yaguchi, 1998, 2000) although we found out they had also presented them earlier at a meeting in Japan. We performed a number of experiments on this phenomenon reported as conference abstracts (Allison, Howard, & Howard, 1998; Howard, Allison, & Howard, 1998) that were subsequently cited. However, we have never properly documented these studies since Shioiri et al. had priority. This chapter reviews these studies in terms of their original context and in the light of subsequent research.

2 Visual Cues to Motion in Depth

The principal monocular cues to motion in depth are changing accommodation, image looming, and motion parallax between the moving object and stationary objects.

Binocular cues take three forms:

1. <u>Changing absolute binocular disparity</u> of the images of the moving object. If the eyes fixate the moving object the changing absolute disparity is

replaced by changing vergence. If the eyes are stationary, the disparity produced by the moving object increases as a function of the tangent of the angle of binocular subtense of the moving object.

2. Changing internal binocular disparity The disparity between the different parts of the approaching object increases in accord with the inverse quadratic relation between relative disparity and object distance.

3. Changing relative binocular disparity between the images of the moving object and the images of stationary objects. The relative disparity increases in proportion to the distance between the objects.

We are concerned with motion in depth simulated by changing relative disparity between the images of two random-dot displays presented at a fixed distance in a stereoscope. The observer fixates a stationary marker so there is also changing relative disparity between the fixation point and the display.

There are three ways in which the visual system could, in theory, code changes in relative disparity. They are illustrated schematically in Figure 1 (Cumming & Parker, 1994; Portfors-Yeomans & Regan, 1996; Regan, 1993). First, the change in binocular disparity over time could be registered. We will refer to this as in the 'change-of-disparity' (CD) signal. Secondly, the opposite motion of the images could be registered. We will refer to this as the inter-ocular velocity difference (IOVD) signal.

These coding mechanisms differ in the order in which information is processed. For the CD signal, disparity at each instant is registered first and then the temporal derivative of disparity codes motion in depth. In the IOVD signal, motion of each image is registered first and then the interocular difference in motion codes motion in depth. The IOVD signal can be thought of as dichoptic motion parallax and may access the same mechanism as monocular motion parallax. The third possibility is that motion in depth could be coded by specialised detectors sensitive to changing disparity in the absence of instantaneous disparity signals. How can we dissociate these binocular signals?

Figure 1 about here

Cumming and Parker designed a display for this purpose. In a central region subtending 1.22˚, each dot moved horizontally for 67 ms and was then replaced by a new dot. The cycle was repeated in a temporally staggered fashion with dots in the two eyes moving in opposite directions. The dots were renewed in such a way as to keep the mean disparity within the central region constant. The surrounding random dots were stationary and unchanging. The short lifetime of the dots was beyond the temporal resolution of the system that detects changing disparity but not beyond the resolution of the monocular motion-detection system. Thus, it was claimed that the display contained a detectable difference-of-motion signal but not a detectable change-of-disparity signal. In a second display of oppositely moving dots, the spatial frequency of depth modulation of a random-dot display was beyond the spatial resolution of the stereoscopic system but not of the motion system. Motion in depth was not seen in either display. However, the unchanging disparity may have suppressed impressions of motion in depth. Furthermore, although monocular motion was visible in both displays, the motion thresholds were considerably elevated, perhaps to a point above the threshold for detection of an IOVD in the dichoptic images. One cannot assume that detectable monocular motions necessarily produce a detectable IOVD signal.

The CD signal can be isolated by using a dynamic random-dot stereogram (DRDS) to remove the motion signals, and hence IOVD, but leave the instantaneous disparities. In a DRDS the dot patterns in both eyes are changed on each video frame, so that coherent monocular image motion is not present. At any instant, the dot patterns in the two eyes are the same so that a CD signal or a dynamic-disparity signal can be extracted. Julesz (Julesz, 1971) created such a DRDS successfully depicting a square oscillating in depth. Pong et al. (Pong, Kenner, & Otis, 1990) noted that the impression of motion in depth in a DRDS was similar to that in a stereogram with persisting dot patterns (a conventional random-dot stereogram, RDS). Thus the CD signal alone is *sufficient* to generate motion in depth. Furthermore, Regan and Cumming and Parker

(Cumming & Parker, 1994; Regan, 1993) found that the threshold disparity and temporal-frequency dependence for detection of motion in depth in a DRDS were similar to those of a conventional RDS. They concluded that the IOVD signal provided no additional benefit. Arguing from parsimony, Cumming and Parker proposed that the only effective binocular cue to motion in depth is that of CD based on differentiation of the same disparity signal used to detect static disparity with no need for an IOVD mechanism.

Before accepting this proposal, we need a measure of motion in depth created by only the IOVD signal. In all the above experiments, the same random-dot display was presented to the two eyes—they were spatially correlated. Motion in depth can be created by changing the binocular disparity between motion-defined shapes in a random-dot stereogram in which the dot patterns in the two eyes are uncorrelated (Halpern, 1991; Lee, 1970; Rogers, 1987). This effect demonstrates that spatial correlation of fine texture is not required for disparity-defined motion in depth. However, the motion-defined forms in these displays were visible in each eye's image even when the forms no longer changed in disparity. In other words, the signal generating motion in depth could have been the changing instantaneous disparity between these motion boundaries rather than a pure difference-of-motion signal.

As we show here, motion in depth can be produced by spatially uncorrelated but temporally correlated displays (Allison, et al., 1998; Howard, et al., 1998; found independently by Shioiri, et al., 1998). Our basic stimulus was one in which distinct random-dot displays were presented to each eye and moved coherently in opposite directions. Chance matches between dots in stationary images produce an impression of lacy depth. When the images move in opposite directions the mean disparity of randomly matched dots at any instant remains constant. There is therefore no change in instantaneous mean disparity and therefore no CD signal. It leaves the IOVD signal intact but also a dynamic disparity signal since all sets of randomly paired dots undergo a change in disparity of the same velocity and sign.

3 Motion in depth from spatially uncorrelated images: Effects of velocity and temporal frequency

The experiment reported here demonstrates that motion in depth can be produced by spatially-uncorrelated but temporally-correlated displays and that effective motion in depth can be produced by either the CD signal or by the IOVD signal. In the first experiment we looked at the effects of dot speed and temporal frequency on the percept of motion in depth in spatially uncorrelated moving displays.

3.1 Methods

The left and right eye's images where superimposed in a Wheatstone stereoscope and presented in isolation in an otherwise dark room. A pair of Tektronix 608 oscilloscope displays were located to the left and right of the subject and viewed through mirrors set at ±45° so that they formed a fused dichoptic image that appeared directly in front of the observer. The displays were computer generated from a Macintosh computer video card at a resolution of 640x480x24 at 67 Hz (Quadra 950, Apple Computer Inc., Cupertino, CA). Monochrome left and right images were drawn into separate bit planes of the colour video card (green and red channels). This allowed for perfect synchronization of the timing of the two video signals. Custom raster sweep generator hardware processed the left and right video signals to drive the horizontal and vertical raster position in concert with the luminance modulation of the left and right displays and draw the images. Images were aligned to graticules (1 cm grid spacing with 2 mm markings) overlaid on the display screen and to each other by reference to an identical grid located straight-ahead of the observer at the fixation distance of 33 cm (seen through the semi-silvered stereoscope mirrors). Spatial calibration resulted in a pixel resolution of 1.7 and 1.3 minutes of arc in the horizontal and vertical dimensions, respectively. Pixel size had no relation to disparity as the disparity signals were provided separately as digitally modulated analogue signals. In this experiment a modulated triangle wave signal was added to the horizontal raster sweep causing the displayed images to oscillate to and fro at constant velocity (between alternations). Digital modulation controlled the peak-peak amplitude of the disparity oscillation (or equivalently peak-peak differential displacement for uncorrelated stimuli) by steps of 3.5 seconds of arc over a range of ±2°.

This allowed for precise disparity signals without resorting to sub-pixel positioning techniques. Switching electronics allowed for different disparity oscillations or stationary stimuli in different parts of the display.

In the first experiment we measured the perceived velocity of motion in depth of a spatially uncorrelated test display with respect to the motion in depth of a spatially and temporally correlated display. The two displays were presented one above and the other below a central fixation point with test and comparison positions periodically interchanged (Figure 2). The basic test and comparison patterns subtended 17º wide by 1.75º high and consisted of bright dots randomly distributed at a density of 1.5% on black background. Fixation helped to control vergence which was monitored by nonius lines. In the test display the patterns of dots in the two eyes were independently generated and spatially uncorrelated. Correlated test images were also presented as controls.

Figure 2 about here

The half images of the test display were moved coherently to and fro in opposite directions (in counterphase) to generate an IOVD signal in the test display or an IOVD and a CD signal in the comparison display. In a given trial, the test images moved from side-to-side in counter-phase with a triangular displacement profile with peak-peak relative displacement amplitude of 3.75, 7.5, 15, 30 or 60 minutes of arc at a frequency of 0.2, 0.5, or 1 Hz, which produced alternating segments of constant differential velocity of between 0.75 and 120 arc min/s. The boundaries of each image were stationary (defined by the display bezel) so that there were no moving deletion-accretion boundaries. Since all the dots in each eye's image moved coherently, there were no motion-defined boundaries. The comparison display was the same except that the dot patterns in the two eyes were identical (spatially correlated). On each trial, the images of the comparison display moved at the same frequency as those of the test display and were initially set at a random disparity oscillation amplitude. The subject then used key presses to adjust the velocity of the images of the comparison display until the display appeared to move in depth at the same velocity as the test display. The motion in depth of the two displays was in phase in one set of trials and in counterphase in another set of trials. This was done to ensure that motion in depth of the test display was not due to motion contrast or depth contrast. It also ensured that motion in depth was not due to vergence tracking. We used a velocity-matching procedure because the amplitude of motion in depth of the uncorrelated display was undefined, although, theoretically, the velocity signal could be integrated to produce an impression of depth amplitude.

3.2 Results and discussion

When the correlated images were stopped or presented statically, the display appeared displaced in depth with respect to the fixation point by an amount related to the instantaneous disparity. The stopped uncorrelated display produced an impression of lacy depth because of chance pairings between dots. Thus, at any instant, the disparity between the correlated images was the same for all dot pairs and related to relative image displacement, while the mean signed disparity between the uncorrelated images was always zero. When the dots in the spatially uncorrelated display move, however, all randomly paired images undergo a consistent change in disparity. This leaves the IOVD signal intact. For both types of display, motion in depth was not visible when the rest of the visual field was blank. A fixation point was sufficient to trigger the percept of motion in depth. Fixation on a point ensures that impressions of motion in depth are not generated by vergence movements of the eyes.

The mean results for 10 subjects are shown in Figure 3. It can be seen that the velocity of motion in depth created by the IOVD signal alone is an approximately linear function of the velocity of motion created by both a CD signal and an IOVD signal. This is true for all three frequencies of motion. Regression analysis confirmed a significant main effect of velocity but not of frequency or the interaction between velocity and frequency and a tight relationship between test and matched velocities ($R^2 = 0.912$). The slope of the regression function indicates that the velocity of the uncorrelated images was about 10% higher than that of the correlated images when the two displays appeared to move in depth at the same velocity. In other words, the absence of the change-of-disparity signal from the uncorrelated display did not have much effect on the efficiency of the motion-in-depth signal.

Figure 3 about here

We have already mentioned that Regan, and Cumming and Parker found little loss in sensitivity to motion in depth in a correlated dynamic random-dot display which lacked the IOVD signal. Similarly we found little loss in apparent depth when the CD signal was absent. It thus seems that good motion in depth is produced by either the CD signal or by the IOVD signal.

4 Effects of Density

In this experiment we investigated whether motion in depth of an uncorrelated display varies with dot density. The range of lacy depth experienced in static uncorrelated random-dot stereograms depends on density which could be a factor in motion in depth elicited by moving uncorrelated RDS.

4.1 Methods

The stimuli and methods were the same as in the previous experiment with the following exceptions. On all trials, the uncorrelated test display moved at a velocity of 30 arcmin/s and a frequency of 0.5 Hz. The subject adjusted the velocity of image motion in the comparison correlated display until the velocity of motion in depth of the two displays appeared the same. The dot density of both displays was the same and varied between 0.35 and 50 %.

4.2 Results and Discussion

Figure 4 shows that dot density had no significant effect on the perceived velocity of motion in depth of the uncorrelated display relative to that of the correlated display. As in the previous experiment the matched velocity of the comparison display was a slightly less than that of the test display.

Figure 4 about here

5 Stimulus features

We explored the effects of varying a number of stimulus features including dot size, continuous motion, motion direction and correlation.

In a control experiment, the test display was the same but the comparison display was a dynamic random-dot stereogram in which the dots were spatially correlated but temporally uncorrelated (dot life time of one frame). As in the main experiments, the subject adjusted the velocity of the images in the comparison stimulus until the two displays appeared to move in depth at the same velocity. We thus compared the efficiency of the pure IOVD signal with that of the pure CD signal. In the main experiment, it was unlikely but conceivable that the subjects could have matched the velocity of monocular motion of the images rather than the velocity of perceived motion in depth. They could not adopt this strategy in this control condition because the comparison stimulus contained no coherent monocular motion. Results of the control condition with DRDS comparison stimuli are also shown in Figure 3. There was little difference between matches made with RDS and DRDS comparison displays suggesting subjects were matching apparent motion in depth.

When the triangle wave disparity modulation was replaced with a sawtooth modulation the IOVD specified constant velocity in one direction with periodic abrupt resets. With correlated displays this gave the expected impression of a stimulus that ramped from near to far (or vice versus for ramps of increasing uncrossed disparity) with periodic resets of position in the opposite direction. With uncorrelated displays there was an impression of continuous motion in the direction specified by the IOVD punctuated by a disturbance as the waveform reset.

When we presented a static uncorrelated test display with a single moving dot in place of the comparison display the dot appeared to move in depth for all four observers. Similarly if the dot was stationary and IOVD was imposed on the uncorrelated display, relative motion in depth was perceived. Thus, a textured comparison display was not required and the subject perceived relative motion in depth based on the relative IOVD between the stimuli.

Anticorrelated stimuli do not normally give rise to reliable impressions of stereoscopic depth (Cumming, Shapiro, & Parker, 1998) although thin anticorrelated features can produce an impression of depth (Helmholtz, 1909). Depth from anticorrelated thin features has been attributed to matching of opposite edges of the features in the two eyes, which have the same contrast polarity (e.g., Kaufman & Pitblado, 1969). Cumming et al. (1998) did not find a large effect of dot size on depth from anticorrelated RDSs and claimed that effects of image scaling were due more to element spacing than size. We studied the response to IOVD in 50% density dot-stimuli with large (45 minutes of arc) or small (2.6 minutes of arc) dots in four observers. If the dots in the test display were anticorrelated (opposite sign in the two eyes) rather than uncorrelated, motion in depth was still perceived from IOVD both for both dot sizes. This observation needs careful follow-up but suggests that matching of luminance patches is not required for perception of motion in depth from IOVD and suggests that instantaneous matches of same polarity edges may be made.

Vertical IOVD signals are not related to motion in depth in real world stimuli. We swapped the horizontal and vertical inputs to the displays effectively turning the displays on their sides. This produced vertical disparities and interocular velocity differences. None of nine observers perceived any motion in depth in these conditions. Rather they reported rivalry or up-down motion. This suggests that motion parallax or binocular rivalry effects were not responsible for apparent motion in depth in the main experiment.

6 Lifetime

If the motion in depth in our displays arises from the IOVD signal then the percept of motion in depth should degrade as the motion signal degrades. We degraded the motion signal by shortening the lifetime of individual dots. We measured the minimum dot lifetime required to produce motion in depth of a spatially uncorrelated random-dot display and the effects of reduced dot lifetime on suprathreshold motion-in-depth percepts.

6.1 Methods

The methods were similar to those described in the main experiment with the following exceptions. In this experiment a fraction of the dots disappeared on each frame and were replaced by randomly positioned dots. The replacement rate was controlled so that dots survived for a variable number of frames.

For suprathreshold measurements, motion-in-depth velocity was matched with a temporally and spatially correlated random dot stereogram, as described earlier. The test display had an inter-ocular velocity difference of velocity of either 30 arcmin/s or 15 arcmin/s at 0.5 Hz.

For testing the discrimination of the direction of motion in depth, the test display had a sawtooth interocular velocity difference profile. The comparison display was a stationary random-dot display. The subject reported whether the test display appeared to approach or to recede relative to the stationary display. We used the method of constant stimuli with the ranges tailored to each subject based on pilot testing.

6.2 Results and Discussion

As dot lifetime was reduced, the matched velocity decreased for spatially-uncorrelated displays but not for spatially correlated ones. Figure 5 shows that, for these two representative subjects, perceived depth declined sharply at shorter dot lifetimes for spatially-uncorrelated but not for spatially-correlated test images. The spatially-correlated display created a strong impression of motion in depth when the images were changed on every frame, at a frame rate of 67 Hz. This percept arises from only the CD signal. A spatially-uncorrelated dichoptic display that changed on every frame appeared as a flickering display of dots. Such a display contains neither the CD signal nor the IOVD signal. Figure 5 shows that for these two representative subjects perceived depth declined sharply at shorter dot lifetimes for spatially uncorrelated but not for correlated test images.

Figure 5 about here

Motion-in-depth discrimination thresholds were also obtained. Figure 6 shows a typical psychometric function. The black circles and solid line show percent correct and a probit fit for motion-in-depth discrimination versus lifetime. When the spatially uncorrelated display was refreshed on each frame performance was at chance, which corresponds to the loss of the motion signal. Performance increased with increasing dot lifetime. 75% correct performance is achieved by about a 40 ms dot lifetime. The crosses and dashed line show the psychometric function for binocular discrimination of left-right lateral motion in the same subject with the same displays when both half images moved in the same direction. It can be seen that 75% correct performance is achieved at approximately the same dot lifetime.

To reach a 75% discrimination threshold our 6 subjects required dot lifetimes of between 2 and 5 frames. Reliable thresholds could not be obtained for a seventh subject. Across the six subjects the thresholds for discrimination of motion in depth and lateral motion were not significantly different for these spatially uncorrelated dichoptic displays (Table 1). On average, a dot lifetime of 52 ms was required for the discrimination of motion in depth. According to Cumming and Parker this stimulus duration should be too short for the system that detects changing disparity but not too short for the motion-detection system. If so then our results demonstrate the existence of an IOVD signal.

Figure 6, Table 1 about here

7 Segregated Stimuli

Dynamic disparity requires matchable features in the two eye’s images. Non-matching moving half images should not produce motion in depth. In this experiment the spatially uncorrelated random-dot display was broken up into strips. The strips in one eye alternated with those in the other eye. Shioiri et al. (2000) observed motion in depth in a spatially uncorrelated display in which the left- and right-eye images were segregated into thin alternating horizontal bands. The display was presented for only 120 ms to prevent subjects fusing the stripes by vertical vergence. They concluded that this effect is due to interocular differences of image motion. However, there would also be shear disparity signals along the boundaries, which may have created motion in depth. We had found that motion in depth was not obtained in such displays when two alternating bands were separated by horizontal lines (Howard, et al., 1998). The horizontal lines acted as a vergence lock as well as a separator so that subjects could observe the display for longer periods. We conducted an experiment in order to try to determine the conditions necessary to perceive depth in vertically segregated displays.

7.1 Methods

The basic stimulus was as in the earlier experiments except for the addition of horizontal lines intended to assist in the maintenance of vertical vergence (Figure 7). The test image was divided into strips of dots, which alternated between the eyes. The strips were either abutting or separated by a dichoptic horizontal line. The lines provided a lock for vertical vergence so that subjects could observe the display for long periods without fusion of the left- and right-eye images. The lines also separated the moving dots so that spurious shear-disparity signals would be weakened or absent. Strip width was varied from between four and 40 pixels per strip (Figure 8).

Figure 7 and Figure 8 about here

7.2 Results and Discussion

Figure 9 shows matched velocity as a proportion of the stimulus velocity as a function of strip width. As strip width was increased, perceived motion in depth deteriorated and switched to a percept of simple shearing of strips of dots against each other. Motion in depth in these displays could arise from the ‘direct’ registration of dynamic disparity from spurious pairings of dots along the abutting edges. This spurious signal would be strengthened as the strip size decreased and the number of abutting edges increased. There was also a weak indication that motion in depth was stronger if the strips abutted rather than being separated by lines. The lines separating the strips retained the relative motion between the strips but weakened or eliminated spurious disparity signals. The fact that motion in depth still occurred with strips separated by lines demonstrates that spurious matches along the borders cannot fully explain the percept of depth in these displays (however, there is considerable tolerance for vertical disparity in human stereopsis, see Fukuda, Wilcox, Allison, & Howard, 2009).

Figure 9 about here

8 General Discussion

The binocular images of an approaching object to move in opposite directions. Their relative image velocity is determined by approach velocity and the ratio of velocities in the two eyes is determined by the point of impact within the observer's frontal plane (Regan 1993; Portfors-Yeomans and Regan 1996). The binocular signals can differ in the order in which information is processed. For the CD signal, disparity at each instant is coded and changes in disparity code motion in depth. In the IOVD signal, motion of each image is detected and the differences codes motion in depth. Alternatively, motion in depth could be generated by specialized detectors sensitive to changing disparity in the absence of instantaneous disparity signals.

In a DRDS, images are correlated spatially but not over time. There is no coherent motion of monocular images in such a display, so that motion in depth must be detected by a pure CD signal. This signal involves detection of moment-to-moment disparity and then extraction of CD by a process of differentiation. As is well known, DRDS displays do not eliminate motion energy but make it incoherent. Thus, as Harris, Nefs & Grafton (2008) point out, IOVD signals are still present in these displays but they do not signal consistent motion in depth.

We found that a sensation of motion in depth can be created by spatially-uncorrelated but temporally-correlated dichoptic images moving in opposite directions. Such a display has no change in mean disparity but produces a consistent IOVD signal. Effects of variation of dot density, dot lifetime, stimulus velocity, and oscillation frequency were studied. All subjects perceived strong motion in depth in the uncorrelated display with many variants of the basic stimulus. No consistent impression of depth was obtained when the motion was stopped. Thus, dynamic depth can be created by changing disparity in a display with zero mean instantaneous disparity.

To control for effects of vergence eye movements, we used a display where dichoptic random-dot fields above and below a fixation point were given opposite IOVD (so that one field appeared to recede as the other approached). In a recent review, Harris et al. (2008) noted that other studies have also used such a configuration. They wondered whether two opposing IOVD signals are necessary to produce a robust perception of motion-in-depth with spatially uncorrelated RDS. However, we produced strong motion in depth in a single spatially uncorrelated RDS with respect to a stationary dot.

Two mechanisms could produce motion in depth in a spatially uncorrelated display. First, the effect could depend on a pure IOVD signal derived from an initial registration of motion in each image. Second, the effect could depend on a mechanism sensitive to a consistent sign of changing disparity between randomly paired dots in the absence of coherent instantaneous disparity signals. This implies persistence in the binocular matching process. In either case the results imply sensitivity to changing disparity without reliance on a consistent static disparity signal.

8.1 Comparison of monocular motion signals

Several lines of evidence favour the existence of a true IOVD mechanism based on monocular motion signals (for recent reviews see Harris, et al., 2008; Regan & Gray, 2009).

8.1.1 Isolation of IOVD cues

Like Shioiri et al. (2000), we have shown that motion in depth can be produced by dichoptic motion in stimuli that are not binocularly superimposed. It is difficult to draw firm conclusions from experiments in which the right- and left-eye images are vertically segregated. Motion in depth in natural scenes involves relative motion of binocularly superimposed images, except in cases of monocular occlusion (Brooks & Gillam, 2007). Motion in depth with segregated images may arise from direct registration of changing disparity in spurious matches along the adjacent image bands. However,our results for bands separated by horizontal lines suggest this may not be the whole story.

Similarly, temporal segregation can be used to stimulate motion sensitive mechanisms in each eye without presenting disparity. We attempted to isolate the effects of IOVD by use of negative motion after-effects (MAE). The logic was that if oppositely directed monocular MAEs were induced in each eye they would combine during subsequent viewing of a stationary binocular stimulus to produce a negative IOVD aftereffect. Initially we could not get the robust negative MAE in depth despite robust monocular MAE. Rather than use negative aftereffects, Brooks (2002a) showed that simultaneous or sequential adaptation of each eye to a moving random-dot display reduced the perceived velocity of motion in depth produced by spatially-uncorrelated images. This appears to be evidence for a pure IOVD mechanism. However, in the critical condition in these experiments, periods of left-eye and right-eye adaptation were alternated temporally. Although left- and right-eye images were not presented simultaneously, it is well established that the visual system integrates disparity signals over time. It is thus possible that CD mechanisms adapted during this period. Even so, one would expect a reduction in the aftereffect for sequential compared to simultaneous adaptation but this was not the case. Later we obtained weak but reliable negative MAE in depth following adaptation to correlated or uncorrelated random-element stereograms moving in depth (Sakano & Allison, 2007; Sakano, Allison, & Howard, 2005; Sakano, Allison, Howard, & Sadr, 2006). However, we could not obtain negative after-effects to motion-in-depth from DRDS stimuli when effects of disparity adaptation were controlled. This finding suggests that pure CD mechanisms do not adapt significantly for constant-velocity stimuli. However, Regan et al. (1998) reported decreased sensitivity to motion in depth oscillations following adaptation to DRDS oscillations so it is possible that CD adaptation could have produced some MAE in the Brooks experiments. Further support for a role of IOVD in perception of motion in depth comes from demonstrations of effects on perceived three-dimensional trajectory of motion in depth following adaptation to monocular motion (Brooks, 2002b; Shioiri, Kakehi, Tashiro, & Yaguchi, 2003) Thus, overall, adaptation evidence suggests the existence of a true IOVD mechanism not dependent on binocular matching although these effects appear variable and relatively weak.

8.1.2 IOVD enhancement of motion in depth

If IOVD mechanisms contribute to perception of motion in depth, then one might expect improved performance with stimuli containing both IOVD and CD compared to those with only CD (see discussion of Cumming & Parker, 1994; Regan, 1993 in the introduction). Brooks and Stone (2004) found that the motion-in-depth speed-discrimination threshold for a DRDS, which contained only the CD signal, was 1.7 times higher than the threshold for a regular RDS, which contained both CD and IOVD signals. Thus, they concluded that the IOVD signal supplements the CD signal. However, Portfors-Yeomans & Regan (1996) found motion-in-depth speed discrimination for RDS stimuli with both CD and IOVD signals was no better than that for DRDS stimuli with only CD. Also, Gray & Regan (1996) found no advantage for detection of motion in depth. Regan & Gray (2009) noted that these null results do not rule out a small contribution of IOVD. They also suggested that the contribution of IOVD mechanisms may differ for suprathreshold speed discrimination compared to motion in depth detections (see also Harris & Watamaniuk, 1995).

8.1.3 Comparison of stereomotion and lateral motion

Another line of evidence for existence of IOVD mechanisms arises from comparison of the properties of stereomotion with those of static stereopsis and lateral motion. Such comparisons have been made for judgements including search (Harris, McKee, & Watamaniuk, 1998), detection (Gray & Regan, 1996), apparent magnitude (Brooks & Stone, 2006b), and speed or direction discrimination (Brooks & Stone, 2004; Fernandez & Farell, 2005; Harris & Watamaniuk, 1995; Portfors-Yeomans & Regan, 1997) as well as for effects of eccentricity (Brooks & Mather, 2000), spatial and/or temporal frequency (Lages, Mamassian, & Graf, 2003; Shioiri, Kakehi, Tashiro, & Yaguchi, 2009), direction (Brooks & Stone, 2006b), velocity, scale (Brooks & Stone, 2006a), contrast (Blakemore & Snowden, 1999; Brooks, 2001), and other stimulus parameters.

The logic is that if IOVD mechanisms exist, they should reflect the properties of motion mechanisms rather than of static disparity mechanisms. For instance, lateral motion discrimination degrades with increasing retinal eccentricity. Therefore, if motion in depth is coded by IOVD, then motion-in-depth discrimination should also deteriorate with increasing eccentricity. Brooks and Mather (2000) found that speed discrimination for lateral motion and for motion in depth were affected in the same way when the stimulus was moved 4˚ from the fovea. Discrimination of stationary depth intervals was not affected. Brooks and Mather concluded that IOVD signals are involved in the detection of motion in depth (see Harris, et al., 2008; Regan & Gray, 2009 for recent review of studies comparing lateral motion with motion in depth).

These types of conclusions are predicated on the idea that, if motion in depth processing resembles lateral-motion processing more than static-disparity processing, then the motion in depth mechanisms are most likely based on monocular motion processing. Processing of changing disparity is subject to many of the same ecological considerations as lateral motion processing and it is conceivable that it could develop properties distinct from static-disparity processing but similar to lateral-motion processing.

8.1.4 Selective deficits or limitations

The case for specialised mechanism for motion in depth is most convincing when stereomotion is possible with stimuli that do not support static stereopsis. In this chapter we report that the impression of motion in depth required a dot lifetime of only about 50 ms. Cumming and Parker have argued that this is below the temporal limits of disparity processing but not too short for motion processing. If their logic is correct then this result supports the pure 'IOVD' hypothesis.

Similarly, selective deficits in either stereomotion perception or in static stereopsis provide evidence that a distinct functional mechanism exists (Richards & Regan, 1973). Recently, Watanabe et al. (2008) found several strabismic subjects who were sensitive to stereomotion but not static stereopsis, although a role for eye movements cannot be ruled out as fixation was not controlled.

8.1.5 Summary

Robust motion in depth perception with spatially-uncorrelated displays, as reported in this chapter, provide strong evidence for mechanisms sensitive to dynamic disparity. Similarly, selective deficits or limitations in static stereopsis, in the face of preserved stereomotion perception, provide evidence for dynamic disparity mechanisms that do not rely on static disparity processing. However, neither line of evidence requires a true IOVD mechanism as in Figure 1. Similarity of lateral motion and stereomotion perception may reflect either an underlying common substrate or similar ecological constraints. The influence of spatially or temporally segregated monocular motion signals on stereomotion perception suggests the existence of a true IOVD mechanism not dependent on binocular matching. However, these effects are variable and relatively weak and it is difficult to truly segregate the inputs.

8.2 Dynamic disparity

Normally, IOVD cues to motion in depth are associated with binocularly paired elements. While evidence reviewed above suggests that unmatched, opposite monocular motion signals may produce motion in depth, an IOVD in a binocularly matched element should produce stronger evidence of motion in depth. We propose that the robust impression of motion in depth in uncorrelated RDS with IOVD might arise more from the consistent sign of changing disparity between randomly paired dots—a dynamic disparity signal. If matching of dots at one instant is influenced by previous matches, then this should provide a coherent motion-in-depth signal from changing disparity. Perception of coherent motion from incoherent disparity signals suggests that binocular matches persist over time and that the changing disparity of a matched feature can be tracked. Thus, even though an uncorrelated RDS appears as an incoherent volume of random depths, each consistently matched pair undergoes coherent change in disparity.

Mechanisms or channels that are selective for both binocular correspondence and interocular velocity difference (and perhaps oscillation frequency or rate of change of disparity) could detect dynamic disparity. Such mechanisms would still rely on binocular pairing of dots but may differ from mechanisms that process static stereopsis. These mechanisms would have evolved under many of the same constraints as lateral motion perception, which may explain why lateral motion and motion-in-depth perception share many common properties. These common properties may also reflect a common neurophysiological substrate without the need for postulating pure CD or IOVD mechanisms. A disparity detector with appropriate spatio-temporal tuning could be sensitive to a preferred change in disparity over time. This is consistent with the known physiology of disparity detection in early vision. Disparity sensitive cells in V1, V2 and MT are jointly sensitive to disparity and motion. This spatio-temporal filtering could provide a substrate for processing changing binocular disparity without an explicit IOVD or CD mechanism. However, to our knowledge the required differences in interocular tuning for motion in cells sensitive to disparity have not been reported.

It is also possible, perhaps likely, that dynamic disparity detectors rely on coarsely matched features. There is compelling evidence that a coarse, transient mechanism guides vergence eye movements and enables transient stereopsis (for a recent review see Wilcox & Allison, 2009). This mechanisms does not require precise matching of binocular features. Stereomotion analogues of this transient mechanism could produce motion in depth from spatially or temporally segregated stimuli. Such mechanisms would permit short-latency responses to rapidly moving objects.

On the other hand, sustained stereoscopic mechanisms rely on precise binocular matching. Stereomotion analogues of these mechanisms would serve the perception and tracking of stereoscopically matched, slowly moving objects. Such sustained and transient stereomotion mechanisms would have complementary functions. Such a functional dichotomy may also help explain apparently conflicting results obtained with different tasks and with supratheshold versus near threshold motion in depth stimuli (Harris & Watamaniuk, 1995; Regan & Gray, 2009).

Acknowledgements

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Table Captions

Table 1 – Dot lifetime thresholds for discriminating the direction of lateral motion and motion in depth. The threshold was the lifetime required to obtain 75% correct discrimination performance as estimated from probit fits to the psychometric functions.

Figure Captions

Figure 1 Motion in depth mechanisms. The ‘Change of Disparity’ operates on the disparity signal (i.e., in the cyclopean domain) to signal changing disparity. The ‘Difference of Velocity’ detector detects a pure inter-ocular velocity difference between monocular motion detectors. The ‘Dynamic Disparity Detector’ is directly sensitive to changing disparity in binocularly matched features.

Figure 2 Basic stimulus arrangement. The observer fixated the binocularly visible dot in the centre of the stimulus and monitored fixation via adjacent Nonius lines (the left eye sees one line and the right eye sees the other). In one half of the stimulus (top in this example) was the test display moving in opposite directions in the two eyes at a given frequency and velocity. For experiments using matching tasks, the oscillation of the correlated comparison image (bottom in this example) was adjusted by the observer to match the motion in depth of the test stimulus.

Figure 3 Matching between spatially uncorrelated and correlated motion in depth displays as a function of the frequency and velocity of the test display (N=10). Data shows the average velocity (± s.e.m.) of a spatially correlated comparison display that was set to match the apparent velocity of motion in depth of the spatially uncorrelated, temporally correlated test display.

Figure 4 Effects of stimulus density (N=5). The uncorrelated test display moved at a velocity of 30 minutes of arc/s and a frequency of 0.5 Hz.

Figure 5 Matching efficiency (proportion of matched velocity to test velocity) as a function of dot lifetime for spatially correlated and uncorrelated displays. Representative results from two observers are shown.

Figure 6 Lifetime thresholds for a typical observer. Smooth curves show a probit fit to the psychometric functions.

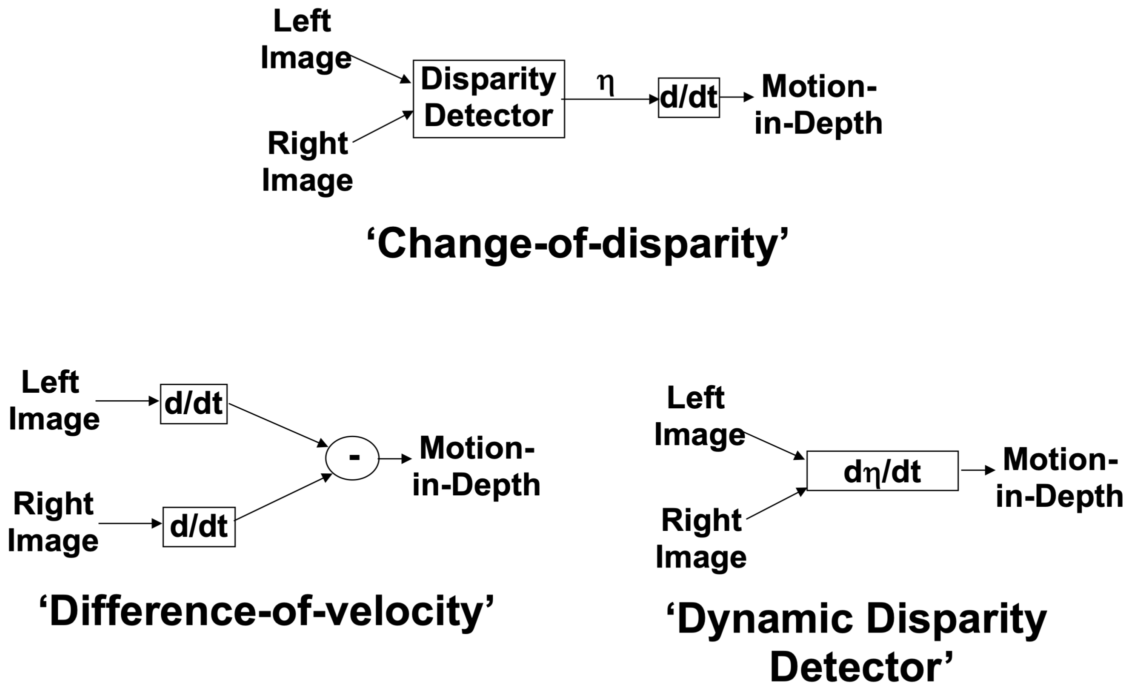
Figure 7 Stimulus for study of effects of IOVD in segregated uncorrelated RDS. The displays are similar to those in Figure 2 except that the test display is segregated into horizontal bands of exclusively left or right eye dots.

Figure 8 Schematic of the vertically segregated display. Right and left eye dots were presented in alternating strips as shown either abutting or separated by a dichoptic line (shown as stippled lines in the figure).

Figure 9 Segregation results (N=8). Matching efficiency for displays where the left and right eye images are vertically segregated into strips is shown as a function of strip width for both abutting strips and strips separated by horizontal lines.

SUBJECT	THRESHOLD (ms)	
	Motion in Depth	Lateral Motion
1	36.1	37.5
2	67.0	54.3
3	45.5	39.9
4	48.7	19.7
5	38.4	42.4
6	76.4	52.8
Mean ± sem	**52.0 ± 5.8**	**41.1 ± 5.1**

Table 1 – Dot lifetime thresholds for discriminating the direction of lateral motion and motion in depth. The threshold was the lifetime required to obtain 75% correct discrimination performance as estimated from probit fits to the psychometric functions.



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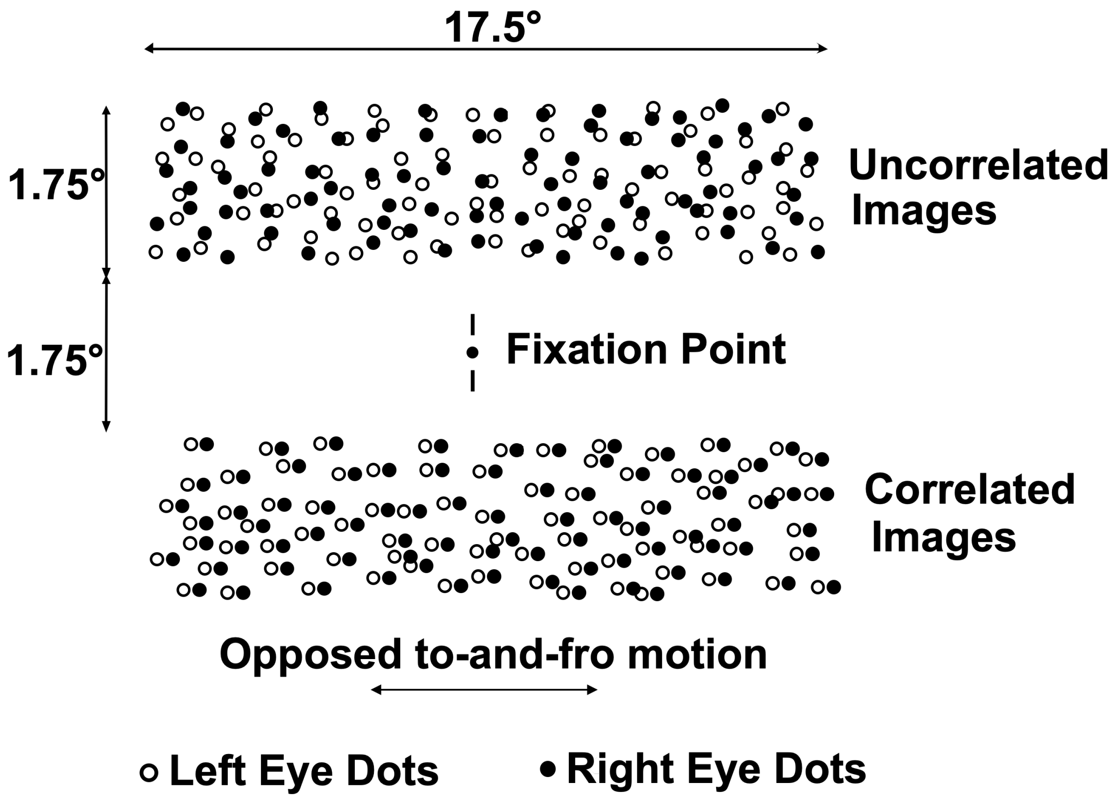

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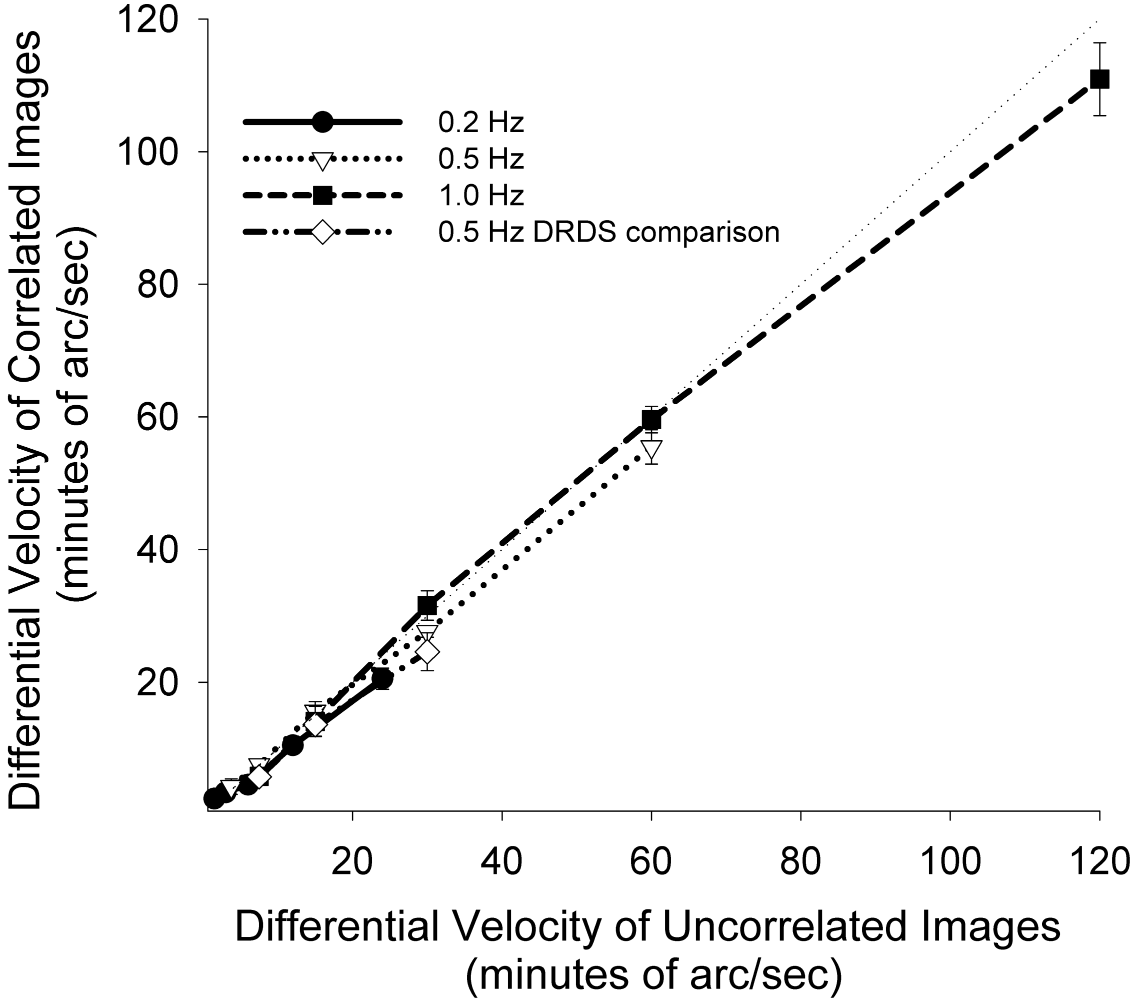

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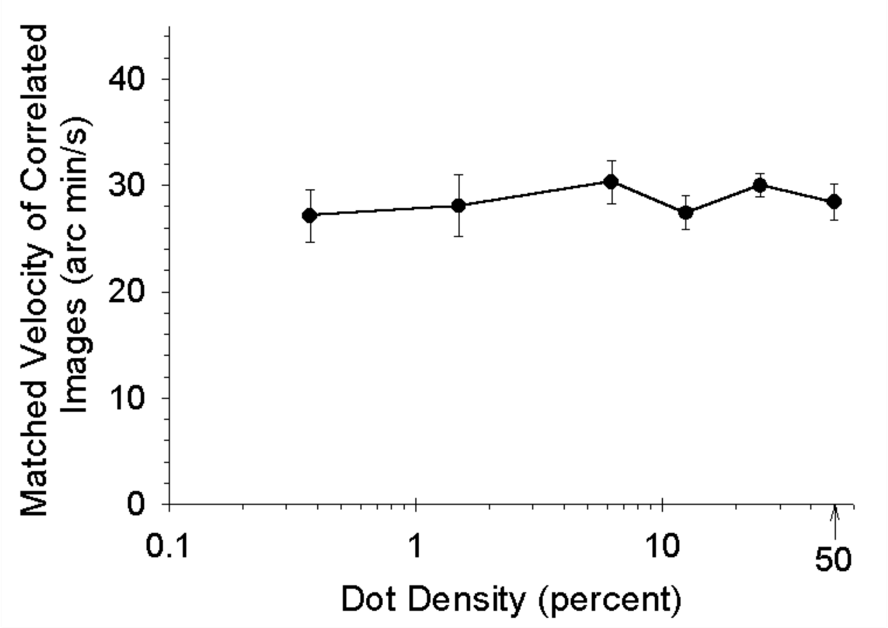

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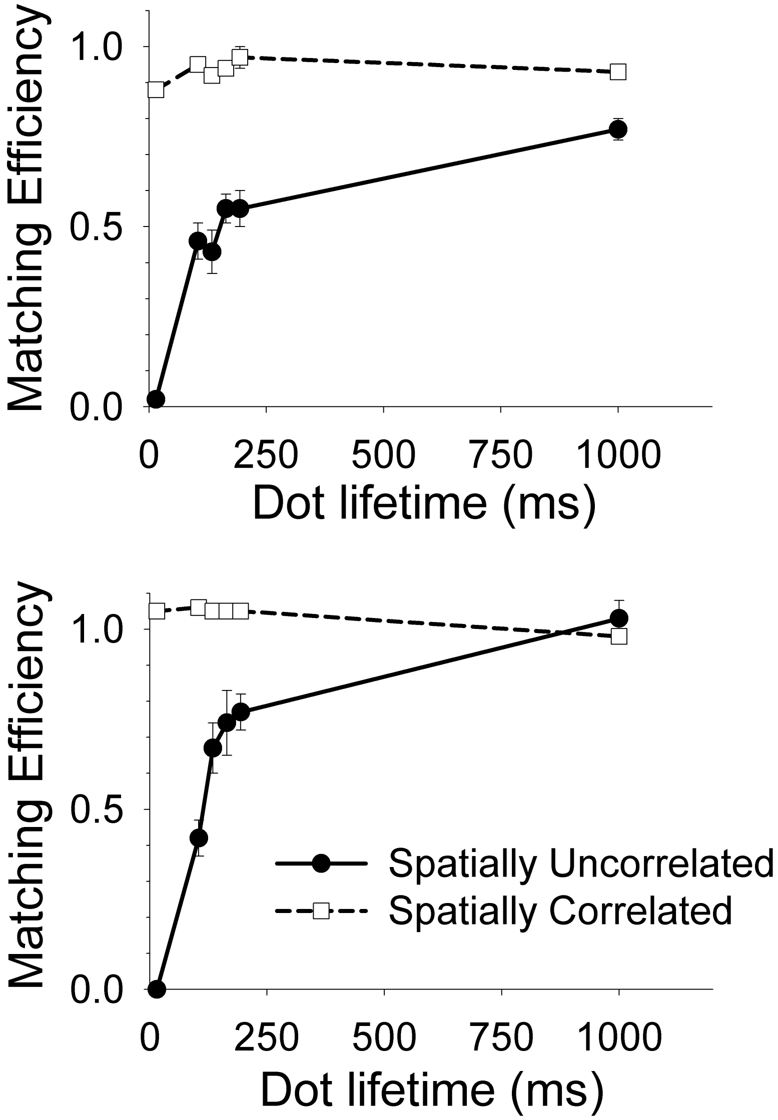

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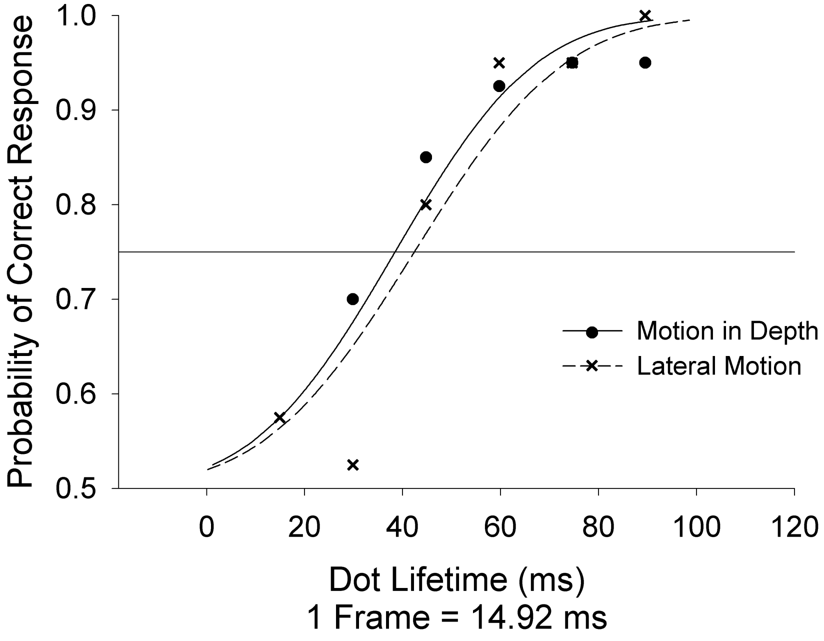

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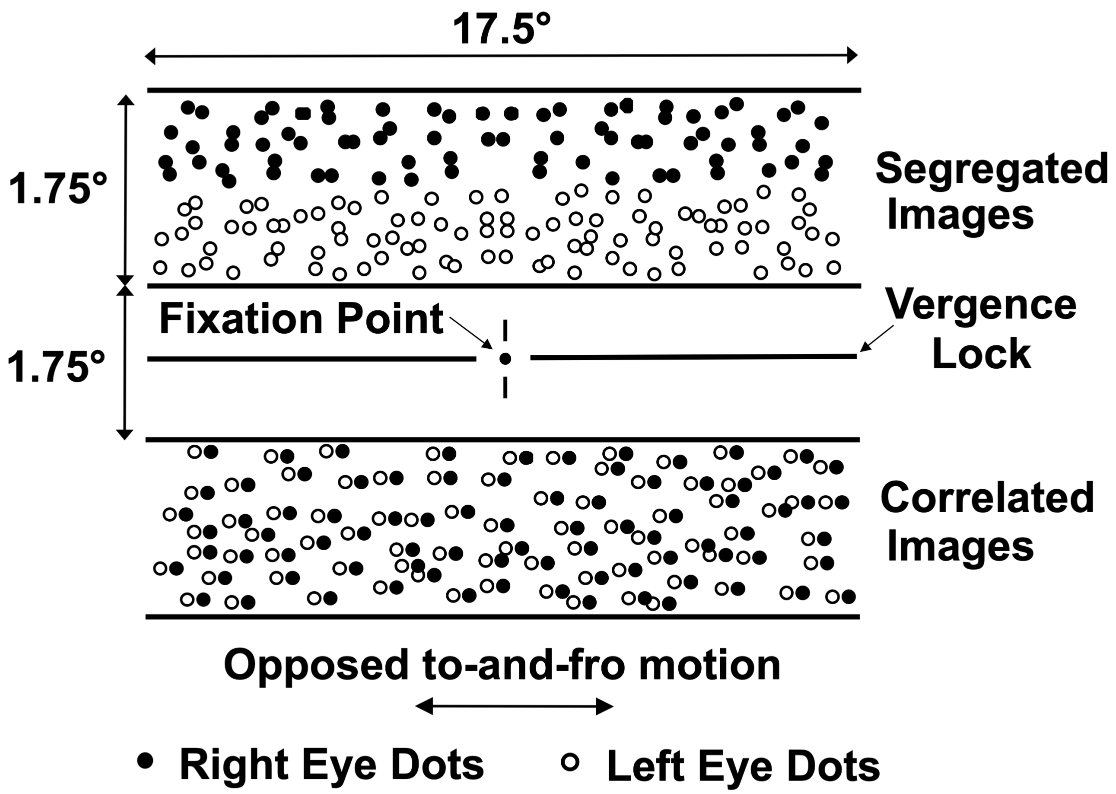

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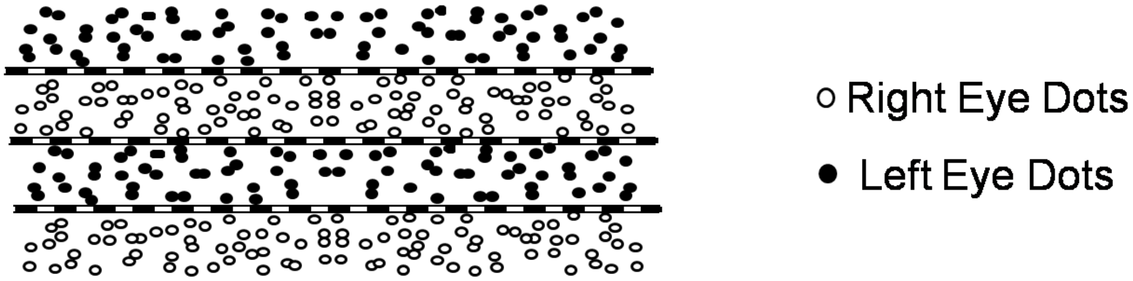

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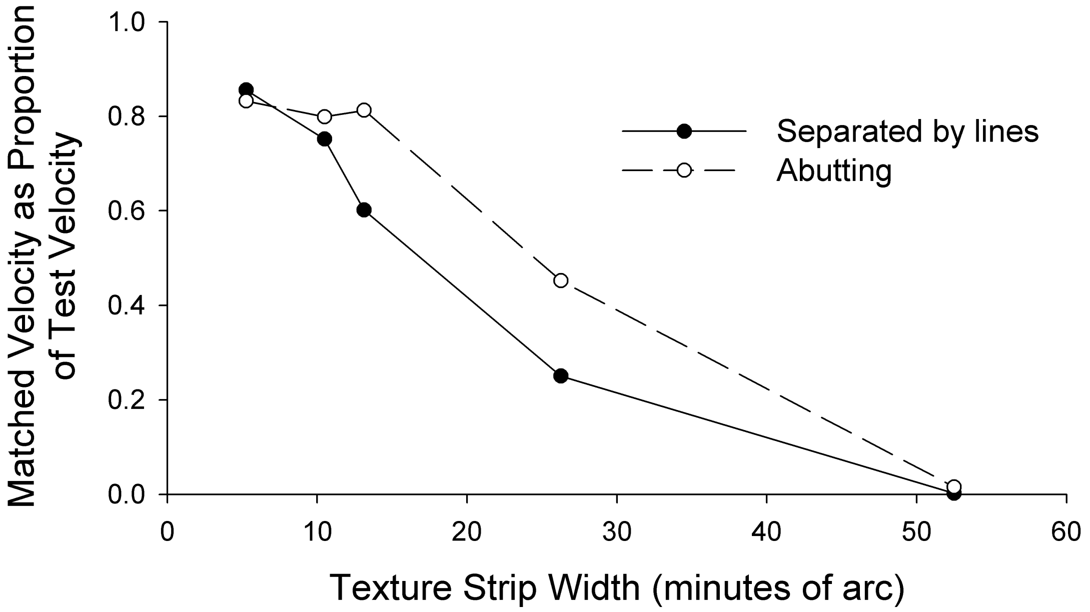

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