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The Contribution of Color to Depth Perceived from Motion Parallax

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Perceived depth was measured in a colored stimulus while stimulus movement yoked to head displacement simulated a depth of 1 cm. Velocity judgments were also made for similar stimuli moving at the same average speed but without head movement. Both measures decreased to a minimum of about 30–40% of the veridical values when the stimuli were equiluminous. Perceived depth and speed also decreased for a monochromatic stimulus as a function of luminance contrast but much more abruptly than for the chromatic stimuli. The results indicate that equiluminous color stimuli contribute to the perception of depth from motion parallax and that the contribution is not mediated by residual luminance.

Motion Color Depth Parallax

Motion parallax refers to the relative displacement of objects produced on an observer's retina during head movements. In general, objects further than the point of fixation will be displaced in the same direction as the head movements whereas those in front of the point of fixation will be displaced in the opposite direction. This signal can produce convincing impressions of depth; moreover, for small head movements and/or small depth values, the impression of depth replaces any sensation of motion (Ono & Steinbach, 1990; Ono, Rogers, Ohmi & Ono, 1988; Ono, Rivest & Ono, 1986; Saida & Ono, 1989). In this paper, we are interested in the contribution of color information to depth from motion parallax. The status of color as a contributor to the perception of speed and depth has been controversial. Several authors have noted that motion and binocular depth can be perceived at equiluminance for figural stimuli, that is when the shape is defined by explicit contours, but not for random-dot stimuli, where the shape only emerges by grouping regions of like motion or disparity. For example, Anstis (1970) and Ramachandran and Gregory (1978) reported that random dot cinematograms did not produce an impression of motion at equiluminance whereas simple stimuli did. Similarly, Lu and Fender (1972) and Gregory (1977, 1979) reported the loss of depth impressions for equiluminous random-dot stimuli but not for figural stereograms. Even though motion and depth impressions are preserved for figural stimuli at equiluminance, it has often been noted that the apparent speed or depth of these stimuli is reduced (*cf* Cavanagh, 1991; Cavanagh, Tyler & Favreau, 1984).

There is one claim that stands apart from this general pattern. Livingstone and Hubel (1987, 1988) reported that motion of simple, color-defined bars did not produce impressions of depth from motion parallax. In this paper, we will examine this claim and show that there is a robust depth impression produced by motion parallax for color stimuli.

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EXPERIMENT 1: EFFECTS OF LUMINANCE CONTRAST ON MOTION PARALLAX

In this experiment, we presented a parallax stimulus which simulated 1 cm of depth in a stationary pattern of bars when the observer's head was moving. We examined the effect of luminance contrast on the perceived depth for heterochromatic red/green and for monochromatic light yellow/dark yellow gratings.

Methods

Observers. Four observers with normal color vision and normal or corrected-to-normal acuity participated. These four included the three authors and one naive undergraduate from the Université de Montréal.

Stimuli. The display was presented on a 13" Apple color monitor controlled by a Macintosh computer and having 640 × 480 pixel spatial resolution, 256 intensity levels per color and a 66 Hz noninterlaced raster. Internal look-up tables in the Macintosh were used to linearize the luminance output of each phosphor independently. Following calibration, the maximum luminances available from the red, green and blue phosphors were 28, 59 and 6 cd/m^2, respectively. The phosphors of the monitor were determined by spectroradiometry to have CIE x and y coordinates of 0.6084 and 0.3479 for red, 0.2490 and 0.6016 for green and 0.1498 and 0.0519 for blue. The yellow of the monochromatic gratings was the mixture of equiluminous red and green (equiluminous for the CIE observer, x, $y = 0.4755$, 0.4419). The stimuli covered 27×27 cm on the screen and were viewed from a distance of 76 cm subtending a visual angle of 8 deg. The display had a mean luminance of 26 cd/m^2 and a dark surround. Observers viewed the display monocularly, with natural pupil, and no correction for chromatic aberration. The stimuli were vertically oriented sine wave gratings. Their spatial frequency was 0.5 c/deg for the red/green and light yellow/ dark yellow stimuli. The heterochromatic grating was produced by superimposing red and green sine waves, 180 deg out of phase. The monochromatic grating was produced by adding the same two sine waves in phase.

The luminance contrast of the monochromatic grating was defined in the usual way as the difference between the maximum and minimum luminances of the grating divided by their sum. The chromatic contrast of a grating was defined in terms of the percentage of the maximum chrominance modulation obtainable with the phosphors involved. Modulating both the red and green phosphors at 100% contrast, for example, and adding them in antiphase was therefore arbitrarily defined as 100% chromatic contrast. The maximum modulation of our phosphors produced approx. 15 and 35% modulation of the red-sensitive and green-sensitive cones, respectively (Smith & Pokorny, 1975). We refer to the red vs green luminance imbalance in the color grating as the luminance contrast of the color grating. The values set by the experimenter are the contrasts between the photometric luminances of the red and green. The photometric equiluminance point may differ from the contrast setting which is actually equiluminous for a given observer (Kaiser, 1988).

The chrominance modulation of the red/green gratings was 40% of the maximum possible between the red and green phosphors of the monitor. The luminance modulation was varied from red 40% darker than green to green 40% darker than red, passing through equiluminance in 8 steps. For the monochromatic stimulus, the luminance modulation was varied from 2.5% to 20% in 8 steps for 3 of the observers and from 5% to 40% for the remaining observer (SS) who could not see the luminance stimulus at 2.5% contrast. Chromatic modulation for these gratings was 0%.

Procedure. The experiment had two phases. In the first phase, observers judged the depth in a parallax display. Four horizontal bands of heterochromatic red/green sine wave gratings moved side-to-side, yoked to the observer's head movement. Observers moved their head in time with green markers which flashed at the sides of the bottom half of the display (Fig. 1). Red markers appeared at the sides of the top half of the display to indicate that the observer had reached the end of the head travel and should reverse direction. The purpose of the red and green markers was to standardize the observer's head velocity and travel. Observers looked monocularly at the display and when moving appropriately, their head moved through 17.5 cm each second. The display motion yoked to head motion simulated a physical surface of alternating stationary bands separated by 1 cm depth when seen from a distance of 76 cm. Observers moved their head side-to-side until they felt that they had appropriate head movement, that they were in synchrony with the timing markers, and that they were ready to report the perceived depth. They then stopped moving, and started the response phase by clicking a mouse button. To report the perceived depth, observers positioned black vertical bars beside the bands that were seen in front and adjusted the length of the bars to match the perceived depth in the display. For example, if they saw 1 cm depth, they adjusted the length of the bars to be 1 cm.

There were eight measurements for each of the eight contrast settings of both color and luminance gratings. These were tested in random order with the hetero- and monochromatic tests blocked in different sessions.

Results

For the color grating (solid functions in Fig. 2), the observers reported depth from motion parallax fairly accurately at high luminance contrasts but saw less depth as the luminance contrast decreased. On average, the minimum perceived depth was 0.4 cm. The photometric luminance contrast which produced the minimum depth judgment was taken to be the equiluminance point of each observer and this varied somewhat from observer to observer (the minima fell at -5, -5, -10 and $+5$% photometric contrast for SS, PC, MAG and JR, respectively). In order to simplify the comparison with the data for the monochromatic stimuli, the contrast values for the red/green gratings shown along the x-axis in Fig. 2 have been shifted for each individual so that they have a value of zero at the observer's minimum perceived depth. These results show that depth from parallax is reduced at this minimum but it is not lost at any luminance contrast.

The data plotted as open symbols in Fig. 2 show the perceived depth as a function of contrast for the yellow monochromatic gratings. We duplicated these data points and reflected them around 0% contrast, so the results could be compared with the ones collected with the red/green stimuli where contrast can be positive and negative. The data show that here too the impression of depth decreased as the luminance contrast decreased. It decreased down to an average of 0.2 cm at the lowest contrast tested.

The results for both hetero- and monochromatic gratings both show a decrease in perceived depth at lower luminance contrasts. However, the results differ in two important aspects. At the lowest contrasts, observers saw more depth with the red/green heterochromatic gratings than with the yellow gratings suggesting that the presence of color adds signal to depth from parallax. On the other

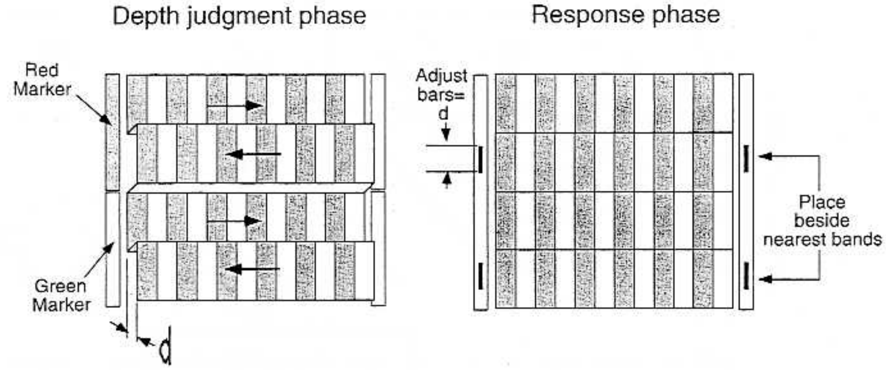

FIGURE 1. The stimuli used in the two phases of the experiment. The horizontal bands of vertical gratings were yoked to move alternately with or against the observer's head motion. The apparent depth seen between the alternate bands of opposing motion is depicted as *d* in the left hand panel. The observer adjusted the length of the short vertical bars on the left and right of the display in the response phase to equal the depth, *d*, seen in the judgment phase. To indicate which bands appeared closer, the observer also moved the markers adjacent to the nearer bands.

hand, at higher contrasts, observers saw *less* depth with the red/green gratings than with the yellow gratings. If adding color were equivalent to adding some small amount of luminance contrast, then the presence of color should add to the effectiveness of the color grating at all luminance contrasts. The actual results are quite the opposite—the color grating is almost always less effective than the monochromatic grating of the same contrast. We can therefore reject the simple notion that color, for whatever reason, is merely contributing a small luminance signal to the perception of depth from motion parallax.

The presence of the color adds a signal for depth at and near equiluminance. In addition, when luminance is present, the color somehow reduces the effectiveness of the luminance contrast in specifying depth from motion parallax.

EXPERIMENT 2: APPARENT VELOCITY OF GRATINGS

In the second experiment, we examined whether the reduced depth for low contrast stimuli is related to the slowing of perceived speed at these contrasts, independently of whether the stimulus was hetero- or monochromatic. In addition, we examined whether the reduction in perceived depth for a luminance grating when color was added to it was predicted by a reduction in apparent velocity for this stimulus. In this experiment, we measured apparent velocity of the gratings as a function of their luminance contrast when there was no head movement. The stimulus motion was therefore sensed directly as motion. In comparison, in the parallax stimulus of Experiment 1, the display motion was often sensed as depth without any accompanying motion.

Methods

Observers. The same observers were tested as in Experiment 1.

Stimuli. The stimulus layout was similar to that of Experiment 1 except that the hetero- and monochromatic stimuli were shown only in the top two bands of the display. These two bands always moved back and forth in opposite directions at the same speed as the average used in the parallax experiments, that is 0.12 cm/sec, but without being yoked to head movement. They reversed direction every second, the same reversal rate as in Experiment 1. The two bottom bands were both 100% contrast black-and-white sine wave gratings of the same spatial frequency as the top two. These two bands also moved back and forth in opposite directions at the speed set by the observer.

Procedure. Observers judged the relative speed of the upper bands in free, monocular viewing. They reported their perceived speed by adjusting the relative speed of a pair of black and white gratings presented in the bottom half of the display. Observers moved their eyes between the test and adjustment bands to make the settings. When they were satisfied with the setting they clicked a mouse button and proceeded to the next trial. The same eight contrast settings as in Experiment 1 were tested eight times each in random order for both the hetero- and monochromatic stimuli.

Results

The results show that, at equiluminance, observers saw the same type of reduction for perceived speed as for perceived depth. The perceived speed of both the red/green and the luminance gratings appeared to decrease as the luminance contrast decreased, and the gratings appeared to move fastest at high luminance contrasts.

However, as for depth, color and luminance interact in their effect on speed. Some observers did not see the luminance gratings move at the lowest contrast but did see the red/green gratings move at the same luminance contrasts. On the other hand, at higher contrasts, they saw the luminance gratings moving faster than red/green gratings. Again the slopes relating perceived speed to luminance contrast were, on average, about three times steeper for luminance alone than for luminance in the presence of color. Here again, the perceived speed of the color gratings can not be explained by residual luminance in the red/green stimulus.

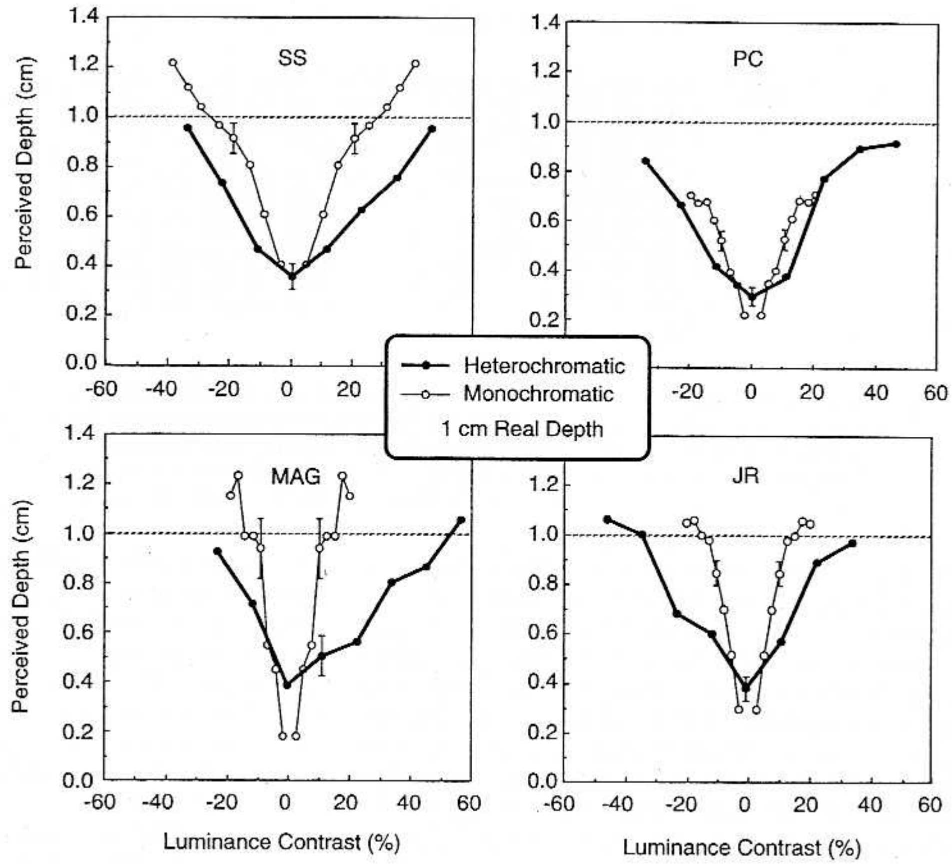

FIGURE 2. Perceived depth as a function of luminance contrast of the heterochromatic, red/green grating (filled symbols) and of the monochromatic, luminance grating (empty symbols). The data are shown separately for each of 4 observers. The depth simulated by the stimulus during head movement was 1.0 cm (shown by the dotted horizontal line). For the heterochromatic grating, luminance contrast is shown as positive when red is more luminous than green and negative when green is more luminous than red. The heterochromatic data for each observer have been shifted along the x-axis so that the minimum perceived depth falls at 0% luminance contrast. For the monochromatic grating, the data are shown for positive luminance contrasts and, for comparison with the heterochromatic data, they are repeated for negative values as well. The median standard error for each condition is shown as a vertical bar around only one datum point (± 1 SE).

These results are qualitatively very similar to those for depth implying that the pattern of results for the perception of depth from motion parallax and for the perception of velocity may be based on an underlying common mechanism. Figure 4 plots perceived depth from Experiment 1 as a function of perceived speed from Experiment 2 with one point for each contrast tested in the two experiments. The results are shown separately for color and monochromatic conditions for each observer.

There is a close link between perceived depth and speed in every case with r^2 values for the linear regressions ranging from 0.78 to 0.98 (median value of 0.90). Despite this highly regular behavior, several aspects argue against a direct relation between the perceived speed and depth measured in these two tasks. First, even though both judgments derive from stimulus displacement on the retina, they are also dependent on head and eye movements and perceived distance. Because of the different task requirements and the possible variations in eye movement strategies adopted by different observers, the pattern of head and eye movements and retinal displacement will be very different in the two tasks used here. Given the degree of these differences, the strong coupling between the two measures is surprising. Nevertheless, there are two interesting departures from direct proportionality between the two measures. First, the slope relating depth to speed varied markedly from observer to observer as well as between the color and monochromatic conditions (particularly for SS and PC). The average slope (6.5) was less than that expected for a veridical correspondence between speed and depth (8.6), implying that additional contrast was more effective at increasing the perceived speed than the perceived depth. Second, the intercepts of the depth vs speed regressions, which would be expected to be 0.0 for a veridical correspondence, were typically but not always, higher, implying that the contrast threshold for perceived speed was higher than that for perceived depth. These departures imply that each task may have had idiosyncratic features which affected judged depth and speed independently. For example, because eye movements were not controlled, the retinal stimulation could be quite different in the two cases depending on whether the observer tracked one or the other band of movement or fixated the motionless separation line between them.

Different observers may have adopted different strategies for exploring the stimuli in these tasks and different strategies as a function of the stimulus type (color or monochromatic) as well.

CONCLUSIONS

Our first experiment showed that there was an impression of depth from parallax for equiluminous color gratings. The magnitude of the perceived depth was reduced to about 40% of the veridical value for the conditions of our display. This result is consistent with previous reports of the perception of motion (Cavanagh & Favreau, 1985; Cavanagh, Boeglin & Favreau, 1985; Cavanagh *et al.*, 1984; Derrington & Badcock, 1985; Gorea & Pappathomas, 1989; Mullen & Baker, 1985; Cavanagh & Anstis, 1991; Dobkins & Albright, 1993), depth from binocular disparity (de Weert & Sadza, 1983; Grinberg & Williams, 1985; Van Sickle & Geisler, 1989; Poeppel & Logothetis, 1990), and stereomotion (Tyler & Cavanagh, 1991) for equiluminous stimuli. The result contradicts Livingstone and Hubel's (1987, 1988) report of loss depth from parallax for equiluminous stimuli.

Livingstone and Hubel (1987, 1988) reported that depth from parallax was not visible at equiluminance. However, this loss may have arisen from the difficulty in resolving their stimulus (a pair of narrow vertical bars) at equiluminance. When we use a grating of low frequency bars, we find no difficulty in resolving them or the depth that they simulate during head movements.

We conclude that color-defined stimuli can support depth from motion parallax. Moreover, color interacted strongly with luminance in determining the perceived depth and did so in a way which ruled out residual luminance as the source for color's contribution to parallax. Specifically, increasing the luminance contrast of the stimulus increased the depth perceived due to parallax for both the color and the luminance gratings but with very different functions in the two cases. If adding color were equivalent to adding some small amount of luminance contrast, then the presence of color would add somewhat to the effectiveness of the grating at all luminance contrasts. (The luminance response to color could result from artifacts in the display or in the eye or nonlinearities in the luminance pathway.) Indeed, the presence of color did add to the effectiveness of a given

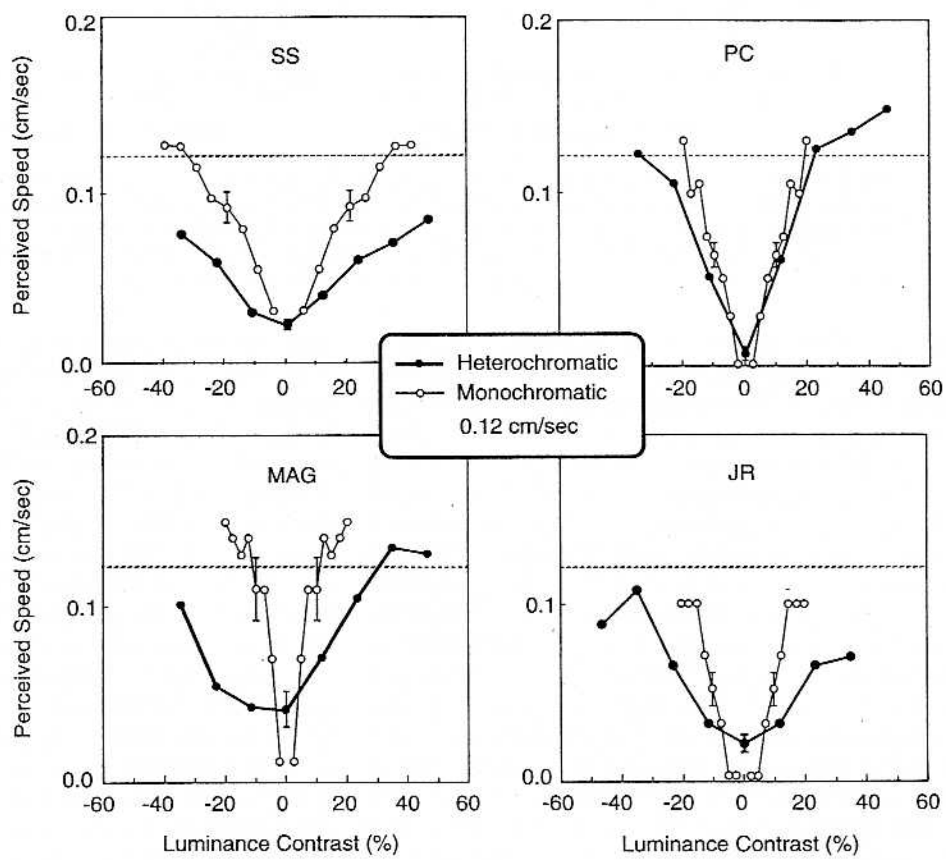

FIGURE 3. Perceived speed as a function of luminance contrast of the heterochromatic, red/green grating (filled symbols) and of the monochromatic, luminance grating (empty symbols). The actual speed of the stimulus was 0.12 cm/sec (shown by the dotted horizontal line), the same as the mean speed of the stimulus in Experiment 1. The data are shown separately for each of 4 observers. For the heterochromatic grating, luminance contrast is shown as positive when red is more luminous than green and negative when green is more luminous than red. The heterochromatic data for each observer have been shifted along the x-axis so that the minimum perceived depth falls at 0% luminance contrast. For the monochromatic grating, the data are shown for positive luminance contrasts and, for comparison with the heterochromatic data, they are repeated for negative values as well. The median standard error for each condition is shown as a vertical bar around only one datum point (± 1 SE).

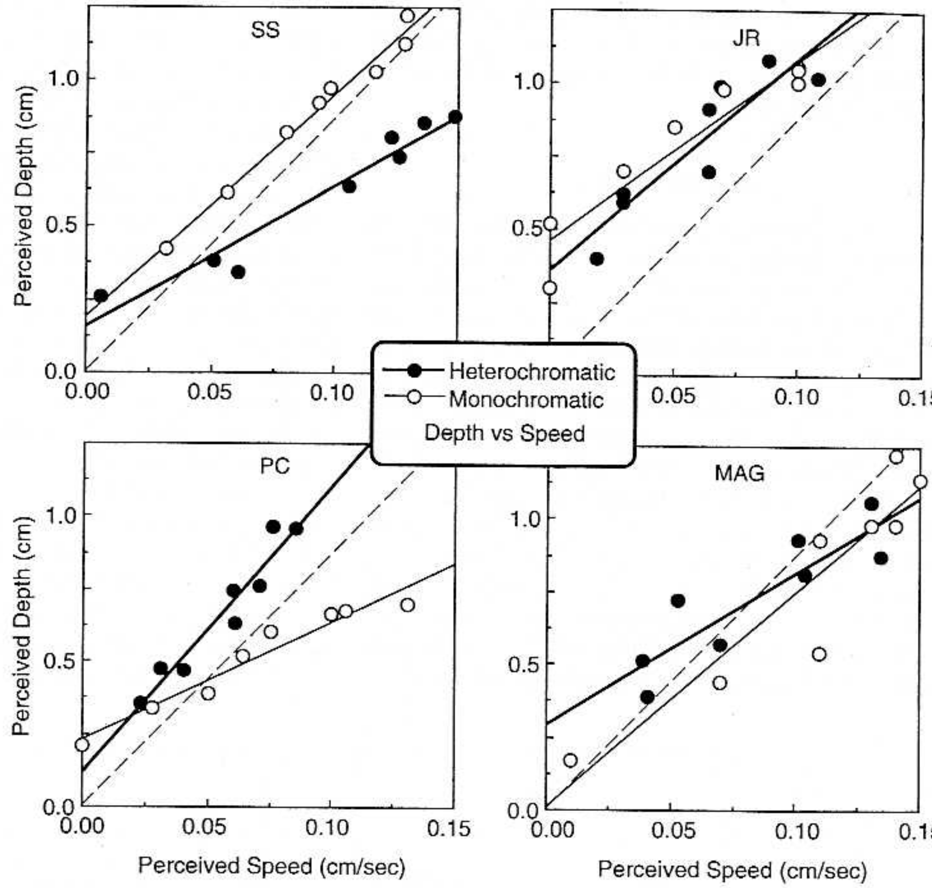

FIGURE 4. Perceived depth (from Experiment 1) as a function of perceived speed (from Experiment 2) of the heterochromatic, red/green gratings (filled symbols) and of the monochromatic, luminance gratings (empty symbols). Each point represents the speed and depth judgments for a given contrast in the two experiments. The solid lines are linear regressions through these data and the dashed line shows the depth of a stationary surface simulated by each stimulus speed if it were yoked to head movement. The data are shown separately for each of 4 observers.

luminance contrast at low values of contrast. However, at higher values, the depth perceived for a given luminance contrast *decreased* when color was added. In general, the slopes relating luminance contrast to perceived depth were much lower when color was present. For example, a 10% increase in the luminance contrast of the light and dark yellow grating produced, on average, an increase of about 5 mm in perceived depth. The same increase in luminance contrast for the red/green grating produced, on average, only an additional 1.5 mm in perceived depth.

The loss of perceived depth as a function of luminance contrast was mirrored by a similar loss in perceived speed for both the luminance and color gratings (see Fig. 4 for a comparison). Most likely, both the speed and depth judgments rely on the responses of a common set of motion sensitive (directionally selective) units activated by the stimulus. Combined in different ways with information on eye and head movements and distance, this common early measurement leads in one case to a velocity percept and in the other to a depth percept. Given the losses at equiluminance, we can be specific about which motion sensitive system is underlying these responses. Several recent results show that judgments involving position or tracking are not degraded at equiluminance: vernier alignment is as good for equiluminous gaussian bars as for luminance-defined bars of the same blur (Krauskopf & Farrell, 1991); optokinetic nystagmus has no loss in gain at equiluminance (Poeppel & Logothetis, 1989); and velocity judgments of equiluminous bars tracked with attention are not slowed at equiluminance (Cavanagh, 1992). Motion systems based on tracking or position are therefore unlikely candidates for the loss in perceived velocity seen in Experiment 2 or the related loss in perceived depth in Experiment 1. We speculate that the loss is based on low-level, directionally selective units.

The response of these mechanisms to color must be qualitatively different from their response to luminance stimuli in our results. Specifically, the slope relating luminance contrast to perceived speed was markedly shallower for red/green gratings than for light/dark yellow gratings. Moreover, the two functions cross over each other for all four observers (Fig. 3). The responses of motion detectors to luminance and to color are clearly not additive. We have no data from our experiments which would help identify the cause of the interesting interaction between color and luminance. We should note that our contrast function for the perceived velocity of luminance gratings is quite unlike that published by Hawken, Gegenfurtner and Tang (1994). They reported that the perceived velocity of luminance gratings was contrast invariant—that is, it was fairly constant for all tested contrasts. To the contrary, we find that the function for luminance gratings was quite steep. A second look at our function reveals the source of this discrepancy. The perceived velocity for luminance gratings rises quickly with contrast to an asymptote, and although we did not test beyond that point, flattens out for higher contrasts. The results of two earlier papers show (Cavanagh *et al.*, 1984; Mullen & Boulton, 1992) similar results. Hawken *et al.* (1994) tested only above the 'saturation' contrast whereas we tested only below. The conclusions of both papers are similar nonetheless: the contrast functions for the perceived velocity of luminance and color gratings differ markedly (note, however, that in Hawken *et al.*, 1994, the contrast variable for the color grating was its saturation, not its luminance contrast). In both cases, these results rule out any simple model whereby the response to color is mediated by some residual luminance component.

In conclusion, we have presented evidence that equiluminous color stimuli contribute to the perception of depth from motion parallax. The results ruled out the possibility of a residual luminance response as the source of color's contribution to motion and to depth from parallax. In fact, the motion system appears to be very sensitive to red/green chromatic stimuli, more so than to luminance stimuli when both are scaled in terms of cone contrast (Metha, Vingrys & Badcock, 1994). The decrease in speed and depth responses for equiluminous stimuli do not arise because the motion system is less sensitive to them—the responses decrease at least in part because even the most saturated red/green stimulus produces only moderate levels of cone contrast at equiluminance compared to the 100% contrast that is easily attainable for luminance stimuli (Stromeyer, Eskew & Kronauer, 1990.

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