

The horizontal disparity direction vs. the stimulus disparity direction in the perception of the depth of two-dimensional patterns

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Horizontal binocular disparity has long been the conventional predictor of stereo depth. Surprisingly, an alternative predictor fares just as well. This alternative predicts the relative depth of two stimuli from the relation between their disparity vectors, without regard to horizontal disparities. These predictions can differ; horizontal disparities accurately predict the perceived depth of a grating and a plaid only when the grating is vertical, while the vector calculation accurately predicts it at all except near-horizontal grating orientations. For spatially two-dimensional stimulus pairs, such as plaids, dots, and textures, the predictions cannot be distinguished when the stimuli have the same disparity direction or when the disparity direction of one of the stimuli is horizontal or has a magnitude of zero. These are the conditions that have prevailed in earlier studies. We tested whether the perceived depth of two-dimensional stimuli depends on relative horizontal disparity magnitudes or on relative disparity magnitudes along a disparity axis. On both measures tested—depth matches and depth-interval matches—the perceived depth of plaids varied with their horizontal disparities and not with disparity direction differences as observed for grating-plaid pairs. Differences in disparity directions as great as 120° did not affect depth judgments. This result, though opposite the grating-plaid data, is consistent with them and provides a view into the construction of orientation-invariant disparity representations.

Keywords: disparity, depth perception, stereoscopic vision, stereopsis

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Introduction

Suppose one views a stimulus with some binocular disparity, D_1 . What is the value of D_2 , the disparity of another stimulus that results in the perception of a depth-match between the two stimuli? If D_1 and D_2 are constrained to be horizontal, the two disparity magnitudes will, other things being equal, have to be the same in order to produce a depth match. However, in the general case of arbitrary disparity directions (so that D_1 and D_2 must be denoted by vector rather than scalar values), equal disparity magnitudes, even equal horizontal and vertical disparity magnitudes, do not necessarily give rise to equal perceived depths (Chai & Farell, 2009; Farell, Chai, & Fernandez, 2009).

The results just mentioned come from experiments in which D_1 was the disparity of a plaid and D_2 was the disparity of a grating. The plaid was the *reference stimulus*, whose disparity was set in advance, and the grating was

the *test stimulus*, whose disparity varied from trial to trial as observers judged the relative depth of the two stimuli. At a perceptual depth match between the stimuli, the magnitude of D_2 is a function of the grating's orientation relative to the direction of the plaid's disparity. Specifically, D_2 is proportional to the sine of the angular difference between the orientation of the grating and the disparity direction of the plaid. Horizontal disparity is not a factor; in general, gratings and plaids have different horizontal disparities when they have equal perceptual depths (Chai & Farell, 2009). Their horizontal disparities can even differ in sign (Farell et al., 2009).

Thus, for stimulus pairs composed of a grating and a plaid—and presumably for other pairings of a one-dimensional (1-D) and a two-dimensional (2-D) pattern—perceived stereo depth depends on the relation between the disparity vectors of the two stimuli; it is not predicted by horizontal disparity. The question addressed by the present experiments is whether this result applies to perceived depth when both stimuli are two-dimensional.

Specifically, we ask whether the disparities of 2-D stimuli are compared along an axis defined by a stimulus disparity direction or along the horizontal disparity axis.¹

This question can be put in context by considering depth matches between a grating and a plaid when the plaid's disparity direction is horizontal. In this case, the two stimuli will appear at the same depth if their horizontal disparities are the same. (The grating's horizontal disparity is its disparity measured along the horizontal axis; the horizontal component of the grating's perpendicular disparity will not equal the plaid's horizontal disparity in general, but only if the grating is vertical.) It is when the reference disparity is non-horizontal that the horizontal disparities of the grating and the plaid are generally unequal when the two stimuli appear at the same depth. To know whether a pair of 2-D stimuli will behave in the same way requires that we measure depth-matching disparities when these disparity directions are non-horizontal and unequal. Previous studies of the relative depth of 2-D stimuli did not satisfy this requirement. Their reference disparities were horizontal or, having magnitudes of zero, lacked a definite direction (Friedman, Kaye, & Richards, 1978; Ogle, 1955). Though these studies examined perceived depth as a function of the vertical component of disparity of one of the two stimuli being judged, this, too, is insufficient. Unless both stimuli have non-horizontal disparities, an effect of a difference in disparity direction cannot be distinguished from an effect of adding a vertical component to the disparity of one of the stimuli.

Seeking a general perceived-depth function of relative disparity for 2-D stimuli, we varied the disparity directions and magnitudes of plaids in depth-matching (Experiments 1 and 2) and depth-interval matching (Experiment 3) tasks.

Experiment 1: Symmetrical plaids

Method

Stimuli

The stimuli consisted of pairs of plaids arranged in center-surround configuration. The central plaid had a fixed disparity direction, which differed between conditions, and a variable disparity magnitude, which changed between trials as described below. The surrounding annular plaid had a disparity that was fixed in both direction and magnitude within a block of trials. Each plaid was made by adding two sinusoidal gratings with differing orientations. These gratings had a spatial frequency of 2 c/d and a Michelson contrast of 0.1.

The plaids' contrast-envelope parameters were identical to those used for the central test grating and surrounding reference plaid by Chai and Farell (2009), whose results we want to compare with data for plaid pairs. In addition to allowing a comparison of the two studies, using the center-surround configuration avoids certain spatial

alignment effects that might otherwise contribute unwanted variability to the data. Alternative configurations have one of the plaid patches laterally displaced with respect to the other. The direction of the displacement will bear some relation to the direction of the disparities of the plaids. (If both disparity directions were 45°, say, they would be parallel to the patch alignment when one patch is above and to the right of the other and would be perpendicular to the patch alignment when one patch is above and to the left of the other.) It is not known what the effects might be in this study. However, an effect on disparity thresholds occurs for grating patches (Farell, 2006). Using a center-surround arrangement eliminates it.

The center plaid was bounded by a Gaussian envelope with a horizontal and vertical standard deviation (σ) of 0.53° of visual angle. The envelope of the surrounding annulus was Gaussian along the radial direction; its standard deviation was 0.34°. Gaussians were truncated at $\pm 2\sqrt{2}\sigma$. The peaks of the center and surround Gaussian envelopes were separated by a distance of 2° of visual angle; we showed elsewhere (Farell & Fernandez, 2008) that spatial separation, up to at least 6°, is not a crucial variable in experiments such as this.

The two sinusoidal components of the center plaid had the same orientations as those of the surrounding plaid. These components were oriented symmetrically about the horizontal and vertical axes: 60° and 120°, 45° and 135°, or 30° and 150° (where 0° is horizontal and angles increase in a positive direction counterclockwise). These stimuli are identified by their 'plaid angles'—the vertically bisected angular separations between the components—which are 60°, 90°, and 120°, respectively.

Either one or both of the sinusoidal components of the annular reference plaid had a fixed phase disparity of 15°. When only one component had a 15° disparity, the other component had a disparity of 0°. Depending on the plaid angle, this produced six oblique plaid disparity directions ($\pm 30^\circ$, $\pm 45^\circ$, or $\pm 60^\circ$) when only one component had a 15° phase disparity, and a horizontal direction (0°) when both components had a 15° phase disparity. Examples of the stimuli appear in Figure 1.

The disparity of the central test plaid varied from trial to trial under the control of a constant-stimulus procedure. This variation in disparity was distributed across the components of the test plaid as it was across the components of the reference plaid. That is, in separate conditions the disparity of one component of the test plaid varied from trial to trial, or the disparity of the other component so varied, or the disparity of both components so varied equally. When only one component had a variable disparity, the other component had a disparity of zero.

With three disparity distributions for the test plaid and another three for the reference plaid, and with three plaid angles applied to each of these combinations of test and reference plaids, the number of disparity-direction pairs in the experiment was 27. For each plaid angle, these

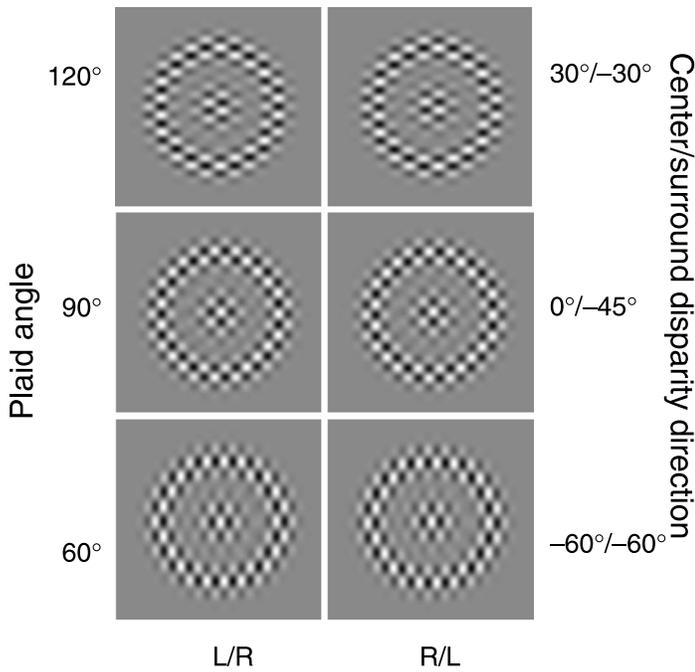


Figure 1. Center-surround stereo plaids of the type used in Experiment 1. Plaid angle is the angular difference between the two sinusoidal components of the plaids, measured such that a vertical line could bisect the angle. The central and surrounding plaids have the same plaid angle in Experiment 1. The disparity directions shown are examples of the conditions 1, 2, and 3 (for plaid angles 60°, 120°, and 90°, respectively) given in Figure 2. Stimulus contrast shown here does not match that used in the experiment. Stereo pairs can be fused convergently or divergently.

stimulus pairs fell into five conditions, which Figure 2 illustrates schematically using 6 of the 27 pairs appearing in the experiment. Note that three conditions—numbers 2, 3, and 4 in Figure 2—preclude a physical match between the test and reference plaids because the disparity directions of the two plaids differ.

The absolute phases of all sinusoids were independently randomized (identically in the left and right eyes) on each trial to eliminate potential monocular cues. The disparities of the contrast envelopes were fixed at zero, as in the experiments of Chai and Farell (2009). The only non-zero disparities were interocular phase shifts of the carriers.

It should be noted that 2-D stimuli whose disparities are non-zero have components that generally differ in their phase disparities, regardless of the disparity direction of the stimulus. Despite this, sinusoidal components of similar spatial frequencies cohere in depth whether their disparities are similar or not (Calabro & Vaina, 2006; Delicato & Qian, 2005; Farell, 1998; Farell & Li, 2004). They are not perceived as superimposed transparent gratings separated in depth. Rather, the stereo plaids used here appear as unified stimulus occupying a single depth plane.

Equipment

Stimuli were presented on a pair of luminance-calibrated CRT monitors, one for each eye, each measuring 49 cm. on the diagonal. The monitors were driven by a Macintosh G5 computer via attenuators that provided high monochromatic (green-gun) luminance resolution (Pelli & Zhang, 1991). Michelson contrast of the individual plaid components was 0.1. The background luminance, 21 cd/m², was also the patterns' mean luminance. Each monitor had a resolution of 1152 × 870 pixels and the refresh rate was 85 Hz. Stimulus presentation duration was 153 ms, with abrupt onsets and offsets. Stimuli generation and presentation were controlled by a Matlab (Mathworks, Inc.) program incorporating elements of PsychToolbox software (Brainard, 1997; Pelli, 1997).

Observers sat upright at a chin rest and viewed the displays with natural pupils in a moderately lit room. Stimuli were viewed at eye-level through a front-silvered mirror stereoscope. The optical distance was 1.25 m. A fixation stimulus could function as an unwanted reference stimulus and was therefore not used; the center-surround patterns were presented on an otherwise blank screen. The contours nearest these patterns were the edges of the monitors' screens, which were located approximately 3.8° vertically and 5.8° horizontally from the outer visible limit of the annulus. As described elsewhere (Chai & Farell, 2009), occluders rendered the vertical contours of the monitor visible only monocularly. This, too, was to

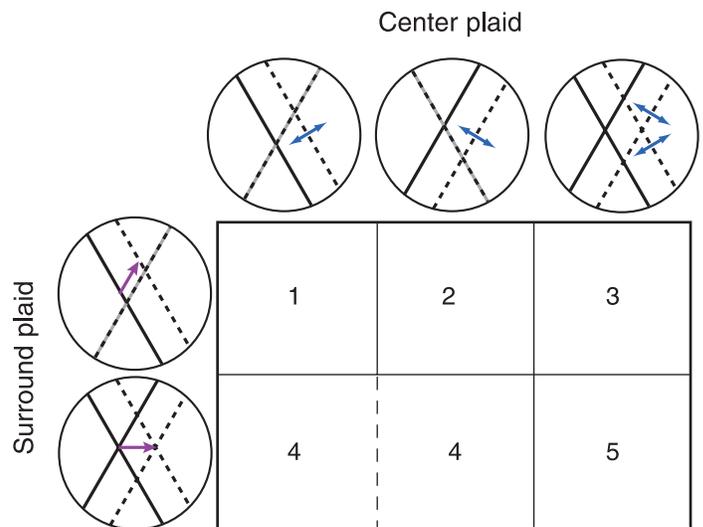


Figure 2. The five conditions of Experiment 1. Numbered conditions are defined by combinations of the surrounding reference plaid (left edge) and the central test plaid. The reference plaid could have one zero-disparity and one 15° phase-disparity component or two 15° phase-disparity components. Violet arrows show the fixed disparities of the reference plaids; blue arrows show the variable component disparities of the test plaids, whose values at the depth match are the PSEs plotted in the data figures.

prevent stimuli other than the annular plaid from functioning as a reference for observers' judgments of the depth of the central plaid. Also, the plaids' contrast envelopes, despite their fixed disparities, were not useful as reference stimuli against which to judge the depth of the test plaid. The disparities appearing in this study are far smaller than the threshold disparity for an isolated grating patch, with an envelope disparity of zero, having the same carrier spatial frequency as used here (Farell, 2006). The observed values in that case are characteristic of absolute, not relative, disparity thresholds.

Procedure

The disparity magnitude of the central test plaid varied from trial to trial under the control of a constant-stimulus procedure. Six disparity magnitudes were identified on the basis of preliminary data as approximately bracketing the point of subjective equality (PSE) for depth. On each trial, the test plaid was displayed with one of these disparities, which was selected at random subject to the requirement that each disparity be sampled 10 times per block. The disparity of the surrounding plaid was constant within a block of trials, as were all other stimulus parameters (except the absolute phases of the sinusoids), including the disparity direction of the test plaid.

The observer's task was to judge the center plaid as having appeared 'near' or 'far' relative to the surrounding plaid. After fixating between and aligning two vertical nonius lines, observers initiated each trial with a click of the computer's mouse. The nonius lines vanished shortly before stimulus onset. A brief 'bing' sounded the onset of the stimulus presentation; observers signaled their decisions by clicking 'Near' and 'Far' buttons that appeared on-screen shortly after termination of the stimulus. Observers were not informed as to which plaid or plaid components had variable disparity, nor were they given feedback about their responses, which reported a subjective perceptual judgment.

Before data collection, observers were given sufficient practice to stabilize performance. Data were gathered in runs of 60 trials, each preceded by 4–6 warm-up trials. At least 3 runs contributed to each data point. Psychometric functions were fit by cumulative Gaussian functions (Wichmann & Hill, 2001a, 2001b). The PSE, the disparity of the test grating that yielded the 50% point on the psychometric function, defined the perceptual depth match between the plaids.

Observers

Two female observers took part in the experiment. They were experienced in stereo tasks but did not know the specific purposes of this experiment. They had normal acuity (in one case with corrective optics) and normal stereo vision. Both observers (as well as the third observer

who took part in Experiments 2 and 3) gave their informed written consent before participating in the experiments, the protocol for which was approved by the Institutional Review Board of Syracuse University.

Results

There are five conditions in this experiment (see Figure 2). To examine whether depth matches is predicted by horizontal disparity or are, instead, a function of relative stimulus disparity direction, we divided the data from these five conditions across three graphs. The first of these graphs (Figure 3) compares conditions 1 and 2; the second (Figure 4) compares conditions 4 and 5; and the third (Figure 5) compares condition 3 across plaid angles. The data shown in Figure 3 come from plaids with oblique disparities; the data shown in Figure 4 come from plaids in which the reference disparity is horizontal and the test disparity is either oblique or horizontal; and the data shown in Figure 5 come from plaids in which the reference disparity is oblique and the test disparity is horizontal. These are all the possible combinations. In all but condition 5, two symmetrical cases, differing by

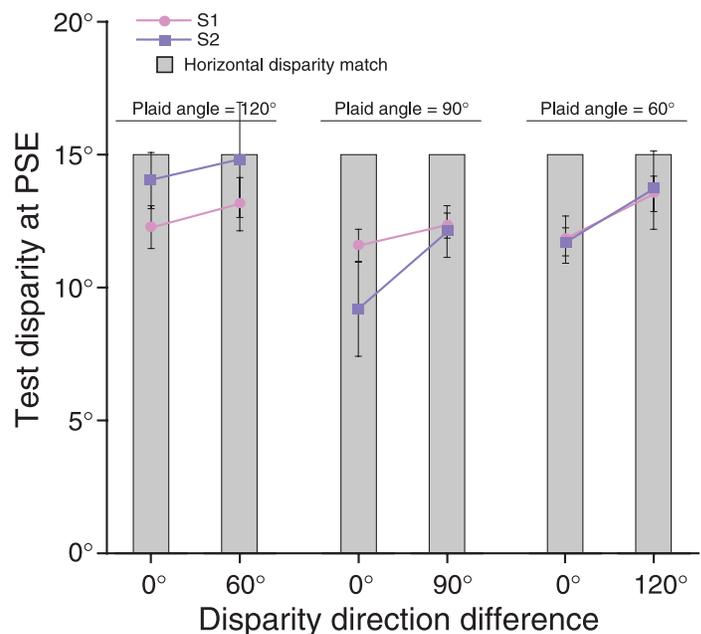


Figure 3. Component depth-matching disparities for the two observers, S1 and S2, in Experiment 1, conditions 1 and 2: Same vs. different oblique disparities. Depth-matching PSEs are shown as a function of the difference between the disparity directions of the central and surrounding plaids. The disparity directions are oblique: $\pm 30^\circ$, $\pm 45^\circ$, or $\pm 60^\circ$ for plaid angles of 120° , 90° , and 60° , respectively. A depth-matching phase disparity of 15° (bars) yields plaids with identical horizontal component disparities in all conditions. Error bars = ± 1 SEM.

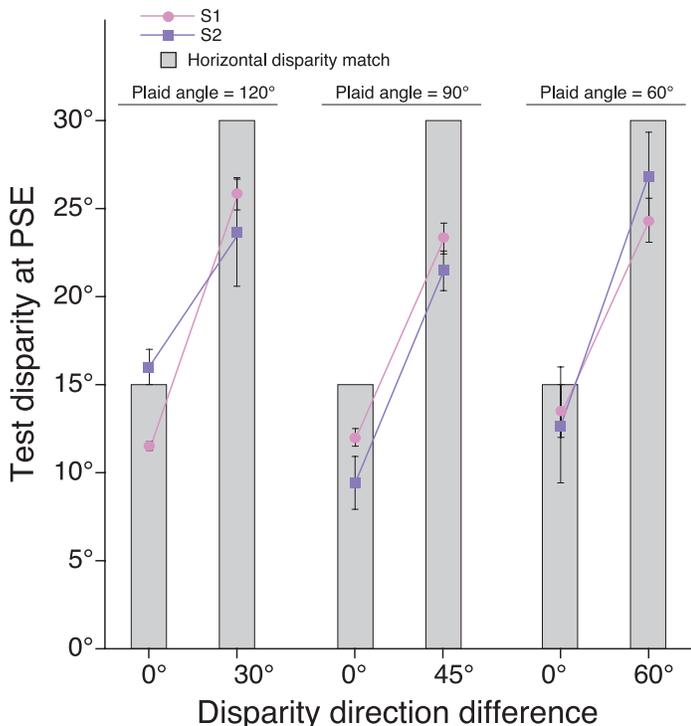


Figure 4. Component depth-matching disparities for the two observers in Experiment 1, conditions 4 and 5: Horizontal reference disparity and horizontal and oblique test disparities. PSEs are shown as a function of the difference in the disparity directions between the central and surrounding plaids. When the disparity direction difference is zero, the disparity directions of both plaids are horizontal. When the difference is non-zero, the reference disparity direction is horizontal and the test disparity direction is oblique. Bars give horizontal-disparity predictions. Error bars = ± 1 SEM.

disparity direction reflected about the horizontal axis. No systematic differences in PSE were found between these cases for either observer and the data for the two cases were averaged.

Figure 3 plots the test component phase disparities required to obtain depth matches in conditions 1 and 2. In condition 1, the plaids' disparity directions were the same; these directions were $\pm 30^\circ$, $\pm 45^\circ$, or $\pm 60^\circ$ from horizontal, depending on plaid angle. In condition 2, the two disparity directions differed by 60° , 90° , or 120° , depending on plaid angle. Despite all this diversity, PSEs are very nearly equal for all the plaid pairs of conditions 1 and 2. There is a difference—test plaids with disparity directions identical to the reference plaid consistently required a smaller disparity for a depth match than those differing in direction. This is a very small difference, well within measurement error, and as can be seen by the bars in Figure 3 that give the prediction for the horizontal disparity hypothesis, the difference nudges the PSEs for the differing-direction conditions slightly closer than the same-direction conditions to the values that this hypothesis

predicts. In addition, the difference in PSEs between these two conditions is unrelated to the size of the difference in disparity directions.

PSEs in all conditions, and for both observers, fell below the phase disparity of 15° predicted by a horizontal disparity metric. This occurred even in the same-disparity-directions conditions, where a physical match between the central and surrounding plaids is possible. Chai and Farell (2009) observed a bias for a central grating to appear more distant than a surrounding plaid when presented in the same envelopes as used here. This, then, seems to be a configurational effect on perceived depth, independent of effects of disparity. Evidence supporting this appears later.

Figure 4 shows results for conditions 4 and 5. In condition 5, the disparity direction is the same—horizontal—for both plaids. In condition 4, the disparity direction for the reference plaid is horizontal and the disparity direction for the test plaid is oblique. For each of the three plaid angles, the PSEs for the same- and different-direction conditions equally approximated the expectation of the horizontal-disparity hypothesis (15° phase disparity for same-direction conditions, 30° phase disparity for different-direction conditions, as shown by the bars in Figure 4). Again, the bias to see the central

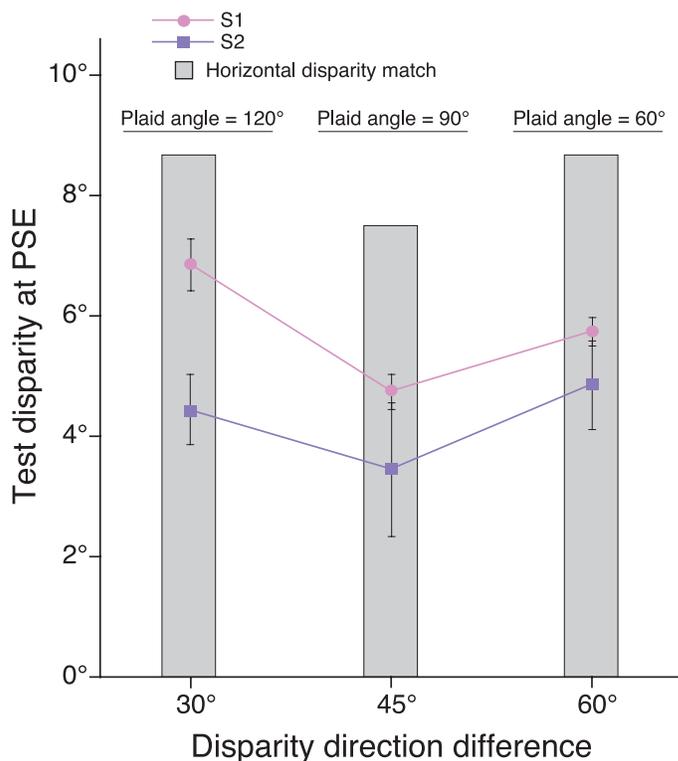


Figure 5. Component depth-matching disparities for the two observers in Experiment 1, condition 3: Oblique reference disparities and horizontal test disparities. PSEs are shown as a function of the difference in the disparity directions of the central and surrounding plaids. Bars give horizontal-disparity predictions. Error bars = ± 1 SEM.

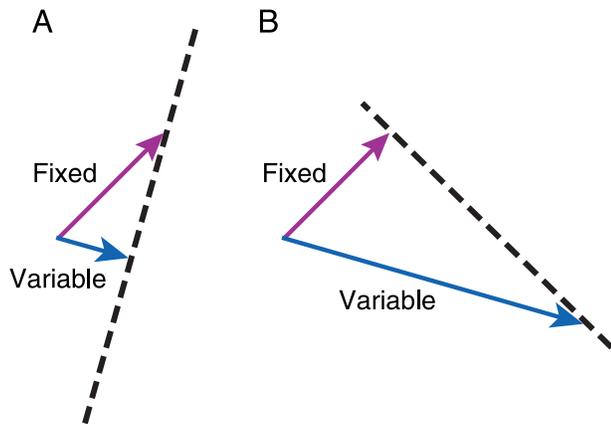


Figure 6. Two cases of disparity projection. The violet arrow represents the fixed disparity vector of the reference stimulus; the blue arrow represents the variable-magnitude disparity vector of the test stimulus. Disparity projection predicts a depth match between two stimuli, *X* and *Y*, when the disparity of *Y* equals the projection of the disparity vector of *X* onto the disparity axis of *Y*. For a pair of 2-D stimuli, one with fixed and one with variable disparity, the predicted depth match can occur in two ways: when the fixed-disparity stimulus functions as *X* and the variable-disparity stimulus functions as *Y* (panel A), and when the reverse is the case (panel B).

plaid as farther than the surround, manifest by the smaller-than-predicted PSEs, appears in almost all cases.

Figure 5 shows results for condition 3 across the three plaid angles. For these data, the disparity direction of the test plaid was horizontal and that of the reference grating was oblique. The disparity direction difference varied between 30° and 60°. PSEs were not monotonically related to this difference. Instead, they were related to the plaids' horizontal disparity components. To equalize the horizontal components of the two plaids' disparities, the test phase disparity must be 8.66° (for disparity direction differences of 30° and 60°) or 7.5° (for a disparity direction difference of 45°), as shown by the bars in Figure 5. In all conditions, and for both observers, PSEs were several degrees of phase disparity below these horizontal-disparity predictions.

Across Figures 3, 4, and 5 there is scant evidence that depth matches are sensitive to a difference in disparity direction between the stimuli. Plaids are seen as matching in depth when they have approximately the same horizontal disparity, whether their disparity directions are the same and both horizontal, the same and both +60° or -60° from horizontal, for example, or different from each other by as much as 120°. In all these conditions perceived depth depends on the relative size of the horizontal components of the plaids' disparity vectors. In deciding on a depth match in our conditions, humans evidently discard vertical disparity differences between the stimuli, both differences in magnitude and differences in polarity. These differences in vertical disparity magnitude can be

larger than the horizontal disparities used for the depth judgment, as was the case in several of the conditions of this experiment.

Projection predictions

As reported elsewhere (Chai & Farell, 2009; Farell et al., 2009), horizontal disparity does not predict depth matches between a grating and a plaid, but a disparity projection calculation does predict them. The prediction is given by the projection of the disparity vector of the plaid onto the grating's disparity axis. A grating whose disparity magnitude equals this projected value produces an approximate depth match between the two stimuli. Figure 6 shows the construction applied to the disparities of a pair of plaids. The variable-magnitude disparity of the test plaid appears as a blue arrow and the fixed-magnitude disparity of the reference plaid appears as a violet arrow. Pairs of 2-D stimuli lack the asymmetry of grating-plaid pairs, requiring two solutions to be considered. Figure 6A considers the case where disparity vector of the reference plaid is projected onto the disparity axis of the test plaid and Figure 6B considers the reverse case. Because the only the reference disparity is fixed in magnitude, these cases lead to different predictions. Both sets of predictions for the conditions of Experiment 1 appear in Table 1.

	Plaid Angle	Disparity Direction Difference	Predicted PSE	
			A	B
Conditions 1 & 2 (Figure 3)	120°	0°	15°	15°
		60°	7.5°	30°
	90°	0°	15°	15°
		90°	0°	0°
60°	0°	15°	15°	
	120°	-7.5°	-30°	
Conditions 4 & 5 (Figure 4)	120°	0°	15°	15°
		30°	22.5°	30°
	90°	0°	15°	15°
		45°	15°	30°
	60°	0°	15°	15°
60°		7.5°	30°	
Condition 3 (Figure 5)	120°	30°	7.5°	10°
	90°	45°	7.5°	15°
	60°	60°	7.5°	30°

Table 1. Disparity projection predictions for Experiment 1. Conditions of the experiment are grouped according to the figure in which their data are plotted. The predicted values, like the plotted values in Figures 3, 4, and 5, are component phase disparities for the test plaids at the perceived depth match. The two sets of predicted PSEs follow the sketches Figure 6: Set A predictions assume the observer calculates the projection as shown in Figure 6A; Set B predictions use Figure 6B in the assumption.

Comparing the values in Table 1 with the data shown in Figures 3, 4, and 5, we find one case where the projected-disparity predictions are the same as the horizontal-disparity predictions (Conditions 4 and 5, Prediction B), and another where the projected-disparity predictions are not grossly far from the observed data (Condition 3, Prediction A). However, it is apparent from Table 1 that neither of the constructions illustrated in Figure 6 alone accords with the data of Experiment 1 overall, and even the most creative switching between or melding of them would not allow observers to approximate the results obtained from Conditions 1 and 2 (Figure 3), which differ qualitatively from predicted values.

Generality and bias

We ran a subsidiary experiment, using a single observer who did not otherwise participate in the study, in order to generalize beyond the specific combination of stimulus and task parameters and to test our interpretation of the lower-than-expected PSEs seen in Experiment 1. We again ran the conditions plotted in Figure 3, adding two new variables that switched the roles of the two plaids. One variable

determined which plaid functioned as the fixed-disparity reference stimulus and which functioned as the variable-disparity test stimulus; the other variable controlled which of these two plaids functioned as the ‘decision stimulus’: the plaid judged as ‘near’ or ‘far’ with respect to the other.

Plaid pairs had components oriented at 60° and 120° , 45° and 135° , or 30° and 150° . The central plaid had the same component orientations as the surrounding plaid. The reference plaid had one component with a phase disparity of 15° and another with a phase disparity of 0° . The test plaid had a component whose disparity varied from trial to trial, and another component with a disparity of 0° . Depending on the orientations of the components and how the disparity values were distributed across them, the two plaids had disparity directions that were identical (with any one of six possible values: $\pm 30^\circ$, $\pm 45^\circ$, or $\pm 60^\circ$; condition 1) or that differed by 120° , 90° , or 60° (condition 2).

We manipulated which of the two plaids had variable disparity and which of the two plaids the observer was to judge as ‘near’ or ‘far’. In separate runs of trials, the plaid having the variable disparity (the test plaid) was in the center, as in previous conditions, or it was in the surround. The observer was not informed about which plaid had

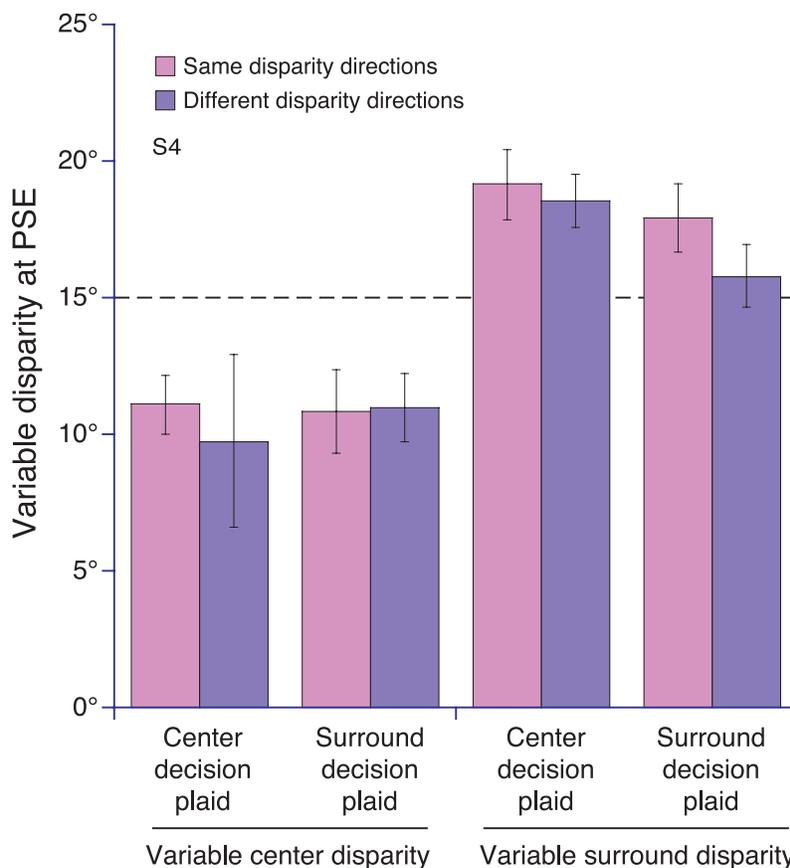


Figure 7. PSEs for variations of conditions 1 and 2 of Experiment 1. The plaid with variable disparity was either the center or the surround, the other plaid having fixed disparity. The ‘decision plaid’ that the observer judged as ‘near’ or ‘far’ was either in the center or the surround. For each of the four combinations of these variables, the plaids’ disparity directions might be the same or different. PSEs are averaged over three different plaid angles and all disparity directions. PSEs of 15° give the plaids equal horizontal disparities. Bars show means ± 1 SEM.

constant disparity and which had variable disparity. For each of these two cases, the observer was instructed to judge the depth of the center plaid as ‘near’ or ‘far’ with respect to the depth of the surrounding plaid, or to judge the depth of the surrounding plaid as ‘near’ or ‘far’ with respect to the depth of the center plaid. The roles of test and reference stimuli and of decision stimulus were constant within a run of trials. In other respects, the experiment was as previously described.

PSEs showed no systematic effect of absolute disparity directions. For example, whether both plaids had a disparity direction of 45° or 135° had no effect, and there was no difference between the three pairs of component disparities (60° and 120° , 45° and 135° , and 30° and 150°). These data were combined in Figure 7, which shows PSEs as a function of the relative disparity direction (same or different), the test plaid (center or surround), and the decision plaid (center or surround). Clearly, whether the variable disparity was in the center or the surround affected perceived depth; the other factors had negligible influence. As in Figure 3, relative disparity direction had scant effect: whether both plaids had the same disparity directions (e.g., both 45° or both 135°) or different disparity directions (one at 45° and one at 135°) was irrelevant to the relative depth perceived. This essential feature of Figure 3 held up whether the decision plaid was in the center or in the surround, a variable that also had no effect on PSEs. It also held up whether the center plaid had constant disparity and the surround plaid had variable disparity or vice versa.

PSEs were consistently lower than the expected 15° phase disparity when the plaid with variable disparity was in the center, replicating the data of Figure 3. Yet PSEs were consistently higher than 15° when the variable-disparity plaid was in the surround. (The overall mean PSE was 14.3° .) This effect of the location of the variable-disparity plaid is what we would expect if the asymmetry between the two plaids’ perceived depths arises from a bias created by their center-surround configuration, a bias to see the center as ‘far’. To overcome this bias the center plaid needs a relatively small variable disparity to match the apparent ‘far’ depth of the fixed-disparity surrounding plaid; and the surrounding plaid requires a relatively large variable disparity to match the apparent ‘far’ depth of the fixed-disparity center plaid. The bias thus arises from the center-surround configuration and not from the specifics of the disparity distribution or the task instructions.

Experiment 2: Mixed symmetric, asymmetrical, and reversed-depth plaids

It is easy to show that, regardless of how disparity is distributed across its components, a symmetrical plaid

with a constant integrated component disparity will have a constant horizontal disparity. Thus, if a depth match is determined strictly by horizontal disparity, one symmetrical plaid having two components with 15° disparity will be matched in depth by a plaid that is identical except in having one component with 30° disparity and the other with 0° disparity. Likewise, a symmetrical plaid with component disparities of 15° and 0° will be depth-matched by a plaid that is identical except that the respective component disparities are 0° and 15° or 7.5° and 7.5° , or any other pair of values summing to 15° .

Integrated component disparity ought to be of little use as a general predictor of perceived depth. Stimuli that are equivalent by this metric can differ in disparity in ways that intuition tells us will certainly affect our stereo depth perception. We next verified that horizontal disparity, not total component disparity, is the effective signal in depth judgments for pairs of plaids. To do this, we determined whether the invariance to vertical disparity differences holds for plaids in the general case, where horizontal disparity and integrated component disparity are decoupled. We tested three classes of such decoupled plaid pairs: pairs of different symmetric plaids, pairs of asymmetric plaids, and ‘depth-reversed’ plaids, whose horizontal disparities are equal only if their component disparities have opposite polarities.

Methods

The methods were identical to those of Experiment 1 except for the way the stimuli were constructed. We constructed pairs of plaids by using all pairwise combinations of sinusoidal gratings with orientations of 30° , 60° , 120° , and 150° such that all four component orientations appeared in each pair of plaids. For each of these distinct pairs, there were four conditions generated by setting the disparity of either of the two components of the reference plaid to 15° (the other component disparity was set to 0°) and varying either one of the two components of the test plaid from trial to trial according to a constant stimulus procedure (the other component disparity being fixed at 0°). Disparity directions of the test plaid and the reference plaid thereby differed by 30° , 60° , 90° , or 120° . The various combinations of component orientation and component disparity fall into the three categories mentioned above: different symmetrical (with component orientations of $30^\circ + 150^\circ$ for one plaid and $60^\circ + 120^\circ$ for the other), asymmetrical ($60^\circ + 150^\circ$ and $30^\circ + 120^\circ$), and reversed-depth ($30^\circ + 60^\circ$ and $120^\circ + 150^\circ$) plaid pairs.² There were two sets of mixed symmetrical plaids; these differed by having the central plaid in one set appearing as the surrounding plaid in the other. This (or some manipulation with equivalent effect) is required to produce variation in the reference plaids’ horizontal disparity in this condition. Across all conditions, there were 16 distinct plaid pairs.

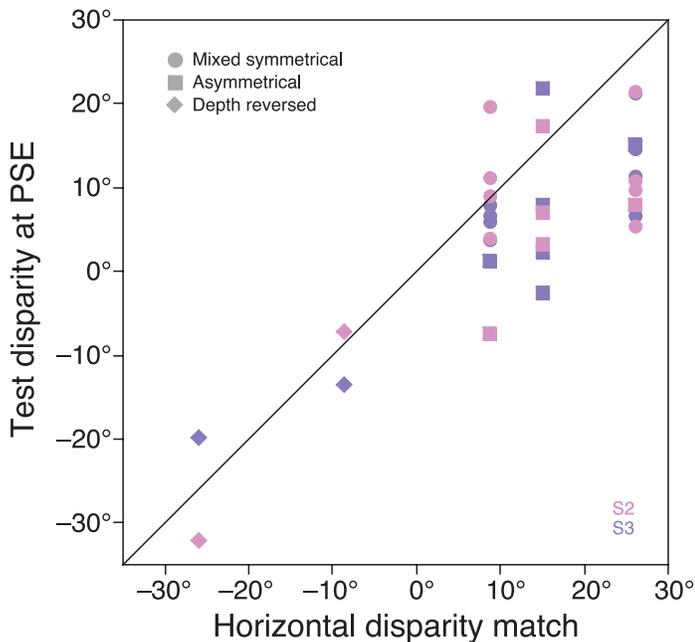


Figure 8. Component depth-matching disparities for mixed symmetrical, asymmetrical, and reversed-depth plaid pairs of Experiment 2, plotted against horizontal-disparity prediction. Data of two observers are plotted separately.

The central plaid again served as the test stimulus whose disparity varied from trial to trial, governed by the constant-stimulus method used in the previous experiment. The surrounding plaid had a fixed disparity across a block of trials, also as in the previous experiment. There were two observers, both experienced in stereo tasks, one of whom ran in Experiment 1. Their task was to judge the depth of the central plaid relative to that of the surrounding plaid.

Results

Results for the 16 stimulus pairs (4 pairs of test and reference plaids \times 4 combinations of component disparities) appear in Figure 8 for the two observers tested. A third observer (one of the authors) was tested in a subset of the conditions and produced similar results (data not shown). Component disparities at the PSE are plotted against the value predicted under the hypothesis that equal horizontal disparities produces equal perceived depth. Despite the compression evident in observed PSEs at large predicted values, horizontal disparity accounts for a considerable proportion of the variation in depth matches. Most of the pairs of plaids had disparity directions that differed by 30° or 90° ; correlations between predicted and observed values were similar for these two cases ($r = 0.86$ and $r = 0.94$, respectively, for S2 and $r = 0.87$ and $r = 0.97$, respectively, for S3). (In the other two cases, where

disparity directions differed by 60° or 120° , predicted disparity is constant at $+15^\circ$.)

This general agreement between the observed PSEs and the horizontal-disparity predictions held despite variation in the plaids' disparity directions and component orientations. Similarity of the plaids' disparity directions showed little linear relation to PSEs ($r = -0.028$ and -0.248 for the two observers, $p > 0.05$ in both cases), as seen in Figure 9. Projected disparity varies with the sine of the disparity direction difference, and similarly shows no relation to the data. Thus, as in Experiment 1, we find the factor that accurately predicts depth matches for grating-plaid pairs (Chai & Farell, 2009; Farell et al., 2009) does not contribute to depth matches for pairs of plaids. Note that for some data points in Figure 8—those for depth-reversed plaid pairs—the predicted (and observed) component disparities at the PSE are negative: The reference plaid had one component with zero disparity and one with positive disparity, while at the depth match the test plaid had one component with zero disparity and one with negative disparity. Component disparity seems to play no independent role in depth perception. (For a discussion of the relation between component and pattern disparity in depth-reversed plaids, see Farell, 1998; also see Farell et al., 2009).

Deviations of PSEs from the values predicted by horizontal disparities in Figure 8 are concentrated at the highest predicted values. All these data points come from a single category of stimuli: The disparity directions were $\pm 30^\circ$ for reference plaids and $\pm 60^\circ$ for test plaids. It is in this category that the horizontal disparity of the reference

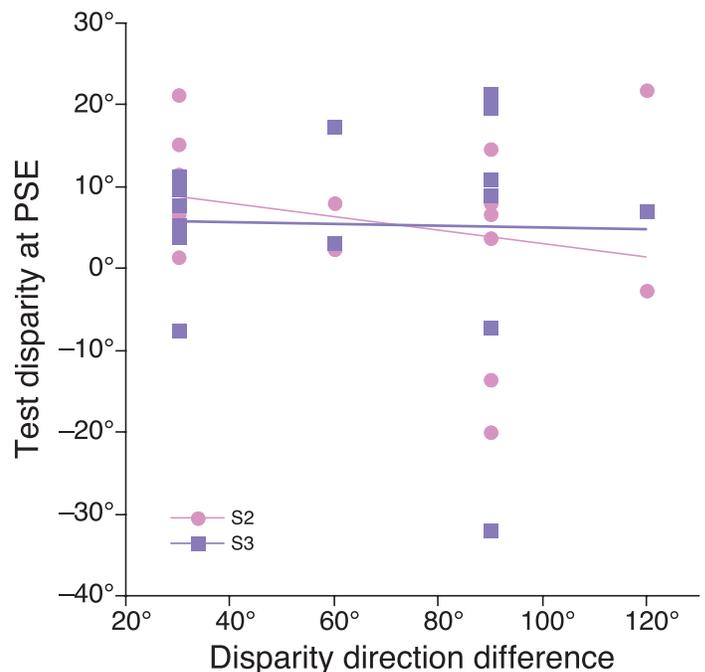


Figure 9. PSEs for Experiment 2 as a function of the difference between the disparity directions of the reference and test plaids. Lines are the linear fits to the data of the two observers.

plaid was largest and disparity direction of the test plaid was most vertical. We suspect that the lower-than-predicted PSEs resulted from the large vertical disparity component of the test plaids required for a depth match. This vertical disparity might have been outside the discountable range for a foveal stimulus. In fact, PSEs for the same plaids were very nearly centered on the predicted value when the roles of test and reference were switched, such that the plaid with disparity direction of $\pm 60^\circ$ was located in the surround rather than the center (Figure 8; mean Test Disparity at PSE = 8.6° for circular symbols at Horizontal Disparity Match = 8.7°).

Experiment 3: Depth-interval matches

Experiments 1 and 2 measured depth-matching disparities. When displayed with these disparities, the test and reference stimuli appear at the same depth. An alternative gauge of perceived depth comes from measuring the apparent depth separation between two test stimuli (the ‘depth interval’). One measures the relative disparity of a pair of standard stimuli that produces the same apparent depth interval as that which separates the test stimuli. In effect, one finds a disparity that reproduces the depth separation between the test stimuli, rather than finding a disparity that nulls the depth separation, as depth-matching measures do. Experiment 3 asks whether the horizontal disparity metric behind depth matches seen in the earlier depth-matching experiments generalizes to the perception of extended depth intervals.

The study of Friedman et al. (1978) suggests that it might not generalize. Observers in that study judged the depth separation between a test disk and a fixation marker as a proportion of the viewing distance. As the disparity direction of the disk went from horizontal to vertical (with a constant disparity magnitude), the perceived depth interval decreased. Control conditions showed that the decrease in perceived depth exceeded the correlated decrease in the disk’s horizontal disparity. The vertical component of the disparity seemed to interfere with the perception of depth from the horizontal component. The fact that Friedman et al. (1978) measured extended depth intervals rather than depth matches might underlie the different outcomes of their study and our Experiments 1 and 2.

Method

The test stimuli were similar to the center-surround plaid pairs used in Experiment 1. However, departing from previous experiments, the two plaids appeared in one of two intervals within a trial and both of them had their disparities fixed during a block of trials.

The other interval contained the standard stimuli, which were a pair of vertical sinusoidal gratings. These gratings also appeared in center-surround arrangement, bound by the same envelope functions used for the plaids. They had the same frequency (2 c/d) and contrast (0.1) as the components of the plaids. The disparity of one grating was fixed at zero; the disparity of the other varied from trial to trial under control of the constant-stimulus procedure used in previous experiments. All stimulus envelopes had the same (zero) disparity.

The plaids had component orientations of 45° and 135° . For the annular plaid, either or both of these components could have non-zero (30°) phase disparity, giving the plaid as a whole a disparity direction of 0° , $+45^\circ$, or -45° . As in Experiment 1, the plaid’s disparity magnitude was greater (here by a factor of $\sqrt{2}$) when its direction was horizontal rather than oblique.

The disparity of the central plaid differed systematically across conditions in magnitude and direction from the disparity of the surrounding plaid. In particular, the central plaid had one component (oriented at 45°) with a phase disparity of 0° , 15° or 30° , and another component (oriented at 135°) with a phase disparity of 0° ; or these disparities were swapped across the two component orientations; or both components had phase disparities of 0° , 15° or 30° .

Stimuli in each interval were centered in the middle of the screen and appeared for 153 ms for one observer (S1) and for 706 ms for the other (S3). The longer duration was adopted after S3 found the shorter one too brisk to allow confident comparisons of the two depth intervals. Both observers had prior experience with single-interval stereo tasks, but none with two-interval tasks. Because the task depended on relative disparity, we expected that stimulus duration, and the possibility of eye movements, would have no systematic effect on PSEs across conditions. The inter-stimulus interval lasted 506 ms; during the inter-stimulus interval and after the second interval, the screen returned to a uniform display of the background luminance.

The observer’s task was to decide whether the depth interval between the central and surrounding patterns was greater in the first interval or the second interval. They did this by using a mouse to click on-screen buttons labeled “1st Interval” and “2nd Interval”, which appeared after a short delay following the second interval. Psychometric functions were fitted to the data; the mid-point of these functions gave the estimated grating disparity difference that yields a perceived depth-interval match.

Each of the two observers ran in a different one of the two previous experiments. Remaining experimental details were drawn from Experiment 1.

Results

The data points of Figure 10 give the relative disparity between the two standard gratings that produced the same

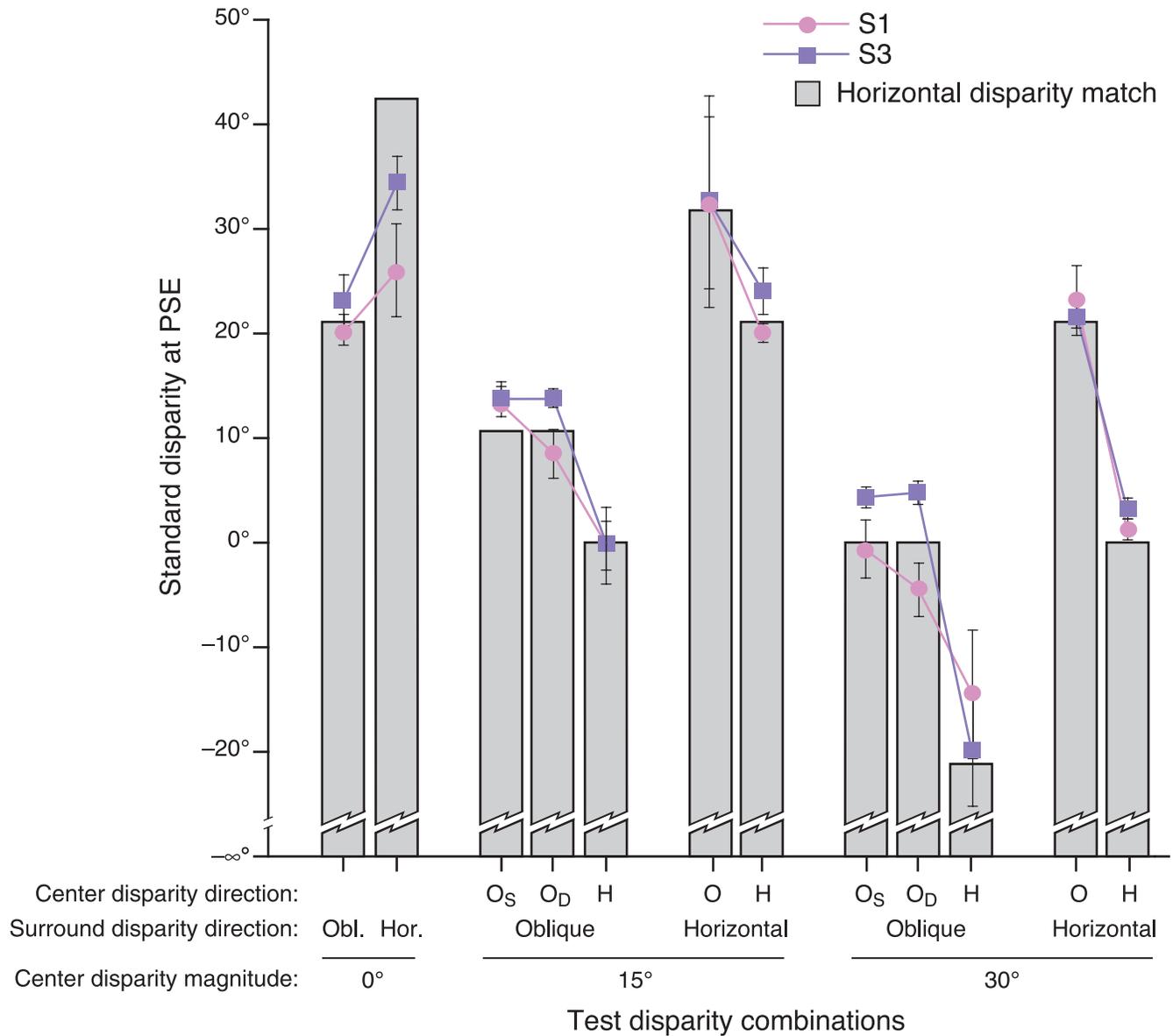


Figure 10. Depth-interval matches for the two observers in Experiment 3. Data show the relative disparity of vertical gratings that produces the same perceived depth interval as that seen between the two test plaids. Test plaids are categorized along the x-axis according to their disparity directions and magnitudes, as explained in the text. Bars show horizontal-disparity predictions. Error bars = ± 1 SEM.

depth interval as observers saw between the two test plaids. The plaids are categorized along the x-axis according to their relative disparities. A horizontal-disparity metric, which predicts the values given by the bars, gives a quite good account generally of the data for each of the observers.

Our interest is in the possibility that differences in disparity direction affect the perceived depth interval. The disparity direction of the surrounding plaid was horizontal or oblique. The disparity direction of the central plaid was also horizontal or oblique (for non-zero disparity magnitudes). The plaids' oblique disparity directions could be the same (O_S) or different (O_D). Similarly, when the disparity of one plaid was horizontal, the disparity

direction of the other plaid could be the same or different. For most of these stimulus conditions, alternatives to the horizontal-disparity hypothesis predict results that are quite distinct. For example, the disparity projection prediction (Chai & Farell, 2009; Farell et al., 2009) is that the plaids' perceived depth-interval ought to differ between same- and different-oblique plaid disparity directions. For the same (O_S) directions, the depth-interval match ought to be 30° and for different (O_D) directions it ought to be 0°. This is not what the data in Figure 10 show. Such a discrepancy between the results and the alternative expectation exists across all conditions in which the disparity directions differ. Therefore, there is no evidence that relative disparity direction, rather than

relative horizontal disparity, affects the perception of depth intervals.

The most noticeable discrepancy between the results of Figure 10 and those predicted by horizontal disparities occurs in the condition that seems most likely on *a priori* grounds to obey a horizontal disparity metric for perceived depth. This occurs in the second column from the left, where the center plaid has a disparity of zero and the surrounding plaid has a horizontal disparity equivalent to 42.42° . The predicted depth-interval match comes at a grating disparity of 42.42° , yet the results of both observers are somewhat lower than this value. This combination of test disparities—one with a zero magnitude and the other with horizontal direction—is by far the most commonly studied; it is the standard condition for measuring stereo-acuity and perceived depth. We suspect that the reason for the discrepancy observed here an effect of exceeding a disparity-gradient limit (Burt & Julesz, 1980). The difference in disparity magnitude between the plaids was largest in this condition and the plaids were not laterally separated much relative to the period of the carrier. This could have decreased the perceived depth between the plaids. Indeed, our impression from informal viewing is that diplopia made a frequent appearance in this condition.

Discussion

The perceived depth of plaids, measured by depth matches and by depth-interval matches, is a univariate function of disparity magnitude. Under the conditions of our experiments, perceived depth depends on disparity magnitude in the horizontal direction. The vertical components of the plaids' disparities, provided they are within tolerated limits, appear to make no contribution to perceived depth whether they are identical across the two stimuli or not. Thus, differences in the disparity directions do not enter into the calculation of the relative stereo depth of our 2-D stimuli.

A vast literature supports the dependence of stereo depth on horizontal disparity. Curiously, though, it has never before been tested as we have tested it here. The reason for this surely is that no need was seen for such a test. However, a stereo depth calculation that does not make use of horizontal disparities has been recently identified. The perceived depth of a grating relative to a plaid depends instead on the magnitude and direction of the disparity of one stimulus relative to those of the other (Chai & Farell, 2009; Farell et al., 2009). This result seems a radical exception to the usual role of horizontal disparity in stereoscopic vision, but there is a region of overlap between the two depth calculations. Horizontal disparity does not predict depth match between a grating and a plaid in the general case. However, in two special-

and important—cases, the depth matches predicted by disparity projection and by horizontal disparity are the same. One case occurs when the disparity direction of one or both of the stimuli is horizontal, and the other occurs when the disparity magnitude of the reference stimulus is zero (Farell et al., 2009).

Of the many studies consistent with horizontal disparity as the metric on which stereo depth is calculated, the bulk falls into one or the other (and most often, both) of these special cases. These studies are also consistent with the projected disparity hypothesis. In the present experiments horizontal disparities and projected disparities predict different outcomes, which accounts for the uncertainty about how the data would turn out.

The outcome of our experiments here differs from what we have observed previously using grating-plaid pairs, yet the two results are compatible, not contradictory. The surprising lack of a contribution of horizontal disparity in the previous studies (Chai & Farell, 2009; Farell et al., 2009) might indicate either of two things. It might be that horizontal disparity is not used to calculate the depth of 1-D stimuli or that horizontal disparity is not used to calculate the depth of stimuli whose disparities are non-horizontal. In fact, projected disparity predicts the depth of 1-D stimuli only; the present results show that the perceived depth of 2-D stimuli depends on horizontal disparities regardless of the stimulus disparity directions.

Perceived depth in our experiments depended on horizontal disparity over the full range ($\pm 60^\circ$ of horizontal) of the disparity directions tested. This outcome held in the absence of a stimulus with a strictly horizontal or zero-magnitude disparity to act as a reference in the relative disparity computation. It held for depth matches, at which the perceived depth separation between the stimuli is zero, and it held for depth-interval matches, at which the same perceived depth separation exists across two stimulus pairs.

The difference in the depth calculations for 1-D and 2-D stimuli prompts an observation and a question. The observation is that this difference can lead to intransitive depth matches: A plaid might have the same perceived depth as a grating that in turn has the same perceived depth as another plaid, but in general these two plaids will not match in depth. The question it raises is, Why does the visual system use more than a single algorithm for calculating relative depth, one when 1-D stimuli are encountered, another when they are not? The relative depth seen between gratings and plaids is generally non-veridical; it does not survive a change in grating orientation (Farell et al., 2009). By contrast, the relative depth seen between two plaids should survive any change in orientation or disparity direction (within the vertical disparity tolerance range) that conserves the difference between the horizontal disparity components. This is an advantage of coding disparity along a stimulus-independent direction. The visual system does not do this with 1-D stimuli like gratings, but rather codes disparity and orientation jointly (Farell, 2006; Farell et al., 2009).

The disparities encountered in natural scenes are typically but not generally epipolar. Effects of occlusions and apertures, ocular torsion, and differential perspective, among other factors, make the distribution of disparity directions two-dimensional. Known physiological mechanisms can find binocular matches, within a limited range of magnitudes, whatever the direction of disparity (e.g., Anzai, Ohzawa, & Freeman, 1999; Barlow, Blakemore, & Pettigrew, 1967; LeVay & Voigt, 1988; Maunsell & Van Essen, 1983; Ohzawa & Freeman, 1986; Prince, Pointon, Cumming, & Parker, 2002; von der Heydt, Adorjani, Hányi, & Baumgartner, 1978; see, however, Cumming, 2002). Presumably, the distribution of preferred disparities of these mechanisms has no direct relation to the two-dimensional distribution of disparity directions encountered in natural scenes. Instead, it would be expected to reflect the distribution of component disparities.

It is unlikely that the disparity-projection calculation exists in order to contribute to our perception of lines or gratings in depth (Chai & Farell, 2009). Rather, it is useful for combining the disparities of the 1-D components of a 2-D patterns (Farell, 1998; Patel, Bedell, & Sampat, 2006; Patel et al., 2003). To arrive at an orientation-invariant disparity, component disparities should be combined along a stimulus-independent disparity axis. Horizontal disparities provide such an axis, and our evidence here shows that horizontal disparities do provide a common metric for comparing the depths of different 2-D patterns, whether their spatial structures and disparity directions are similar or not. However, horizontal pattern disparities are probably not calculated from component disparities directly, but rather from an intermediate computation that yields the two-dimensional pattern disparity vector. This appears computationally easier than the direct route. Data for depth matches between gratings and plaids (Chai & Farell, 2009; Farell et al., 2009) show that a representation of these two-dimensional pattern disparities exists and is used.

Friedman et al. (1978) and Ogle (1955)

Large differences in the vertical components of disparity did not influence the relative depth seen between our stimuli. Of course, arbitrary local vertical disparities are not usually encountered; nor, if encountered, are they necessarily interpretable. Nevertheless, they are interpreted and used in judgments of the relative depth of a 1-D and a 2-D stimulus, as we've demonstrated elsewhere. The fact that they need not affect judgments about the depth of a pair of 2-D stimuli means that the two-dimensionality of the disparities of these stimuli is not the essential property for interpreting their stereo depth that it is in the case of 1-D stimuli.

We have previously reviewed prior studies of the perceived depth between 1-D and 2-D (Chai & Farell, 2009). As already mentioned, prior studies of 2-D

stimulus pairs do not address the question we posed here, but two of these studies are still relevant, for they measured the effect on perceived depth of differences in vertical disparity.

Ogle (1955) used a spot of light as a test stimulus and measured the horizontal disparity at the threshold for depth-polarity discrimination and at a perceived depth match between the test spot and a reference stimulus. This reference stimulus, a vertical luminous “needle”, was presented either on the horopter or with a horizontal disparity of -8.5 arcmin. Ogle asked how adding a vertical component to the disparity of the test spot would change the relative depth of the stimuli. For near-foveal test spots, he found that vertical disparities as large as 20 arcmin had essentially no effect on depth matches. [See Lothridge (1953) for a similar set of results from an experiment in which reference disparity was kept at zero.]

In a study we earlier summarized, Friedman et al. (1978) used a bright disk as the test stimulus and presented it with a fixation mark; they assessed perceived depth interval using a form of magnitude estimation. In contrast with Ogle (1955), they found that adding vertical disparity to a stimulus with a constant horizontal disparity diminished its perceived depth. Clearly, vertical disparity differences can affect perceived depth, if for no other reason than any disparity that is large enough can disrupt binocular fusion. Indeed, in comparison with Friedman, Kaye and Richards, our stimuli lacked component wavelengths that were short relative to the size of the disparity (which was large— 1° —in their study). But as is clear from our data and those of Ogle (1955), vertical disparity differences need not affect perceived depth. The stereo system can discard them.

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Footnotes

¹The disparity we discuss in this article can be thought of as physical disparity. We do not consider issues raised by stereo matching. Here's why. For periodic stimuli (and one-dimensional stimuli whether periodic or not), there are multiple disparity vectors that yield binocular

matches. With knowledge of an arbitrarily chosen disparity vector and of the spatial structure of the stimulus (available monocularly), the set of possible matches can be calculated. Any disparity vector will result in the same set of alternative matches. And any disparity vector will reveal the same physical disparity of the stimulus as any other (ignoring disparities that are multiples of the stimulus period, for they lead to descriptions of indistinguishable stimuli). The smallest physical disparity is the one we discuss here and is the disparity usually thought of as corresponding to the stereo match.

²The sign of component disparities is reversed between plaids having the same horizontal sign in two of the four of the cases tested with these plaids. It is reversed when the component with non-zero disparity is the more-horizontal or the more-vertical of the two components in both plaids. In other conditions these same plaids have component disparities of the same sign and fall into the ‘asymmetrical plaids’ condition.

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