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Attentional selection in judgments of stereo depth

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Stereoscopic depth is most useful when it comes from relative rather than absolute disparities. However, the depth perceived from relative disparities can vary with stimulus parameters that have no connection with depth or are irrelevant to the task. We investigated observers' ability to judge the stereo depth of task-relevant stimuli while ignoring irrelevant stimuli. The calculation of depth from disparity differs for 1-D and 2-D stimuli and we investigated the role this difference plays in observers' ability to selectively process relevant information. We show that the presence of irrelevant disparities affects perceived depth differently depending on stimulus dimensionality. Observers could not ignore disparities of irrelevant stimuli when they judged the relative depth between a 1-D stimulus (a grating) and a 2-D stimulus (a plaid). Yet these irrelevant disparities did not affect judgments of the relative depth between 2-D stimuli. Two processes contributing to stereo depth were identified, only one of which computes depth from a horizontal disparity metric and permits attentional selection. The other uses all stimuli, relevant and irrelevant, to calculate an effective disparity direction for comparing disparity magnitudes. These processes produce inseparable effects in most data sets. Using multiple disparity directions and comparing 1-D and 2-D stimuli can distinguish them.

1. Introduction

A small change in binocular disparity might appear as a conspicuous change in stereoscopic depth while a large one might go unseen. Whether the disparity is absolute or relative is one factor (among many) that determines which outcome occurs. Without a reference stimulus to provide a relative disparity signal, absolute disparity has a high detection threshold (Westheimer, 1984; Erkelens & Collewijn, 1985; Regan, *et al.*, 1986; Cormack & Riddle, 1996; Farell, 2006) and might not be accessible for explicit judgment ('the absolute disparity anomaly'; Chopin *et al.*, 2016). Access to relative disparities requires two or more stimuli, or a stimulus with multiple disparities, and these disparity sources have to be near enough to one another, laterally and in depth, to support task performance. In generally, though, how similar the stimuli with respect to properties other than disparity is not of primary importance: Judging stereoscopic depth is a ‘where’ task, not a ‘what’ task. For example (and rather surprisingly), spatial frequency differences between target and reference stimuli have little influence on stereoacuity (Siderov & Harwerth, 1993). One exception to this generality is orientation: Two stimuli that are similar in orientation are systematically more stereo-depth discriminable than stimuli that have a larger orientation difference (Farell, 2006).

Another effect of this type, one that interacts with the orientation-difference effect, arises when the difference is one of stimulus dimensionality, specifically when one stimulus is one-dimensional (1-D) and the other is two-dimensional (2-D). This difference affects not only the perception of depth, but also the depth-from-disparity computation. While relative horizontal disparity is the classical stereo signal and largely determines the perceived stereoscopic depth between 2-D stimuli, horizontal disparity magnitude plays no special role in computing the stereo depth between a 1-D stimulus and a 2-D stimulus. Perceived depth in this case depends on the difference between the two disparity vectors—the disparity directions as well as magnitudes (Farell, *et al*., 2009; Chai & Farell, 2009)[1]. Here we further compare these two depth-from-disparity computations by examining their responses to the disparities of irrelevant stimuli, which observers have been instructed to ignore.

1.1 Disparity direction and dimensionality

Physical disparities—the relative positions of left and right retinal image points—might be horizontal, vertical, or oblique, but the quantity that appears to matter most for perceiving the stereo depth of 2-D stimuli is the size of the disparity component in the horizontal direction. Thus, the effective disparity—the value used for stereo-depth computations—may differ from the physical disparity. Horizontal disparity, as the effective disparity, provides a ‘common currency’ for depth-from-disparity computations of 2-D stimuli. (Of course, the weight given to the horizontal disparity component can be modulated by a variety of other parameters, including the vertical disparity component.)

1-D stimuli lack such a common currency. Each 1-D stimulus brings to the display its own orientation-contingent disparity direction, a 'local currency' (Farell, 2006). This holds as well for the 1-D components of 2-D stimuli (Farell, 1998; Patel *et al.*, 2003, 2006). What lies behind these differences between 1-D and 2-D stimuli—and what makes 1-D binocular stimuli problematic and interesting—is the stereo aperture effect (Morgan & Castet, 1997; Farell, 1998). As with the aperture effect in motion, where only movement perpendicular to the stimulus orientation is recoverable, the stereo aperture effect limits the effective disparity to this same perpendicular direction (Morgan & Castet, 1997; Farell *et al.*, 2009; Chai & Farell, 2009). Depth from the disparity of 1-D stimuli is generally non-veridical, a consequence of the orientation dependence of the effective disparity direction. Pairing a 1-D and a 2-D stimulus can result in depth-order reversals and non-transitive depth relations (Farell *et al.*, 2009; Farell & Ng, 2014). Although the computations at play are assumed to be the same in kind regardless of disparity direction, a difference in disparity direction is needed to reveal them. When all the disparities are horizontal, the effect of dimensionality is hidden. For that reason, the stimuli we use here have disparities that are non-horizontal and across stimuli may be the same or different in direction.

In one condition of the present study, observers judged the depth of a 1-D target stimulus relative to the depth of 2-D reference stimuli. When these stimuli have the same disparity directions and magnitudes, they should have the same apparent depth, as measured by the point of subjective equality (PSE). When their disparity directions are perpendicular, however, the 1-D stimulus has an expected disparity magnitude of zero at the PSE, independent of the disparity magnitude of the 2-D stimulus (Farell *et al.*, 2009; Chai & Farell, 2009; Farell & Ng, 2014). These expectations for depth matches between 1-D and 2-D stimuli are sketched in Figure 1. This figure holds for depth judgments in displays containing a single pair of stimuli, one 1-D and the other 2-D. The presence of other stimuli, even if irrelevant to the task, can affect the perceived depth of 1-D stimuli relative to 2-D stimuli (Farell & Ng, 2014) in ways we explore in detail below.

In another condition, the target stimulus was 2-D, the same as the reference stimuli. In this case, we expect to find the perceptual depth match occurring when the target and reference stimuli have disparities with horizontal components that are equal,

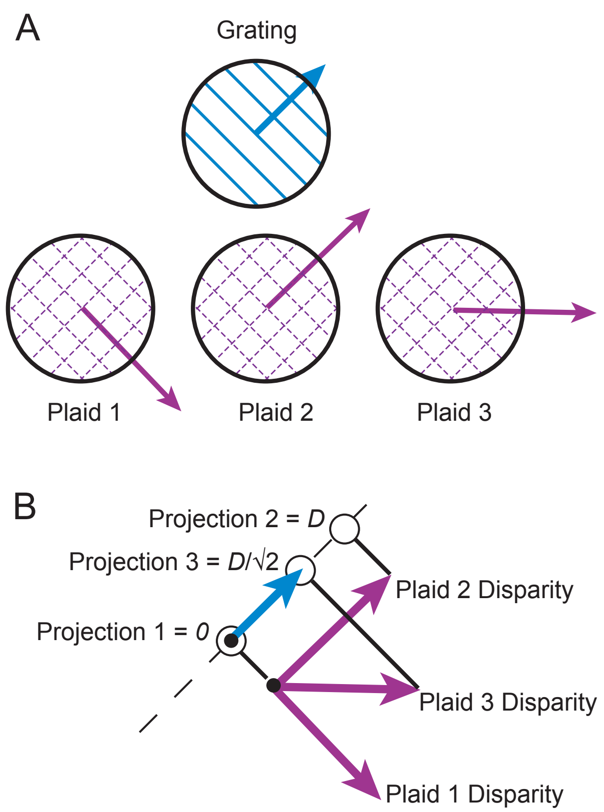

Figure 1. Perceived depth predicted from projected disparities. (*A*) Arrows showing disparity vectors of sample grating (top) and three plaids (with disparity magnitudes exaggerated relative to the pattern wavelength). Disparity directions are 0° (horizontal) and ±45°. (*B*) Plaid disparities projected onto the grating's disparity axis. This axis is indicated by the dashed line. For clarity, the origins of the plaid disparity vectors are displaced from the origin of the grating disparity vector. The solid oblique lines intersect the grating's disparity axis perpendicularly, giving the projections of the plaids' disparities. The three plaids have disparity magnitudes of *D* and projected magnitudes of $D*\cos(\theta g - \theta p)$, where the θ's are the disparity directions of the grating and the plaid. The relative sizes of disparities along the grating's disparity axis predict that a grating with the disparity depicted here will appear farther in depth than one plaid, nearer than another, and at the same depth as the third, despite the equal horizontal disparities of two of the plaids. Reprinted from Farell and Ng (2014).

regardless of whether the disparity directions are parallel or perpendicular (Farell *et al.*, 2010). For example, a pair of 2-D stimuli whose disparity directions are at +45° (where 0° is horizontal) should be seen as equal in depth when their disparity magnitudes are equal. The same holds for the case in which one stimulus has a disparity direction of +45° and the other, -45°. That's because the horizontal disparity components are equal; both are cos(45°) times the size of the oblique physical disparities. Whether judgments of depth from disparity are conserved in the presence of irrelevant disparities will be measured in these two stimulus conditions.

1.2 Depth judgments and irrelevant disparities

We previously used the effect of irrelevant stimuli to investigate the mechanisms contributing to the perceived depth between 1-D and 2-D stimuli (Farell & Ng, 2014). Displays consisted of a grating and two pairs of plaids. One plaid pair was designated as relevant to the task, the other being irrelevant. Observers were instructed to attend to and judge the depth of the grating relative to the relevant plaids (whose disparities were identical) and to ignore the irrelevant plaids. We found that observers' depth judgments were influenced by the disparities of all stimuli in the display. Observers showed no ability to selectively attend to the relevant stimuli. The disparity of the irrelevant plaids affected observers' depth judgments as much as the disparity of the relevant plaids.

This apparent failure of attentional selection is surprising, especially so because the locations of relevant and irrelevant stimuli were constant throughout a block of trials and thus known well in advance. In order to understand this phenomenon, we would like to know if it is unique to the computation of the depth of 1-D stimuli, a quirk of non-horizontal disparity processing, or a general property of stereo depth judgments. In order to determine the most likely of these alternatives, we compared depth judgments between 2-D stimuli in the presence of irrelevant stimuli with those between 1-D and 2-D stimuli. We found that these two judgments responded differently to the disparity signals of irrelevant stimuli. The results indicate that attention can select only some disparity information for depth computations and cannot exclude others. Observers judging relative depth can selectively compare the disparity magnitudes of relevant stimuli and ignore those of irrelevant stimuli. But both relevant and irrelevant stimuli contribute to the scaling of the axis along which relevant disparity magnitudes are compared. Hence, this contribution to the depth-from-disparity calculation is 'pre-attentive'.

1.3 Experiment

We compared judgments of the depth between 2-D stimuli in the presence of irrelevant stimuli and those between stimuli that are identical except for one of the stimuli being, as in our earlier study, 1-D (Farell & Ng, 2014). The sole difference between these two cases is the presence of a zero-disparity grating. When superimposed on the variable-disparity target grating, this grating changes the dimensionality of the stimulus from 1-D to 2-D. Though these two gratings have different disparities, they are not seen in separate depth planes. Superimposed static sinusoidal gratings with similar frequencies are seen as a depth-coherent plaid, despite a disparity difference between them (Adelson & Movshon, 1984; Farell, 1998; Farell & Li, 2004). Because in this study one component had zero disparity and the orthogonal orientation, the resulting plaid has the same disparity magnitude and direction as its other component.

While not affecting the disparity, the change in dimensionality is expected to change the depth-from-disparity computation, which necessitates a modification of the displays used previously. The modification was the introduction of two levels of disparity magnitude among the comparison stimuli, rather than one. Disparity magnitudes differed between relevant and irrelevant stimuli, functioning as a tracer of the source of contributions to perceived depth.[2]

2. Methods

2.1 Stimuli

A display containing five stimuli appeared on each trial. The stimuli were arranged in a quincunx, as shown in Figure 2A. The center stimulus was the *target*, which the observer judged relative to a subset of the *comparison stimuli* that made up the four corners of the surround. The target was either a grating or a plaid. The four surrounding comparison stimuli were plaids. The disparity of the target varied from trial to trial, while the comparison disparities were fixed throughout a trial block.

Grating disparity magnitude was measured as a disparity phase angle. Thus, a disparity of 30° of phase is equivalent to a spatial disparity extending 1/12 of the grating's period, with a direction perpendicular to the grating's orientation. The plaids' disparity magnitude was similarly defined by the disparity phase angle of the 1-D component perpendicular to the plaid's disparity direction (the disparity of the other component was in all cases zero). (Stimulus orientation, disparity direction, and visual angles are also measured in degrees. When angular measures are used, context will resolve which of these parameters is referred to; e.g., in discussions of disparity, 'degrees' means degrees of phase).

The comparison stimuli consisted of two pairs, one along each diagonal. The plaids within each pair were identical except for the absolute phases of their component gratings. Each pair of comparison plaids had a disparity either in the +45° direction or the -45° direction (where 0° is horizontal). The pairs could have the same disparity direction or different disparity directions. In all cases the pairs differed in disparity magnitude, one having a disparity phase angle of 10° and the other having a disparity phase angle of 20°. Thus, disparity magnitudes of 10° and 20° of phase appeared in every display. The

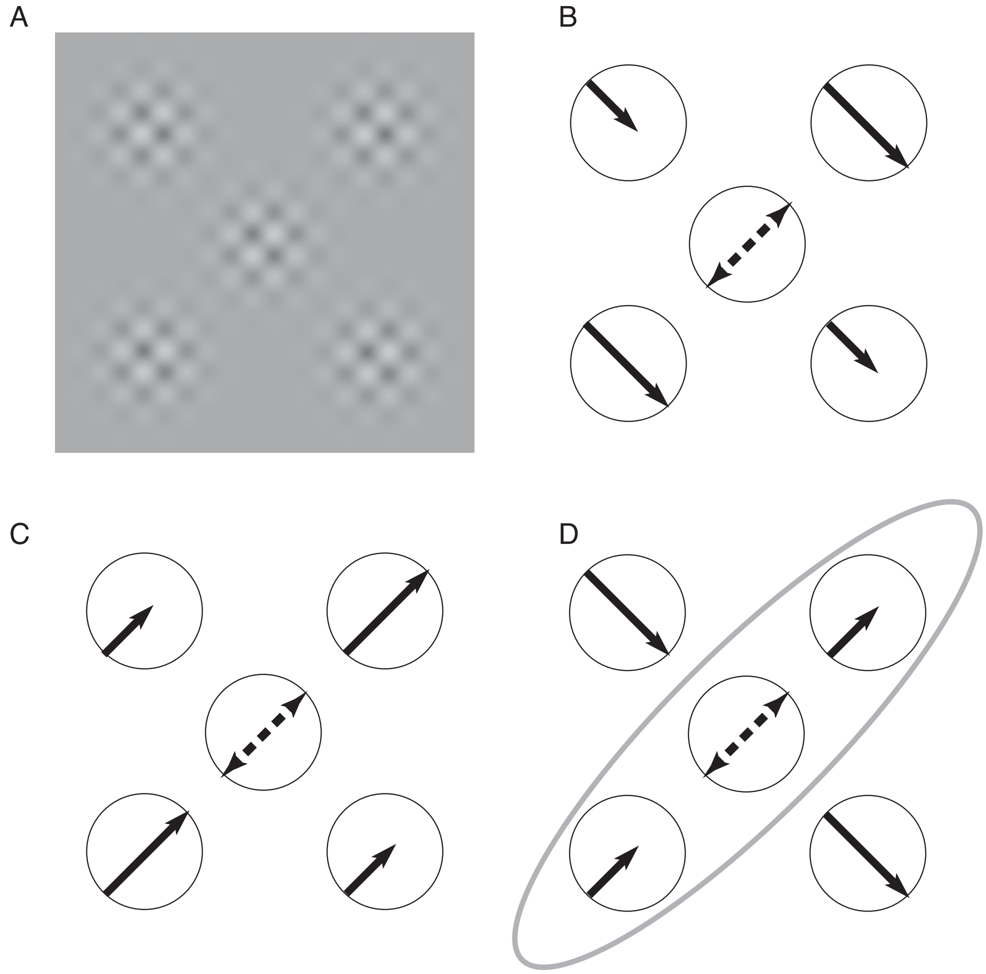

Figure 2. Display geometry. (*A*) Monocular view of a plaid target display. Contrast shown here is higher than in the experiment. (*B-D*) Examples of disparity conditions. Target disparity (dashed arrow) varied along +45°/-135° axis, while the directions of the four fixed comparison disparities were all orthogonal to the target disparity (*B*), all parallel (*C*), or a mix of parallel and orthogonal (*D*). Comparison disparities along one diagonal had a magnitude of 10° (short arrows) and along the other, 20° of phase (long arrows). Stimuli along one of the diagonals (for example, those enclosed by the ellipse in *D*) were designated as relevant throughout a block of trials; irrelevant comparison stimuli were to be ignored. In other examples, not shown here, target disparities varied along the -45°/+135° axis.

horizontal components of these disparities had magnitudes cos(45°) ≅ 0.7 as great. The comparison disparity values were positive, corresponding to a depth on the far side of the computer screen. (The purpose of the redundant pairing of comparison plaids was to form a display in which the relevant stimuli were symmetrically distributed about the observer's fixation. This makes attending to the relevant stimuli easier and fixating less subject to bias.)

Each target and comparison plaid consisted of two summed sinusoidal luminance gratings with a spatial frequency of 2.0 cycles/deg. The orientations of these component gratings were 45° and 135°. Target gratings also had a spatial frequency of 2 c/d. Their orientations were either 45° or 135°, giving them a perpendicular disparity direction along the +135°/-45° axis or the +45/-135° axis, respectively. Each plaid also had a disparity direction along one of these axes. Grating target displays and plaid target displays differed by the presence of a zero-disparity grating. When present, the target was a plaid. When absent, the target was a grating.

All the stimuli had the same contrast envelope, a 2-D Gaussian with a sigma of 0.53° vertically and horizontally. Grating contrast reached a maximum of 0.1 within this envelope and plaid contrast reached a maximum of 0.2. The center-to-center distance between the target and a comparison stimulus was 2.5° of visual angle. The horizontal and vertical spacing between comparison stimuli was just over 3.5°. The entire display of 5 stimuli was centered on the monitor and on the observer's fovea.

2.2 Experimental conditions

Sixteen experimental conditions resulted from combining target type (grating, plaid), relevant comparison disparity magnitude (10°, 20°), relative disparity direction of target and relevant comparison stimuli (parallel, orthogonal), and relative disparity direction of target and irrelevant comparison stimuli (parallel, orthogonal). Figure 2B-D shows sketched examples of disparity parameter combinations.

2.3 The 64 displays

Each of the 16 experimental conditions was represented by four displays. These displays differed in how the disparity magnitudes and relevance of the comparison plaids were arranged across the major and minor diagonals of the display layout. For each condition, the comparison plaids with 10° phase disparities appeared in one display on the major diagonal or in the another display on the minor diagonal (Fig. 2B-D). The full set of 64 displays was realized by presenting each of the 32 physically distinct displays under two different attentional conditions. In one of these conditions, the comparison plaids along the major diagonal were designated as relevant and those along its minor diagonal as irrelevant. In the other condition, this assignment of relevance was reversed (see

Fig. 2D).

The disparity directions of all stimuli within the display were constant throughout a block of trials. The disparity magnitudes of the comparison plaids were also constant. Two parameters varied across trials within a block: the disparity magnitude of the target stimulus and the absolute phases of all stimuli. Absolute phases varied randomly for each stimulus and equally for the left and right eyes' views of the stimulus, eliminating potential monocular cues by shifting the grating or plaid within its contrast envelope, but producing no other change.

The experimentally manipulated disparities were parameters of the grating or plaid carrier patterns. The Gaussian envelope that defined the frontoparallel position of each stimulus had a disparity of zero, as in the Farell and Ng (2014) study. The envelope is 2-D; dissociating carrier and envelope disparities makes the gratings' deliminators extrinsic properties and preserves the gratings' 1-D status.

2.4 Experimental procedure and task

The observers' task was to judge the target stimulus as 'near' or 'far' relative to the relevant plaids and to ignore the irrelevant plaids. One of the two diagonal pairs of comparison plaids was designated as relevant before the start of a trial block and remained relevant throughout the 64-trial block (which included 4 initial warm-up trials). The other diagonal pair was irrelevant and to be ignored throughout the trial block. Each diagonal pair was relevant equally often. Observers were made aware that the two relevant comparison plaids had the same disparity and, though non-contiguous, could be judged as a perceptual unit.

The disparity of the target stimulus varied from trial to trial according to a constant-stimulus procedure. There were five equally-spaced disparity values, chosen to approximately bracket the observer's point of subjective equality (PSE) and presented repeatedly in random order.

Trials began with a fixation point and vertical and horizontal nonius lines. Observers initiated the presentation of the display with a click of a mouse. The click extinguished the fixation point and nonius lines and, following a brief (~50 ms) blank screen, the display appeared for 176 ms (15 monitor frames). Onsets and offsets were abrupt.

2.5 Equipment

Our intention was to measure the perceived depth available from a comparison of the disparities of experimental stimuli. This required the exclusion of non-experimental stimuli as indirect mediators of perceived depth. What must be avoided, in other words, is the ability of observers to infer the relative depth of relevant stimuli from evidence about the relative depth of each of these stimuli with respect to a non-experimental stimulus. We therefore followed our earlier practice (Chai & Farell, 2009; Farell & Ng, 2014) of extinguishing the fixation stimulus before the presentation of the experimental display, using stimuli with soft-edged contrast envelopes, and obscuring contours and terminators that might function as uncontrolled reference stimuli, such as the monitors' vertical edges and the ends of their horizontal edges, from binocular viewing by use of construction paper occluders attached to the mirrors.

On both experimental setups this resulted in a visible screen width of approximately 15° in each eye, the left edge of the left monitor being occluded from the left eye's view and the right edge of the right monitor occluded form the right eye's view. The binocularly visible portion was approximately 13° wide. The self-luminous portion of the screen was limited to 6.4° above and below the center of the screen. Because of the occluders, the terminators of these horizontal boundaries, both intrinsic and extrinsic terminators, were not binocularly visible.

The stimuli were centered on CRT monitors with screen dimensions of 37 cm by 28 cm, one monitor for each eye. There were two setups, one in which the displays were viewed was at an optical distance of 1.25 m through a front-silvered mirror stereoscope, the other where the distance was 0.93 m. The screens contained 1152 pixels horizontally and 870 vertically. Observers' eyes were on the same horizontal plane as the centers of the monitors; their heads were perched on a chin-rest in upright posture. The apparatus gave observer's vergence angle the value appropriate for the viewing distance. The mean luminance of the targets and gratings was 21 cd/m^2, which was also the background luminance. Look-up tables linearized the luminance of the monitors, which were driven through their green guns after the R, G, and B signals were combined via attenuators to increase luminance resolution (Pelli & Zhang, 1991). The testing room was illuminated indirectly with an incandescent bulb and had an average luminance of approximately 6 cd/m^2.

Observers viewed each of the 64 distinct displays for two or three runs. Data from these 120-180 trials per display were combined with the data from the three other displays used for each of the 16 experimental conditions to obtain a psychometric function. Each observer encountered the 64 displays in a different randomized order, with each of the 64 displays run once before any was run twice. Trials were self-paced. Data were collected after observers were familiarized with the task through practice with several blocks of trials in randomly chosen conditions.

2.6 Contrast control

The target grating had the same contrast as each of the two sinusoidal components of the plaids, giving the two stimulus types a factor-of-two difference in contrast. One observer was run in an additional series of trials to assess the effect of target contrast, in which the contrast of the grating was doubled to 0.2 on a subset of the displays.

2.7 Observers

Four Syracuse University graduate and undergraduate students and one of the authors served as observers. The students' previous experience in psychophysical testing was moderate and restricted to stereo studies in this laboratory. The author (observer L3) had much previous experience. The students were informed about the purpose of the experiment only after their participation in it had ended. All had normal acuity (with spectacle correction, if needed) and normal stereoacuity.

All procedures carried out in the study reported here followed the tenets of the World Medical Association Declaration of Helsinki and were approved by the Institutional Review Board of Syracuse University. All participants in the experiments gave their informed consent.

3. Results

The data of interest are the points of subjective equality (PSEs): the disparity of the target stimulus that results in a perceived depth match between the target and relevant comparison stimuli. Figures 3 and 4 show the data for the 16 conditions of the experiment. Figure 3 shows the mean PSEs for the five observers when the target was 1-D, a grating.

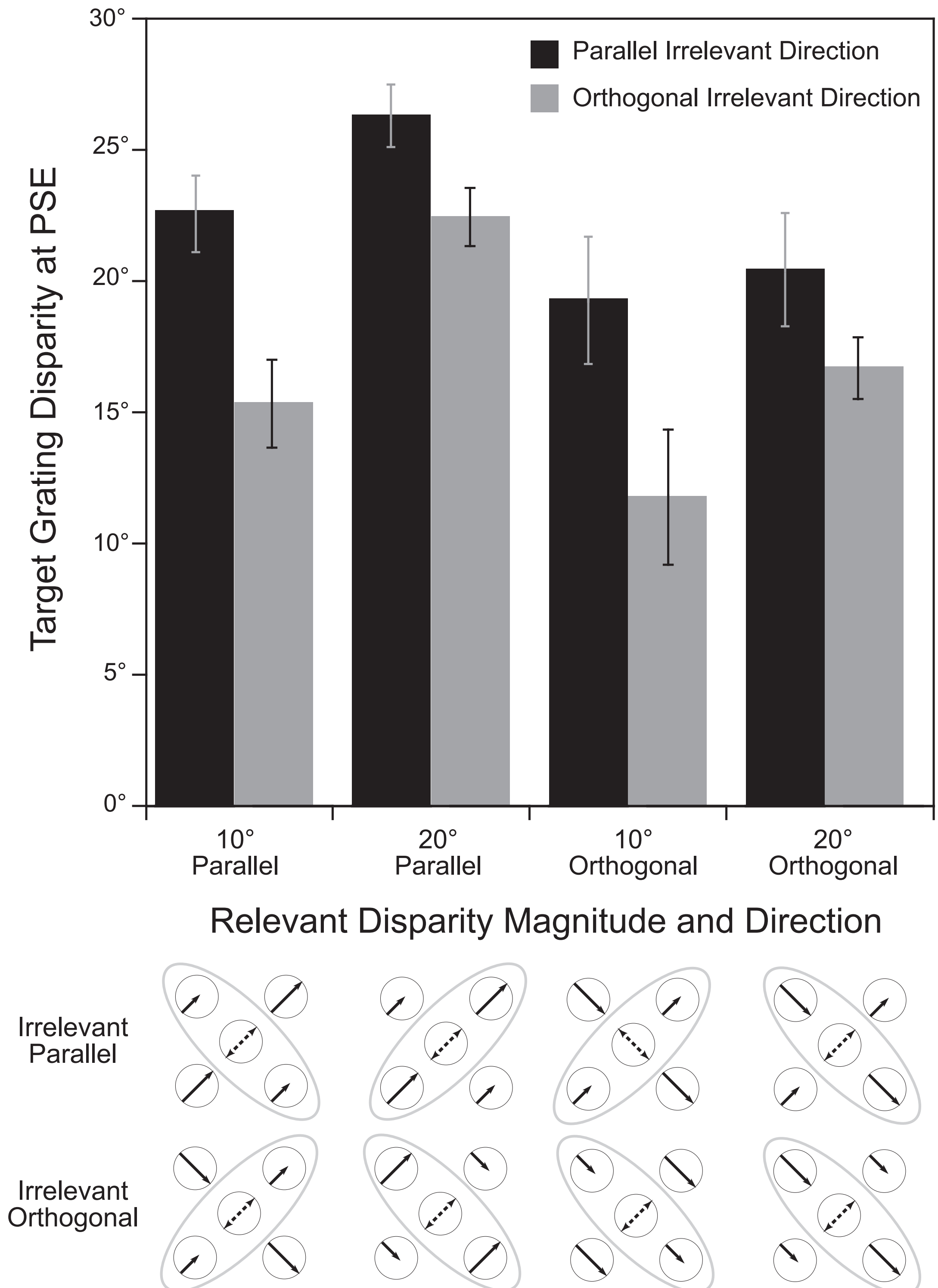

Figure 3. Grating PSE as a function of relevant comparison disparity. PSEs are plotted separately for parallel and orthogonal irrelevant comparison disparities. Error bars: ±1 SEM. Sketches in the format of Figure 2 below the data plot are arranged in four columns and show examples of displays used in the conditions labeled above them.

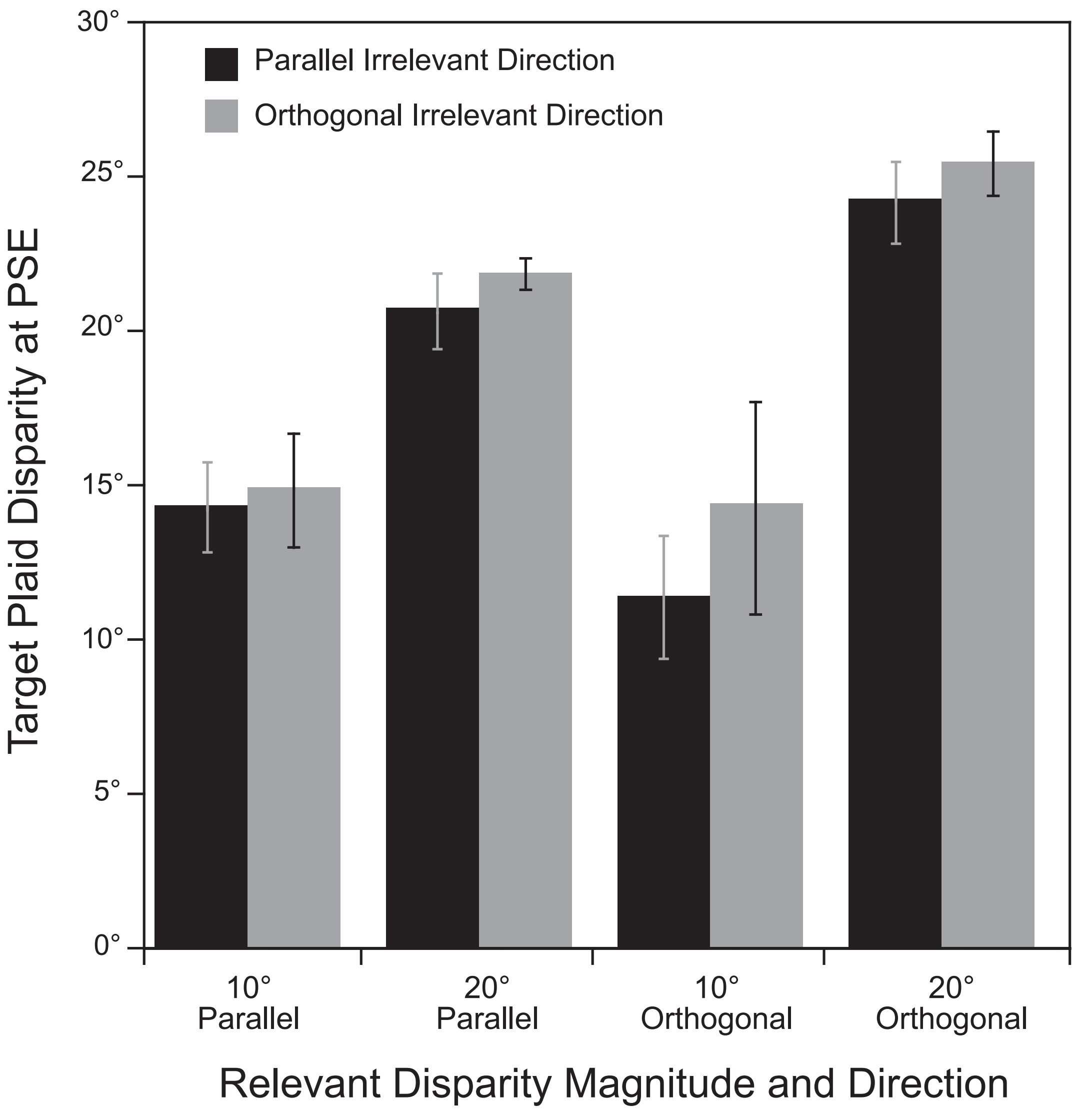

Figure 4. Plaid PSE as a function of relevant comparison disparity. PSEs are plotted separately for parallel and orthogonal irrelevant comparison disparities. Error bars: ±1 SEM. The sketches at the bottom of Figure 3 apply here as well.

Figure 4 shows the same when the target was 2-D, a plaid. Individual observers' data appear in the Supplementary Figures S1 and S2. Examples drawn from the 320 psychometric functions we collected (64 displays x 5 observers) are also shown in Supplementary Materials (Fig. S3).

PSEs in Figures 3 and 4 are plotted as a function of the disparity of the relevant comparison plaids, with the relative disparity direction of the irrelevant stimulus pair as a parameter. The disparity of the relevant comparison plaids was either parallel or orthogonal to the disparity of the target and had a phase magnitude of 10° or 20°. (Recall that within each display the relevant and irrelevant disparity magnitudes were not independent but complementary.) If observers' judgments were influenced only by the disparities of relevant stimuli, target grating PSEs should be equal in magnitude (10° or 20°) for relevant comparison plaids with parallel disparity directions and approximately 0° for relevant comparison plaids with orthogonal disparity directions (Farell, *et al.*, 2009; Chai & Farell, 2009), as sketched in Figure 1. By contrast, target plaid PSEs should equal the magnitude of relevant comparison plaids whether their disparity direction is parallel or orthogonal (Farell, *et al.*, 2010). We will go over data for grating targets (Fig. 3) first and then note the differences between the two cases when describing data for plaid targets (Fig. 4).

The grating PSEs (Fig. 3) tend to be larger when the disparities of the relevant comparison plaids were parallel to the target disparity rather than orthogonal and when they are large (20°) rather than small (10°). Grating PSEs were also larger when the irrelevant disparities were parallel to the target disparity rather than orthogonal to it. The data were entered into a repeated-measures ANOVA with the three parameters of comparison disparity—relevant magnitude and direction, and irrelevant direction—as variables. This showed significant effects of relevant disparity magnitude ($F[1,4] = 13.79$, $p < 0.05$), relevant disparity direction ($F[1,4] = 9.59$, $p < 0.05$), the interaction of these two variables ($F[1,4] = 11.29$, $p < 0.05$), and also the main effect of irrelevant disparity direction ($F[1,4] = 24.12$, $p < 0.01$). All remaining interactions were non-significant ($p > 0.05$).

The pattern of results is different when the target is a plaid rather than a grating. Comparing Figure 4 against Figure 3 shows the relevant disparity magnitude had a larger effect on plaid PSEs than on grating PSEs. By contrast, disparity direction, which affected grating PSEs regardless of whether the disparities were relevant, had no evident effect on plaid PSEs. A repeated-measures ANOVA of the plaid PSE data, with the same factors used for the grating data, showed a significant effect only for relevant comparison disparity magnitude ($F[1,4] = 20.64$, $p = 0.01$). The overall mean difference between PSEs for grating and plaid targets was slight (19.33° vs. 18.44°) and not statistically significant ($F[1,4] = 0.78$).

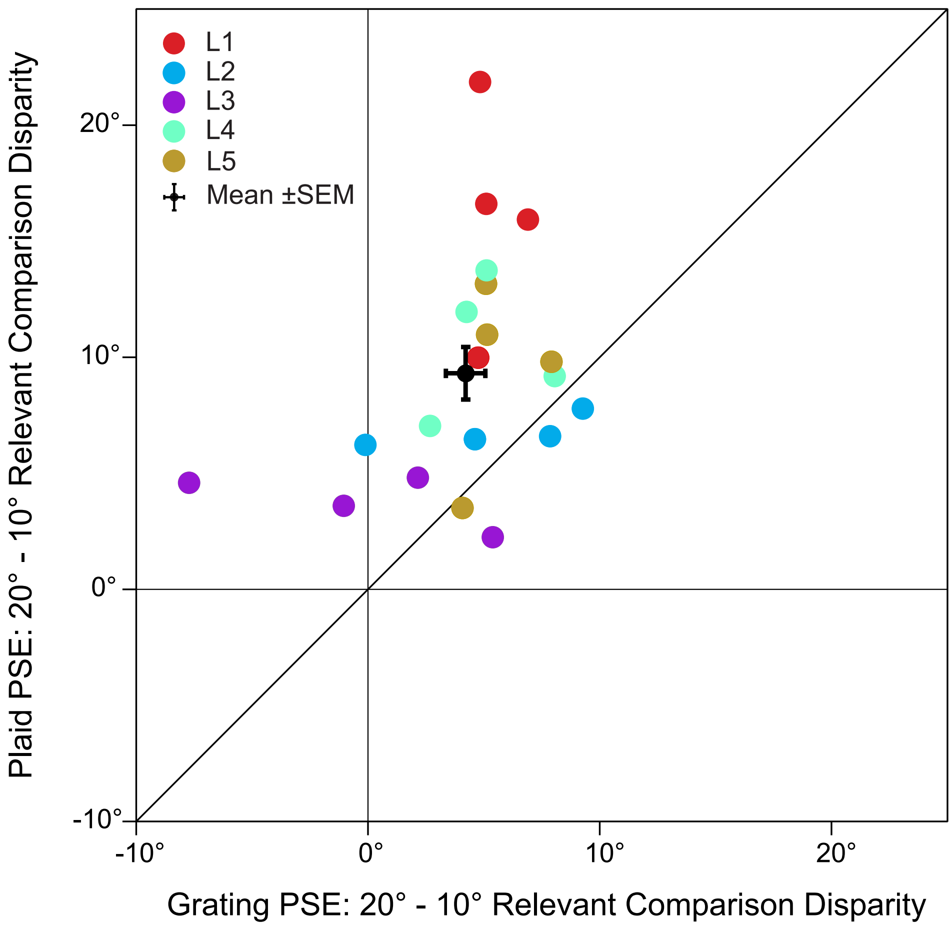

Figure 5. Effect of relevant comparison disparity magnitude. Difference between grating PSEs for 20° vs 10° relevant comparison disparities are plotted against the same difference for plaid PSEs. For each observer data for four different parallel and orthogonal direction conditions are plotted separately. Black disk gives the mean (±1 SEM) of the 20 data points.

3.1 Target Dimensionality and the Effects of Comparison Disparity

Our principle interest is in the differences between the depth matches observers make when the target stimulus is 1-D versus 2-D. The only physical difference between these stimuli is the presence of a non-informative zero-disparity grating, yet this difference had pervasive and rather complex effects on performance. We use Figures 5 through 8 to clarify how disparity magnitude and direction combine with stimulus relevance to differentially affect grating and plaid PSEs. The Discussion takes up reasons for the difference.

3.1.1 Effect of disparity magnitude. Figure 5 plots for each observer the effect of the magnitude of the relevant comparison disparity on grating PSEs against its effect on plaid PSEs. Relevant comparison disparity magnitude was either 10° or 20° of phase. For both grating and plaid targets, each observer contributed four such PSE differences from the various parallel and orthogonal direction conditions. Figure 5 shows PSEs for both gratings (abscissa) and plaids (ordinate) tended to be larger when the relevant comparison disparity magnitudes were 20° rather than 10°, but for plaid PSEs the difference (23.1° vs. 13.8°; $t[19] = 7.34$, $p < 0.00001$) was roughly twice as great as it was for grating PSEs (21.4° vs.17.2°; $t[19] = 5.02$, $p < 0.0001$)—9.3° versus 4.2°.

3.1.2 Effect of disparity direction

We can consider the effect of disparity direction on PSE by pooling data from all comparison plaids, regardless of their relevance. Figures 6 and 7 plot PSEs as a function of the sum of the disparity magnitudes of all comparison plaids with a disparity direction parallel to that of the target. Each of these sums—0°, 20°, 40°, and 60°, from zero parallel comparison plaids to all four—is subdivided according to the size of relevant comparison plaids' disparity, either 10° or 20°. Figure 6A plots grating PSEs this way and Figure 7 does the same for plaid PSEs. Figure 6B shows schematically the disparities for each of the eight cases appearing in Figures 6A and 7, with corresponding left-to-right order. Data for individual observers appear in Supplementary Figure S4.

PSEs for grating targets (Fig. 6A) increase with the overall number of parallel comparison disparities. The rate of increase is similar whether the relevant plaid disparities had a phase magnitude of 10° or 20° and was independent of stimulus relevance. These grating PSEs differed from plaid PSEs (Fig. 7) in two major ways. The effect of relevant disparity magnitude on grating PSEs was approximately half its effect on plaid PSEs, as seen earlier (Fig. 5). In addition, grating PSEs increased linearly as a function of total parallel comparison disparity overall and for each observer (see Suppl. Fig. S4A). The mean of the slope values was +3.36°±0.68° per parallel comparison disparity increment. Plaid PSEs, by contrast, tended not to increase, but rather to decrease slightly with total parallel comparison disparity (see Suppl. Fig. S4B), with a mean value of -0.65°±0.48° per parallel comparison disparity increment. A 3-factor repeated-measures ANOVA showed significant main effects of total

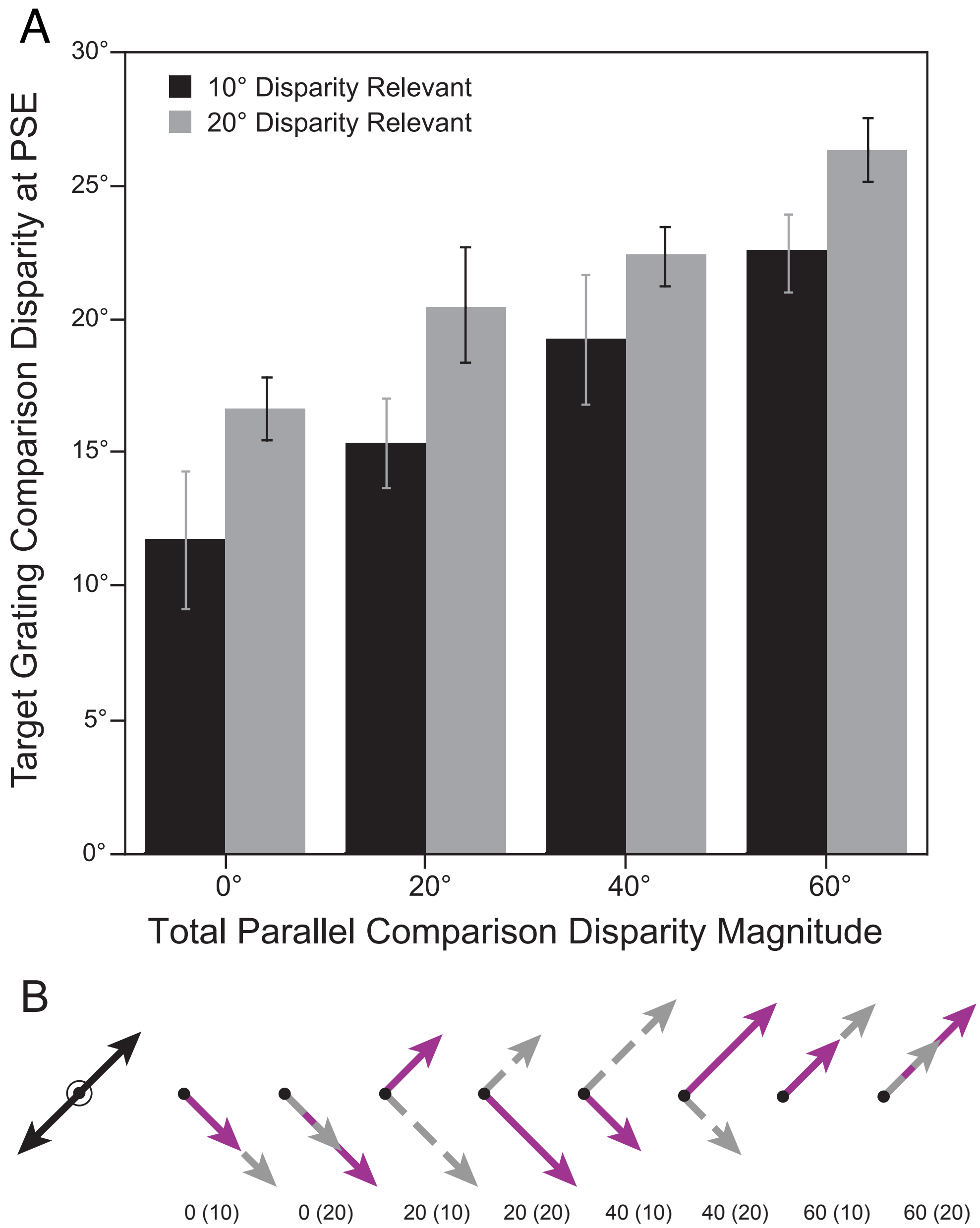

Figure 6. Grating PSE as a function of the sum of comparison disparities parallel to the target disparity. (*A*) The sum was calculated over the four comparison plaids without regard to relevance. PSEs are plotted separately for the two relevant comparison disparity magnitudes. Error bars: ±1 SEM. (*B*) Sketch of disparities contributing to each of the eight total parallel disparity magnitude conditions along the abscissa of Figures 6*A* and 7. On left, target disparity varying along the +45°/-135° axis serves here as a reference for classifying the eight comparison disparity conditions shown in the rest of the figure. The two pairs of comparison disparities (gray and maroon) can appear in any combination of parallel and orthogonal directions relative to the target disparity. One pair has a disparity magnitude of 10° of phase, the other, 20° of phase (indicated by vector length), and one (maroon) is relevant while the other is irrelevant (gray). The numbers below each pair of disparity vectors are the sum of the parallel disparity magnitudes and (in parentheses) the magnitude of the relevant disparity. The left-to-right sequence of disparity pairs corresponds to the left-to-right series of conditions in the abscissa of Figures 6A and 7.

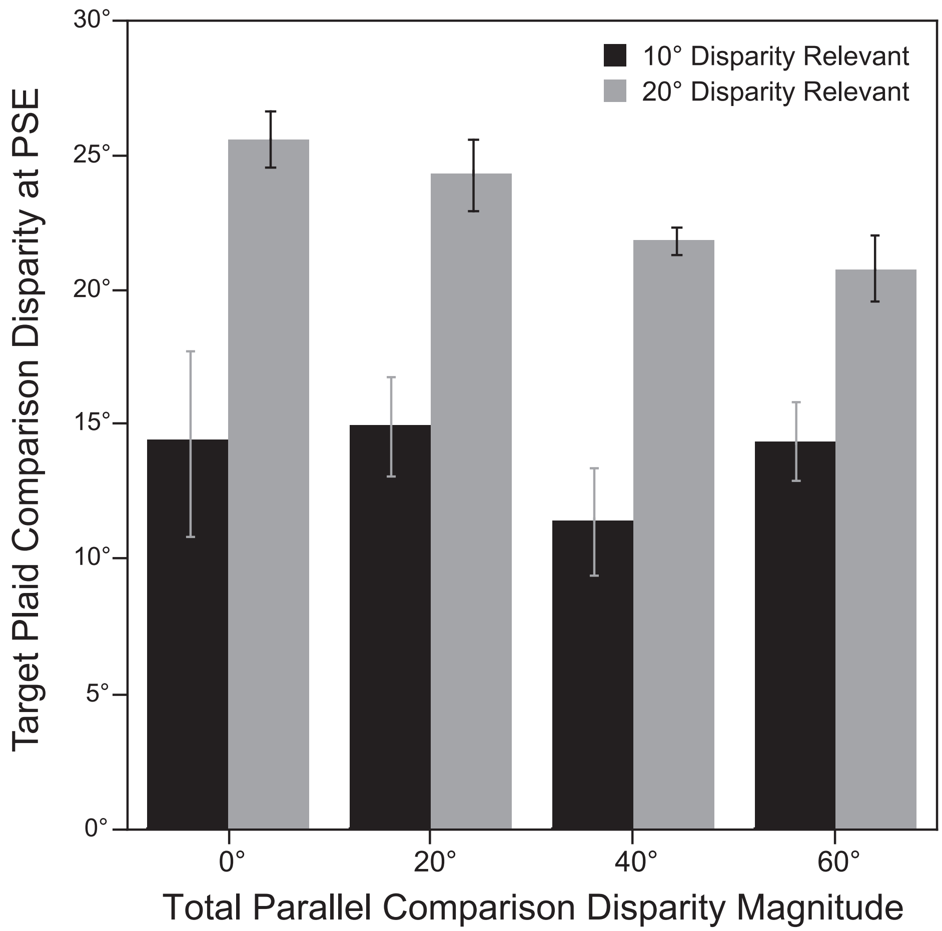

Figure 7. Plaid PSE as a function of the sum of comparison disparities parallel to the target disparity. The plot is the plaid-target counterpart of Figure 6.

parallel disparity ($F[3,12] = 6.96$, $p < 0.01$) and the size of the relevant disparity ($F[1,4] = 21.32$, $p < 0.01$). Target type interacted significantly with these two variables ($F[3,12] = 19.66$, $p < 0.0001$, and $F[1,4] = 10.84$, $p < 0.05$, respectively), but was not independently significant, nor were other interactions significant (ps > 0.05).

Note that grating PSE varies with the disparity direction of comparison stimuli whether they are relevant or not, yet plaid PSE is little affected by disparity direction at all. This is shown directly in Figure 8, which plots for each observer the difference between PSEs for parallel and orthogonal disparity directions; data are pooled over the two relevant comparison disparity magnitudes. For grating targets (abscissa), parallel comparison disparities are associated with larger PSEs (~5°) whether the disparities are relevant (circles) or irrelevant (squares). For plaid targets (ordinate), the difference

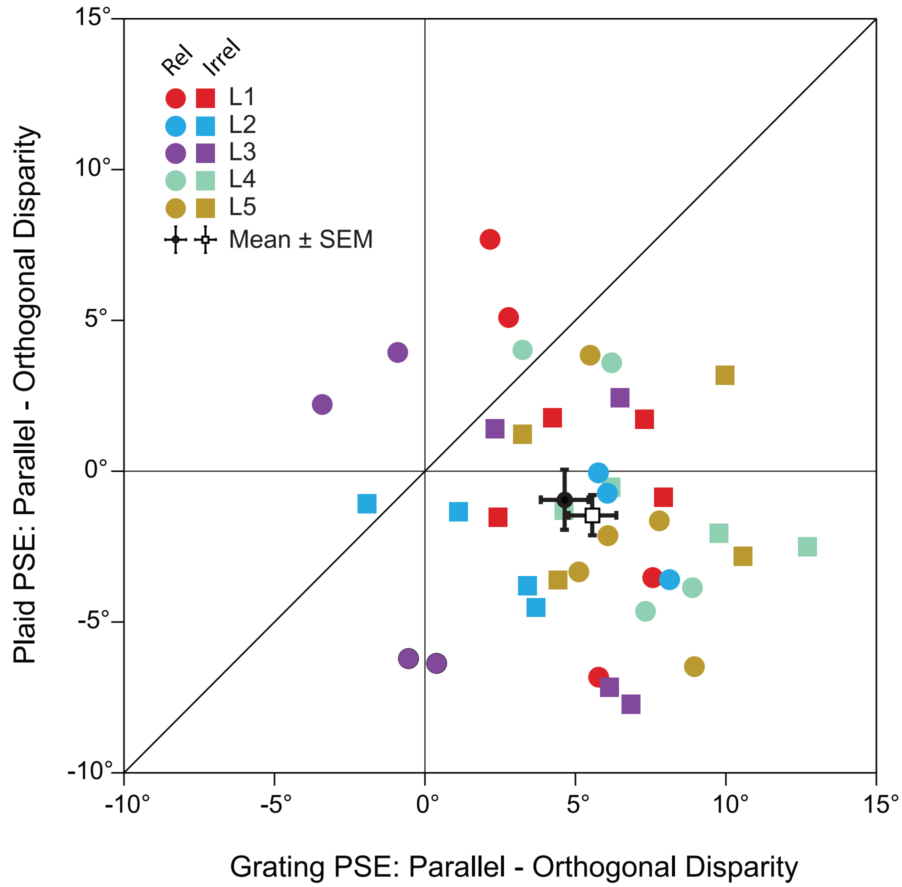

Figure 8. Effect of comparison disparity direction. Difference between parallel and orthogonal comparison disparities for grating PSEs are plotted against the same difference for plaid PSEs. Circles show PSEs as a function of relevant parallel vs orthogonal disparity directions and squares do likewise for irrelevant parallel vs orthogonal disparity directions. The four data points per observer within each of these categories are from different sub-conditions. Black symbols give means (±1 SEM) of relevant and irrelevant data points.

between parallel and orthogonal directions is negative and close to zero for both relevant and irrelevant disparities.[3]

3.2 Effect of grating contrast

The contrast of all 1-D components was the same, 0.1. This gave the target grating, consisting of one such component, half the contrast of the plaids, which consisted of two. We collected data from Observer L1 on a subset of grating-target displays for which target contrast was doubled to 0.2. Comparison plaid contrast remained at 0.2. Increasing contrast modestly increased PSEs by a mean of 4.2°±1.2°, indicating that higher contrast made the grating targets appear nearer. The change in contrast had an approximately constant effect across

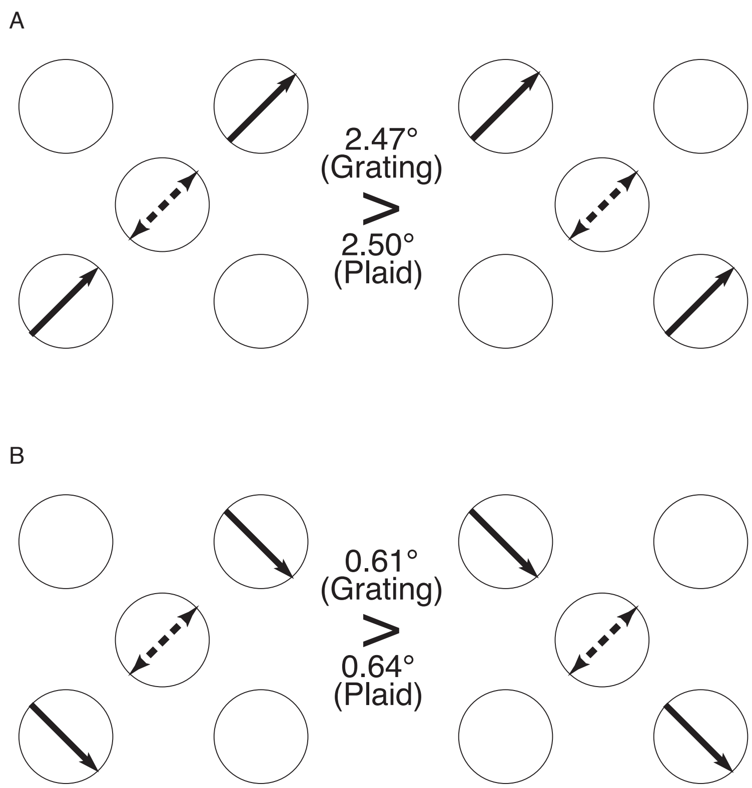

Figure 9. Effect of disparity alignment, with example arrangements. (*A*) PSEs for parallel relevant disparities in aligned (example on left) and flanking (example on right) arrangement, showing slightly higher PSE for the aligned case for both grating and plaid targets. (*B*) Same for orthogonal disparities, showing a smaller difference.

conditions, suggesting that only the overall mean difference between grating and plaid PSEs would be affected by a different set of grating and plaid contrasts.

3.3 Effect of Disparity Alignment

The three relevant stimuli were linearly arranged, with the target in the middle. The target's disparity might be parallel to this row (the 'aligned' configuration) or perpendicular to it (the 'flanking' configuration). The PSEs discussed above were derived equally from displays having these two configurations. In order to see whether configuration influenced perceived depth, we compared aligned and flanking configurations separately for the two target types (grating vs. plaid) and the four combinations of parallel vs. orthogonal target-comparison disparity direction. The differences due to configuration, shown pooled across observers in Figure 9, were small. Both grating and plaid PSEs tended to be larger for the aligned configuration. The effect was larger for parallel disparities for three of the five observers, but for no observer was the difference between aligned and flanking configuration statistically significant for either grating or plaid targets, of either parallel or orthogonal disparity direction ($p >> 0.05$). Alignment seems not to be an important factor.

3.4 Results Summarized

Stimulus dimensionality had two distinct effects on perceived depth in the presence of irrelevant disparities. Dimensionality determined whether irrelevant disparities influenced depth judgments and it affected the size of the contribution of relevant disparities to the PSE. Observers could selectively judge the depth between relevant 2-D stimuli and ignore irrelevant stimuli. However, in judging the depth between 1-D and 2-D stimuli observers were affected by the direction of irrelevant comparison disparities and showed what appears to be only a partial ability to select relevant stimuli. This latter result appears to conflict with our earlier study (Farell and Ng, 2014), which showed no evidence of selection. In fact, as shown below in Section 4.4, the seemingly minor difference in the comparison disparities used in the two studies explains their conflicting results. The Discussion also describes the apparently partial selection of relevant comparison disparities in grating-target displays as mechanistically identical to the fully effective selection seen in plaid-target displays.

4. Discussion

It is usual in laboratory settings for the stimuli whose presentation defines an experimental trial to be the stimuli that are relevant to the task. In naturalistic settings, it is usual for the task at hand to designate a subset of stimuli as relevant. Others are irrelevant. Optimal task performance requires selecting relevant stimuli for analysis, decision, and response and ignoring the rest. Observers in this study had the task of judging the depth of a target grating or plaid relative to the depth of two relevant comparison plaids, which shared the same disparity value, and ignoring the two irrelevant comparison plaids. Characterizing the conditions in which performance varies with the irrelevant signal and those in which performance is the same whether the irrelevant signal is present or absent can help us understand the limitations of attentional selection or, to rephrase, understand how context contributes to task performance.

We previously reported a failure to selectively process relevant stereo depth signals. In that experiment, irrelevant disparities contributed as much as relevant disparities to observers' depth judgments (Farell & Ng, 2014). This raises a string of questions: Under what conditions is selection of relevant stereo depth signals possible? What properties of irrelevant stimuli obligatorily alter our perception of the depth of relevant stimuli? And so forth.

Here we examined how stimulus dimensionality influences the answers to these questions. We were interested in how observers' judgments of the depth separating 1-D and 2-D stimuli in the presence of irrelevant stimuli differed from their judgments of the depth separating 2-D stimuli. What makes this question interesting is that the disparity-from-depth computation differs between these two case. The results can be understood by expanding on two points:

1. Plaid PSEs varied with relevant disparity magnitude and were little influenced by irrelevant disparities or by disparity direction. This is as expected if observers attentionally gated relevant stimuli and calculated depth from the horizontal component of disparities only. (The possibility that the role played by horizontal disparity is a function of spatial parameters of the stimuli, whether the stimulus is 1-D or 2-D, is discussed below.)

2. Grating PSEs varied with the disparity direction of both relevant and irrelevant comparison stimuli. The effect of relevant disparity magnitude on grating PSEs was only half as large as it was on plaid PSEs.

We argue that the effect of stimulus dimensionality is a result of two distinct processes that operate in the computation of relative disparity. Only one is sensitive to attentional conditions and they play out differently for 1-D and 2-D stimuli.

We assume that 1-D stimuli inform observers about disparity magnitudes only along an axis perpendicular to the stimulus orientation. This is what makes them one-dimensional in the stereo domain. When one stimulus is 1-D and another 2-D, it is the disparity components of the stimuli in the direction of this perpendicular axis that matters for the purpose of comparing the two disparity values. We assume further that comparisons between two 2-D stimuli do not have this constraint. For example, the relative depth of a pair of 2-D stimuli with oblique disparity directions—the same oblique direction or different—might be calculated from their horizontal disparity components. Horizontal is not the physical disparity direction of these stimuli, but it is the effective disparity direction for stereo depth comparisons, either because horizontal is special, because horizontal is the average of the perpendiculars to the components' orientations, or because of some other stimulus properties.

We will consider plaid PSEs next, followed by grating PSEs. We then extend the consideration of grating PSEs in Section 4.3 and in Section 4.4 ask why the grating PSEs observed here differed from those of our earlier study (Farell & Ng, 2014).

4.1 Plaid PSEs

PSEs for plaid-target displays were higher when relevant comparison phase disparities were 20° than 10° in magnitude. The mean PSE difference between these two cases was approximately 10° (9.3° ± 1.14°). The mean absolute PSE values (23.1° ± 1.1° and 13.8° ± 0.64°, respectively) were reasonably close to the physical values. Plaid PSEs varied little between different comparison disparity directions. Relevant and irrelevant disparities could be parallel to the target disparity, orthogonal to it, or a mix of parallel and orthogonal, and in all cases the main determinant of plaid PSE was the size of the relevant comparison disparity. Since the horizontal components of the plaids' disparities (Fig. 10A) were the same whether the disparity direction was parallel or orthogonal, the plaid PSE data are what would be expected from observers who based their judgments on a comparison of the horizontal components of the disparities of relevant stimuli only (Fig. 10B). Thus, a perceptual depth match is expected to occur when the relevant comparison disparity (*P10* in Fig. 10A) and the target disparity (*PSE10* in Fig. 10B) have the same horizontal components (gray arrow in Fig. 10B).

4.2 Grating PSEs

Grating PSEs for relevant comparison plaids with phase disparities of 10° and 20° differed by approximately 5° (4.2°, or 5.3° if observer L3's data—those of one of the authors, whose grating PSEs show little of the effects present in others' data—are excluded). There are two notable facts about this ~5° PSE difference: its size and its independence

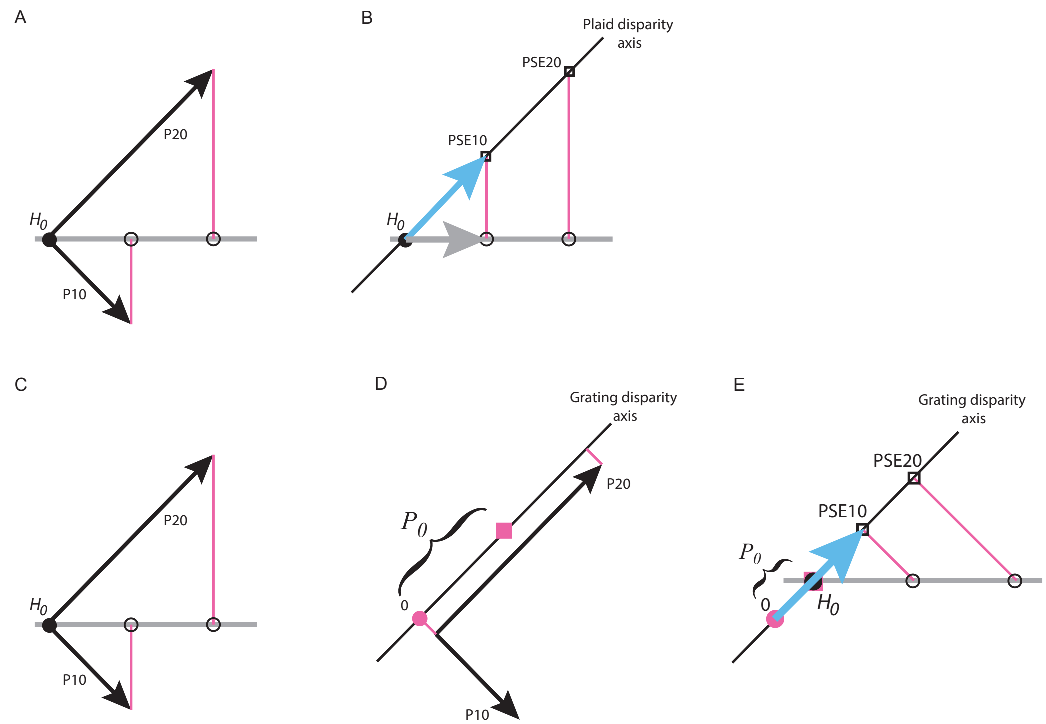

Figure 10. Disparity comparisons for plaid targets (*A, B*) and grating targets (*C, D, E*). The comparison stimuli are plaids with disparity magnitudes *P10* and *P20*. All stimuli have a disparity direction either $+\theta$ or $-\theta$. (*A*) For comparison with the target plaid disparity, the disparities of comparison plaids are represented by their horizontal components. (*B*) The target plaid disparity at the PSE (blue arrow) has a horizontal component equal to that of the relevant comparison disparity *P10*. (*C*, same as *A*) For comparison with the target grating disparity, the disparities of comparison plaids are represented first by their horizontal disparities. (*D*) A common zero-disparity point is calculated as the average comparison disparity, P_0, in the direction of the disparity of the target grating. (*E*) The target grating disparity at the PSE (blue arrow) is the sum of the zero-disparity offset, P_0, and the component of the relevant comparison disparity in the direction of the target disparity.

of disparity direction (Fig. 6A).

This PSE size difference is understandable once Figure 1 is adapted to the context of the displays used in our experiment. Figure 1 shows the disparity of a 2-D stimulus relative to the disparity of the only reference stimulus available, which is 1-D. But in the grating target displays used here, the disparity of the 2-D stimulus can be calculated relative to both the 1-D stimulus and to other 2-D stimuli. These calculations give different outcomes. Here we consider what happens when both calculations occur in succession.

Figure 1 shows the effective relative disparity direction of a 2-D stimulus depends on the disparity direction of the 1-D stimulus it is paired with. However, the effective disparity direction of 2-D stimuli relative to other 2-D stimuli is horizontal, as discussed above. Therefore, for the displays used here the disparities of comparison plaids are represented by their horizontal components. These plaids have the same horizontal components regardless of whether their disparity directions are +45° or -45°. The horizontal magnitudes are just over 7° and 14° (that is, 10°*cos(45°) and 20°*cos(45°)), the same values as in plaid-target displays (Figs. 10A,C).

We have assumed that the disparities of 1-D and 2-D stimuli are compared in the direction of the grating's disparity (Farell *et al.*, 2009; Chai & Farell, 2009). This requires a calculation of the projection of the plaids' horizontal disparities onto the grating's disparity axis. The horizontal disparities for comparison disparities of 10° and 20° are, as just seen, approximately 7° and 14°. Projecting these horizontal disparity values onto the grating's axis gives values of approximately 5° and 10° (that, ~7°*cos(45°) and ~14°*cos(45°)). The difference between these values, ~5°, agrees with the observed differences in grating disparities—the PSEs—required for a depth match.

By this account, depth judgments of both grating targets and plaid targets make use of the horizontal components of comparison disparities. One case results in a ~5° PSE difference between relevant comparison disparities of size 10° and 20°, while the other case results in a ~10° difference. The two cases differ in the axis along which the relevant disparities are compared. In one case, the plaid's horizontal disparities are projected onto the grating's perpendicular disparity axis for comparison; in the other case, both relevant disparities are those of plaids and are compared along the horizontal axis itself.

This captures the ~5° difference between grating PSEs for relevant comparison disparities of 10° and 20°, but it still misses the mark on three counts, all readily seen in Figure 6A. First, the predicted grating PSE values of 5° and 10° are far from the mean observed values—17.2° and 21.4°. Second, the prediction is 5° and 10° regardless of disparity direction, whereas the data show that grating PSEs varying with comparison disparity direction, being larger for comparison plaids disparities parallel rather than orthogonal to the grating disparity. Third, it offers no account for the effect of irrelevant disparities. These three issues stem from the effect of disparity direction of all comparison stimuli, relevant and irrelevant. A single hypothetical process of the sort considered next provides an account of them.

4.3 Disparity direction and calibration

As Figure 1 showed, in a display consisting of a target grating and a single comparison plaid the relative disparities of the two stimuli are represented along the grating's disparity axis. The previous section examined the comparison of disparities represented along two axes. Along the horizontal axis were the relative disparities of the 2-D comparison stimuli and along the 1-D disparity axis the relevant disparities were compared. Disparities along the 1-D disparity axis were assumed to be represented as in Figure 1 in both cases. In particular, it was assumed that the scaling of this axis was the same, the zero point on the axis being equal to a disparity of absolute zero.

When there are two disparity axes, however, absolute zero may not be the only alignment point. As an alternative, we suggest the possibility of a calibration-like process that uses the disparity parameters themselves to align the zero points of the 1-D and 2-D disparity axes. This can be done in several ways (though no calibration will be 'veridical'). The one we will describe sets zero on the 1-D axis to a point such that comparison disparity components in the direction of this axis are balanced between positive and negative: a point that evenly divides the component magnitudes that are greater than this zero value from those that are less. Once this zero point on the 1-D axis is aligned with the zero point on the horizontal axis, disparity magnitudes can be compared across the two axes in the manner described in the previous section. Calibration and comparison can therefore be regarded as successive operations, the first being entirely pre-attentive in that all stimuli in the display contributing to it, and the second being attentional, the selected (i.e., relevant) disparities providing the only input.

According to Figure 1, the grating PSE equals the projection of the disparity a single comparison plaid's onto the grating's disparity axis. A grating with a disparity equal to the average of all the comparison plaids' disparity projections would appear nearer than some plaids and farther than others, at a zero-point separating the relatively negative comparison disparity components from the relatively positive (Figure 10D).

Aligning this zero point with zero on the horizontal disparity axis gives it the role of a pedestal in the depth judgment task. Thus, achieving a depth match between the grating

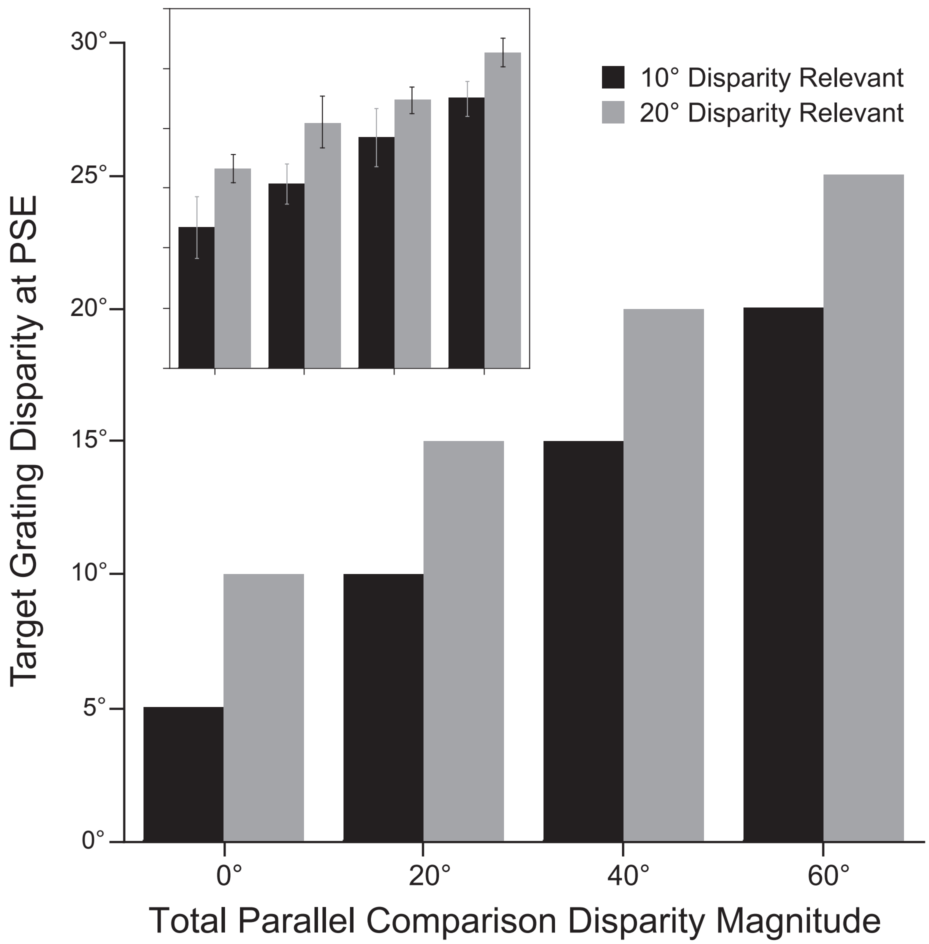

Figure 11. Grating PSEs predicted from sum of the projection onto the grating disparity axis of two terms: the mean of all comparison disparities and the horizontal disparity of the relevant comparison disparity. The corresponding observed data are those of Figure 6A. On the ordinate is plotted the predicted grating PSE:

$$PSE_{gr} = P/N\, \Sigma\mu_i \cos(\theta_i - \Phi) + \mu_r \cos(\theta_r)\cos(\Phi),$$

where Φ is the target grating disparity direction, and the comparison diparity magnitudes μ and directions θ are summed over all i of N stimuli, one of which, designated r, is relevant. P (about which see text) is set here to 1.0. PSE_{gr} is plotted as a function of $\Sigma\mu_i \cos(\theta_i - \Phi)$ for displays with different combinations of comparison disparity directions and magnitudes, as in Figure 6A, shown here in inset.

and any plaid with positive or negative horizontal disparity requires incrementing or decrementing, respectively, the grating's disparity beyond the zero-point (Fig. 10E).

In our experiment this means incrementing the grating's zero-point disparity by either 5° or 10°. This comes from projection of the relevant horizontal comparison disparity (discussed in Section 4.2) and gives the predicted PSEs shown in Figure 11, plotted in the same way as the observed data of Figure 6A. The two graphs are in close agreement, differing principally in a small overall offset between the two sets of PSEs. The offset is consistent with a bias to see the central target as nearer than the surrounding comparison stimuli after compensating for the effect of disparity differences.[4]

By this interpretation, two additive sources contribute to grating PSEs, one a calibration across disparity axes, the other a comparison of disparities across these axes. Plaid PSEs, by contrast, are determined solely by horizontal disparities and are predicted to equal the 10° or 20° magnitude of the relevant comparison disparity, in reasonable agreement with the data shown in Figure 7.

The differences between grating PSEs and plaid PSEs include those that are qualitative —the direction of comparison disparities and their task relevance affect one PSE but not the other. These differences warrant something along the lines of the proposed calibration process, but the proposal is untested and rather arbitrary. It also lacks generality; for example, the predicted PSEs for vertical gratings are double, on average, the disparity magnitudes of comparison plaids whose physical disparities are horizontal. Perhaps calibration occurs only to the extent that 1-D and 2-D disparity axes are distinct. This can be addressed by weighing the effect of calibration inversely with the angular difference between the disparity axes. So, P (see Fig. 11 caption) could be set to α*(1-cos(Φ)), where α is a scaling parameter and Φ is that angular difference.

In any event, it is also unlikely that such an elaborate multi-stage process exists solely for the purpose of comparing the disparities of 1-D and 2-D stimuli. It is possible that the sequence of pre-attentive calibration and attentional selection of relevant signals is the standard operating procedure whatever the stimuli. It would be obscured in the laboratory, where, in almost all cases, not only are disparities horizontal but orientations are constrained, being isotropic, vertically oriented, or symmetrical about the vertical axis, either individually or over the ensemble from which data are averaged. Hence, their physical and effective disparity directions are confounded: Their perpendicular disparity direction (after down-weighting the contribution of horizontally oriented components) is horizontal. Had these stimuli been obliquely oriented, their effective disparity directions might have been found to be, like those of the gratings used here, perpendicular to their orientations rather than horizontal (Farell & Ng, 2018).

4.4 The computation of relative horizontal disparity

Our earlier study of the depth between 1-D and 2-D stimuli showed no evidence of selection of relevant disparities (Farell & Ng, 2014). Relevant and irrelevant comparison disparities had indistinguishable effects on grating PSEs. There was also no evidence of computations on horizontal disparity components. Instead, disparity computations followed those depicted in Figure 1. In the present study we do find evidence in grating PSEs that relevant disparities were selectively processed and that the horizontal magnitude of comparison disparities contributed to perceived depth matches. These are substantial differences, but they can be explained by the minor stimulus difference between the two studies.

The grating-target displays used in the earlier study were identical to those used here, with one exception: All the earlier comparison disparities had the same magnitude, 20° of phase, rather than being evenly split between 10° and 20°. This quantitative difference in disparity magnitude could produce a qualitative shift in the computation of relative disparity, as shown by contrasting two types of display:

Case 1. 1-D reference displays. Consider two grating-target displays. In both displays all the comparison plaids have disparities that are identical in magnitude and direction. In one display this direction is parallel to the grating's disparity and in the other it is orthogonal. We have collected data from such displays (the transitive conditions of Farell & Ng, 2014) and found that the PSEs for the target grating were large for the parallel display (similar in magnitude to the plaid disparities) and much closer to zero for the orthogonal display, in agreement with Figure 1. Similar effects of relative disparity direction come from displays containing a single grating and a single plaid (Chai & Farell, 2009; Farell *et al*., 2009).

All these displays, regardless of the number of comparison stimuli, can be grouped into a single class characterized as containing a single grating and a single plaid. All four were essentially identical, absolute phase being the only property other than position to distinguish one plaid from another. Neglecting the phase difference (which is imperceptible during task performance), the plaids in these displays were equivalent to four spatial samples of a single plaid. This single plaid had only the grating to function as the reference stimulus for the purpose of computing relative disparity (cf. Erkelens & Collewijn, 1985; Regan, *et al.*, 1986). Under these conditions, the perceived relative depth between the grating and the plaid is a function of their disparity vectors, as illustrated in Figure 1, with the horizontal disparity components playing no special role.

Case 2. 2-D reference displays. Consider next a display in which the comparison disparities differ in direction or magnitude. In this case the plaids are not interchangeable samples of a single stimulus. Each has another to serve as a reference stimulus. Relative disparity can then be calculated as differences in horizontal disparities (Farell *et al,*, 2010).

The experiment in this study is an example of Case 2. Our earlier study (Farell & Ng, 2014) was an example of Case 1 when all comparison plaids had the same disparity direction and of Case 2 when half the comparison plaids had a disparity direction perpendicular to that of the other half. But the Case 2 representation of horizontal disparity differed between the two experiments. In one experiment, the horizontal disparities of relevant and irrelevant plaids differed in magnitude. In the other experiment, the magnitudes were the same. And when they are the same, selecting between relevant and irrelevant horizontal disparities leaves no imprint on the data. Thus, while attention appears to be responsive to task relevance in one study and not in the other, the difference is artifactual. The data are consistent with observers in both studies performing in the same way in Case 2 conditions—able to select one parameter, the horizontal magnitude of these disparities.

4.5 Vertical disparities

The vertical component of disparity has a distinctly malleable role in the results reported here, affecting grating PSEs whether they are relevant or not, yet having no noticeable impact on plaid PSEs. This may be due in part to how disparities were manipulated. The disparities of the grating and plaid carrier patterns were dissociated from the disparities of their contrast envelopes, the latter being fixed at zero. This makes the stimuli used here different from the broad-bandwidth stimuli classically used in stereo studies. Nevertheless, the results do not give support to the notion that humans use either a local or a regional vertical disparity signal to correct or scale horizontal disparities (see Gårding *et al*. 1995; Adams *et al*., 1996; Howard & Pierce, 1998; Kaneko & Howard, 1996; Stenton *et al*., 1984). The disparities of the comparison plaids in our experiment might all have had the same direction or they might have been split evenly between +45° and -45°. The two cases differ in both the local and the integrated disparity signals, yet the uniformity of disparity direction did not in itself affect perceived depth. And while comparison disparity direction did have an effect, it was a relative direction effect, varying with the disparity direction of the target stimulus. Moreover, the effect depended on the dimensionality of the target, reliably observed only if the target was 1-D. Thus, the effect of vertical disparity on perceived depth was entirely contextual, not intrinsic. (See Supplemental Section S5 for additional information about the discriminability of plaid disparity directions.)

5. Conclusion

We examined observers' judgments of relative stereoscopic depth. The data show that the disparities of stimuli that were irrelevant to the task could nevertheless influence how the task was carried out. The effects of irrelevant stimuli varied with the dimensionality of the stimuli. These effects were evident in judgments of the depth separating a 1-D stimulus from 2-D stimuli, but not in judgments of the depth separating one 2-D stimulus from another. The effect of irrelevant stimuli can be seen when observers compared the depths of stimuli with different effective disparity directions. It would not have been seen if the grating had been vertical, for the same reason it was not seen when all the stimuli were 2-D: All the effective disparity directions would be horizontal. These cases are similar to that of a single 1-D stimulus paired with a single 2-D stimulus, where the effective disparity axis is that of the 1-D stimulus. The 1-D disparity axis functions as the horizontal disparity axis does when there are multiple 2-D stimuli.

It is along the effective disparity axis that disparity magnitudes are compared for the purpose of judging relative stereo depth. This axis is perpendicular to the orientation of 1-D stimuli, consistent with the dimensionality of these stimuli. But why is it horizontal for a 2-D stimulus presented among other 2-D stimuli? The physical disparity direction may be non-horizontal, either individually and on average, so physical disparity does not determine the effective disparity axis. An alternative is that the 1-D case is general. The principle function behind it, one might imagine, is to calculate an effective disparity axis for 2-D patterns by pooling the perpendicular disparities of their 1-D components. If so, the effective disparities of 2-D stimuli are horizontal for the same reason as 1-D stimuli have the effective disparities that they do: Both are perpendicular to the orientation of the stimulus. Accordingly, obliquely oriented 2-D stimuli, rather than the symmetrical patterns used here, might produce data that look much like those produced by obliquely oriented 1-D stimuli (Farell & Ng, 2018).

Footnotes

1. The disparity of a component is distinct from a component of the disparity. The first refers to the disparity of a component of a higher-dimensional stimulus, e.g., the disparity of a 1-D component of a 2-D stimulus. The second refers to the magnitude of a disparity as measured along a particular axis. Thus, all disparities have horizontal and vertical components. If a 1-D component has an orientation of +45° or -45°, its horizontal disparity cannot refer to the disparity of a component and must be a component of its disparity.

2. Suppose there were a pair of 2-D stimuli having the same disparity magnitude, one with a disparity direction of, say, +45° and the other, -45°. One disparity will be parallel to that of a 1-D stimulus oriented at 45° and the other will be perpendicular to it. Therefore, despite the equality of their disparity magnitudes and of their horizontal disparities, the 2-D stimuli will have different perceived depths relative to the 1-D stimulus. Suppose now we make the 1-D stimulus 2-D, leaving everything else the same. Perceived depth will now result from a different calculation, one that depends on horizontal disparity. But 2-D stimuli that have equal horizontal disparities should have similar perceived depths relative to another 2-D stimulus. Their perceived depths do not differentiate them. Here we gave them different disparity magnitudes, which allow us to distinguish their contributions to perceived depth.

3. Certain hypotheses about why attentional selection fails in similar displays (Farell & Ng, 2014, and the grating-target displays here, for which selection was partial) can be rejected by this result. For example, hypotheses that locate the source of the failure in display parameters, such as spatial

proximity that leads to crowding between relevant and irrelevant stimuli, can be ruled out, since these parameters are the same in plaid-target displays, where selection was unimpeded.

4. A similar discrepancy can be seen between the values of 10° and 20° predicted from horizontal-disparity matching and the observed plaid PSEs in Figure 7. It can be seen again in our earlier study (Farell & Ng, 2014), which used similarly arranged displays.

Keywords: stereoscopic vision, attention, depth perception, stimulus dimensionality.

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Supplementary Materials

Attentional selection in judgments of stereo depth

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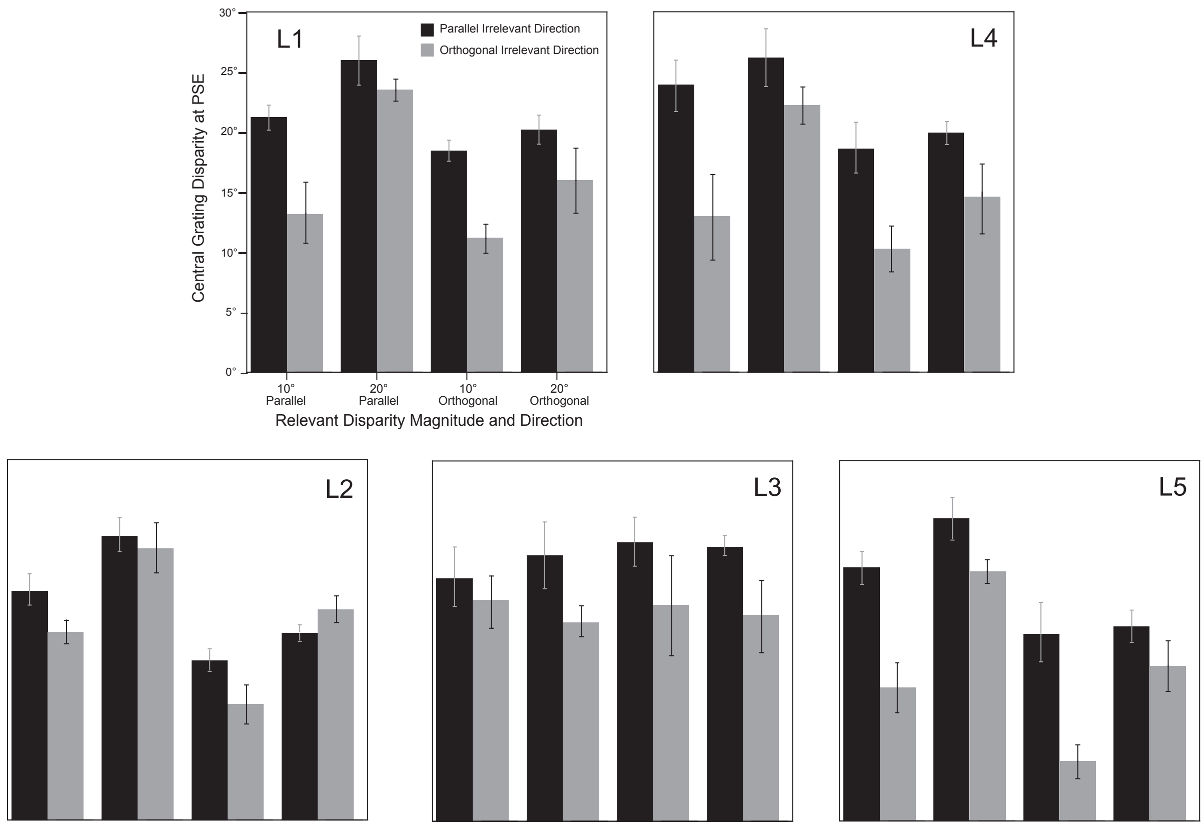

Figure S1. Grating PSE as a function of relevant comparison disparity for each observer. Mean values appear in Figure 3 of the article. Error bars: ±1 SEM.

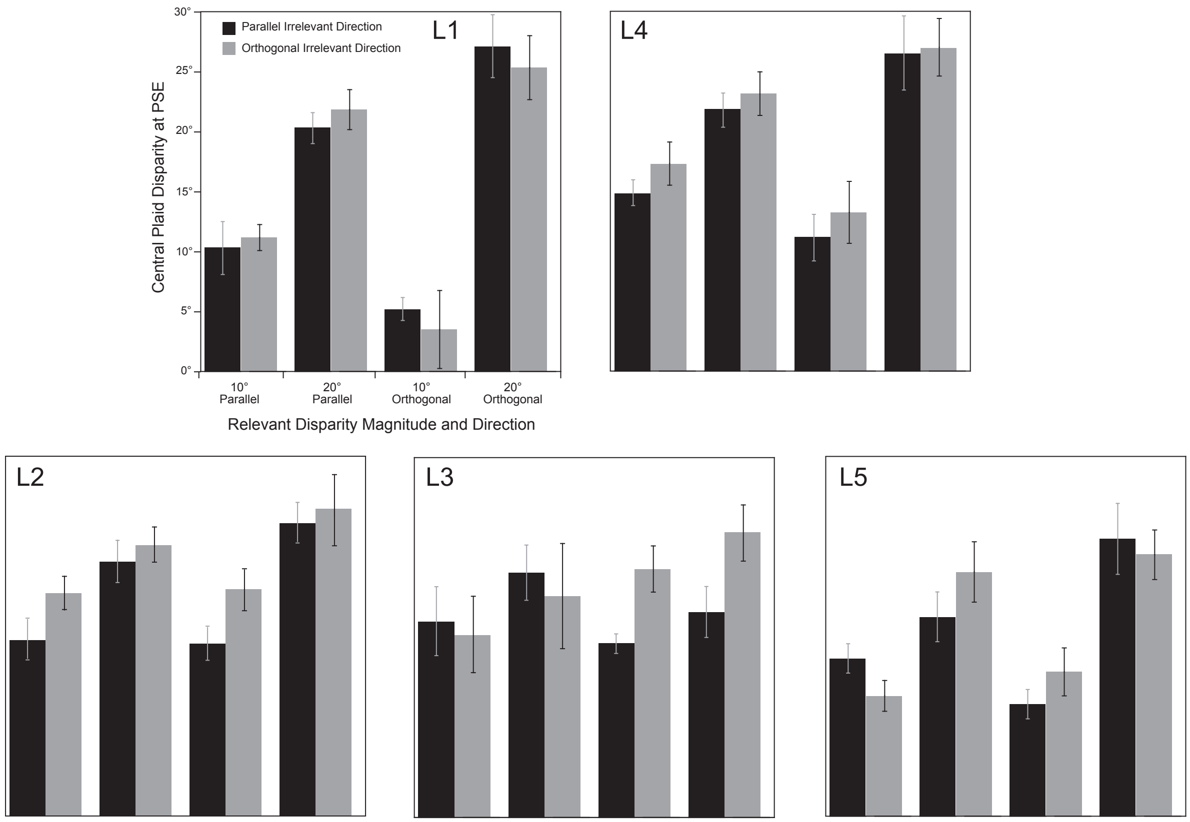

Figure S2. Plaid PSE as a function of relevant comparison disparity for each observer. Mean values appear in Figure 4 of the article. Error bars: ±1 SEM.

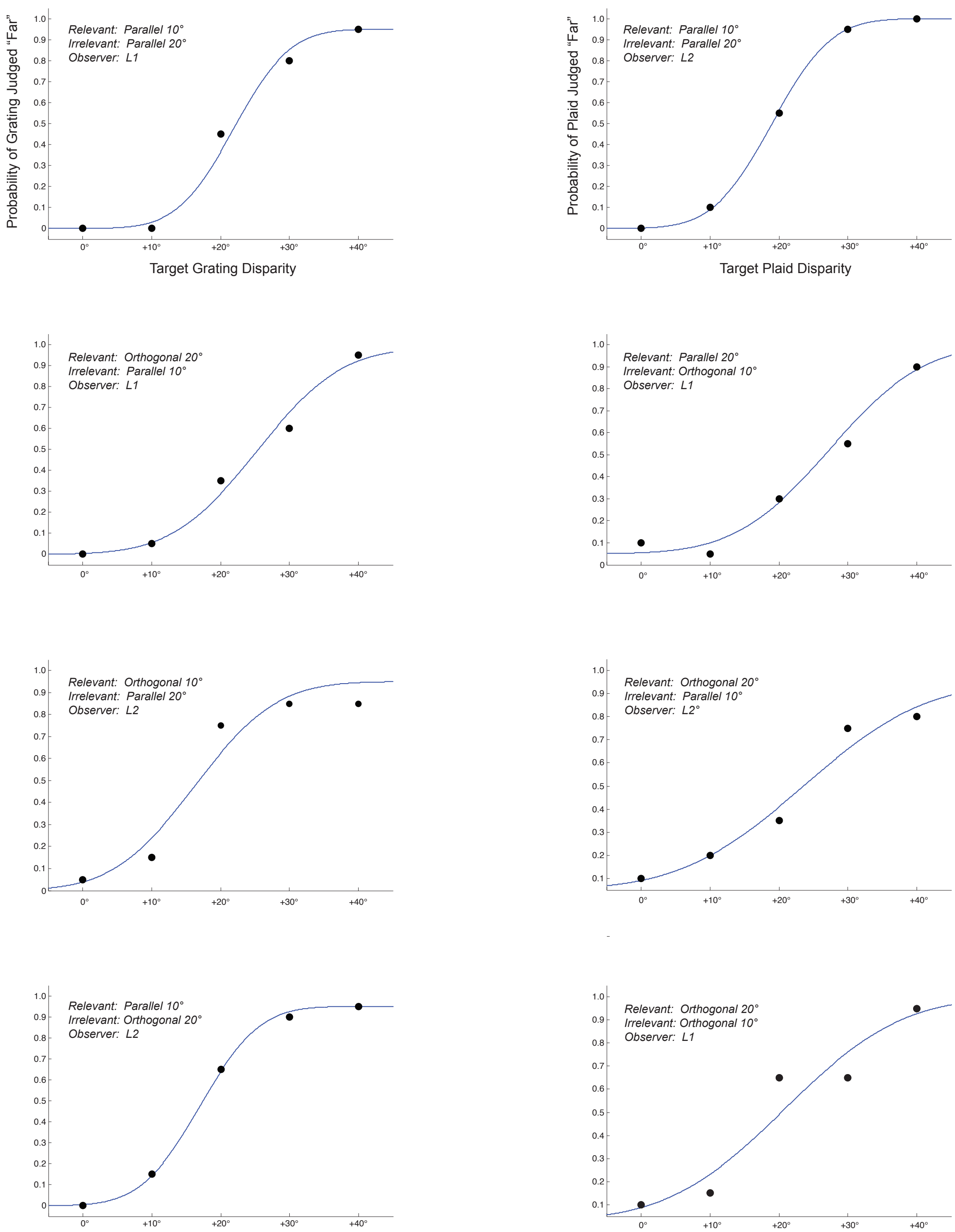

Figure S3. Example psychometric functions for grating targets (left column) and plaid targets (right column). Each plot shows one observer's data for one of the 64 displays. Relevant plaid disparity direction was parallel to the target's disparity direction in half the cases and orthogonal in the other half, as indicated on individual plots. Also indicated are other comparison disparity parameters and the observer (L1 in half the cases, L2 in half). Data points in each plot, from two blocks of trials, are fit with a cumulative Gaussian function.

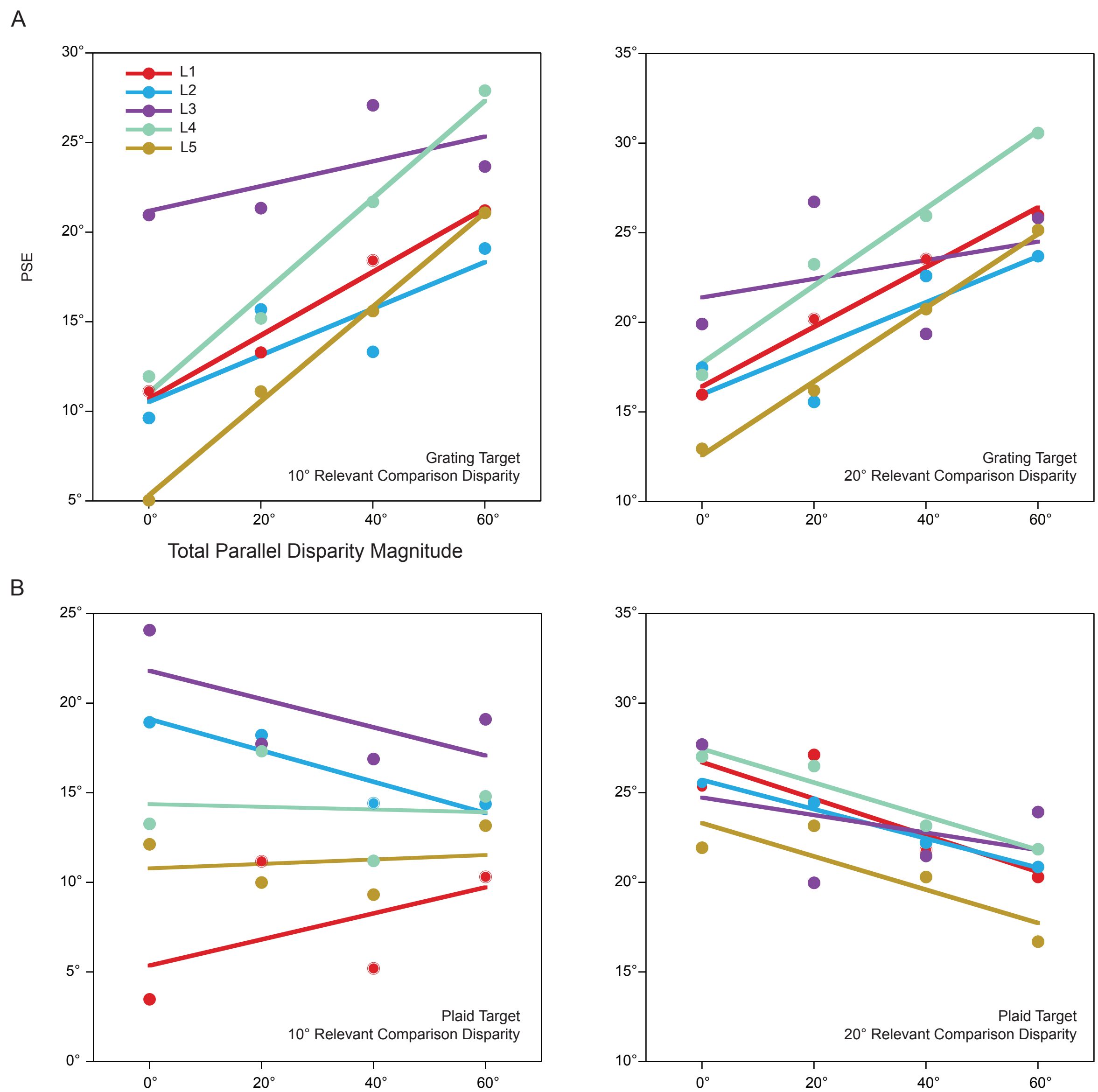

Figure S4. Grating (*A*) and plaid (*B*) PSEs as a function of total parallel disparity magntiude for the five observers. Data are plotted separately for relevant disparities of 10° (left column) and 20° (right column).

Note S5. We asked whether observers could discriminate the obliquely disparate experimental plaids of the experiment from plaids with horizontal disparities. An isotropic, zero-disparity fixation point that serving as the reference stimulus—neutral in orientation and disparity direction—provided the context in which these plaids appeared. On each trial we presented a single plaid centered on the fovea. One type of plaid had a disparity direction of +45° or -45° and a disparity magnitude of 10° or 20°, identical to a comparison stimulus in our main experiment. The other plaid type differed by having a disparity that was horizontal with a magnitude 0.707—that is, cos(45°)—times as great. Thus, the horizontal component of disparity was the same whether the disparity direction was horizontal or oblique. Horizontal and oblique disparity directions and large and small disparity magnitudes appeared equally often within blocks of trials. Presentations were again 176 ms long. Of the two observers, one (L3) had been in the main experiment and the other hadn't participated but had considerable experience in other stereo studies. The task was to classify the plaid as having a horizontal or an oblique disparity direction, using the auditory feedback following each response to learn the distinction and maximize performance. After many hundreds of trials, neither observer managed to discriminate horizontal and oblique disparities with above-chance performance. The two stimulus types appeared identical. One observer was given the additional opportunity to learn to discriminate disparity directions of +45° and horizontal in separate trial blocks from -45° and horizontal. Again, there was no evidence that the task could be done successfully.

Yet, even vertical disparities that are below perceptual threshold can elicit ocular motor responses, if the stimulus is high in enough contrast and long enough in duration (Duwaer & von den Brink, 1981). While our presentation durations were too short for this (Houtman, Roze & Scheper, 1981; Howard & Rogers, 2002a), displays presented on successive trials within a run contained comparison stimuli with fixed disparities and the target stimuli had fixed disparity axes. So, perhaps incipient eye movements could accumulate across trials, eventually resulting in a vertical fixation disparity that partially or fully nulled some or all the vertical disparity components present in the display.

However, such a process of accumulation would have to overcome not only nonius alignment, but also the countervailing effect of the more lengthy viewing of the fixation and response screens appearing before and after each experimental display, in addition to the upper and lower edges of the screen, which were constantly in view—all containing high-contrast, sharp-edged stimuli. They have a nominal disparity of zero. But if a vertical fixation disparity had been induced by the experimental displays, they would be imaged on the retina with a vertical disparity in the opposite direction, which would also accumulate, dissipating the effect. Nor is it clear how a vertical fixation disparity would account for the data observed here or how it would operate differently in grating- and plaid-target displays. In any case, evidence against the accumulation hypothesis already exists. If vertical fixation disparities did accumulate, they would not have been seen in the data of Duwaer and van den Brink (1981), who randomized the magnitude and direction of vertical disparities from one presentation of the inducing stimulus to the next. The inter-trial interval they used (at least in their Experiment 2) was comparable to ours.

Thus, the evidence weighs against the vertical component of the disparity of our stimuli having an intrinsic perceptual consequence or an influence on eye position. The effect of the vertical component of disparity, shown in the grating PSEs data, can therefore be taken as a result of the processing of the relative disparity between stimuli, both relevant and irrelevant.

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