A contrast paradox in stereopsis, motion detection and vernier acuity

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ABSTRACT:

Stereoacuity improves with increasing contrast, unless the increase is monocular. In this case performance paradoxically suffers. This study examined whether this "contrast paradox" occurs for two other classes of visual judgment: two-frame motion and vernier acuity. We constructed three homologous tasks in which the two components of a gabor stimulus (stereo half-images, motion frames, vernier components) were either both high contrast, both low contrast, or mismatched. The contrast paradox was evident in all three tasks and showed a similar spatial frequency dependence. We suggest the contrast paradox results from the combination of mismatched signals by a single filter.

Keywords: contrast stereopsis motion vernier acuity

Introduction:

The “contrast paradox” in stereopsis was originally reported by three separate groups as part of larger studies into the influence of contrast on stereoscopic depth judgments (Halpern & Blake, 1988; Schor & Heckman, 1989; Legge & Gu, 1989). A subsequent study showed that the perturbing effects of different contrast in the two eyes was spatial frequency dependent, being more exaggerated for low spatial frequency stimuli than for high (Cormack, Stevenson, & Landers, 1997). Explanations for the phenomenon have been specific to binocular vision, being based on mutual inhibition between left and right eye monocular processes (Kontsevich & Tyler, 1994), or correlations between noise components in the left and right eye images (Legge & Gu, 1989).

Insert Fig. 1 about here.

The present study was motivated by the computational similarity of two-frame motion and stereoscopic processing. In both cases, the visual system is faced with the problem of determining matching features in a pair of images and identifying the displacement or disparity of those matches. Figure 1 shows how a stereo stimulus (top) can be converted to a homologous motion stimulus (middle) by presenting half images across time instead of eyeball. If the contrast paradox is a general phenomenon related to the neural comparison of matched signals, and not specifically related to binocular interactions, then it seemed likely to show up in this sort of motion. Similarly, the motion stimulus can be converted to a homologous vernier stimulus by substituting a second spatial dimension for time. Note the similarity of the x-t plane in the motion stimulus (middle) to the x-y plane in the vernier stimulus (bottom). Thus, all three tasks are conceptually equivalent in that they require observers to identify a displacement between two halves of a stimulus. Moreover, they are commonly thought to depend on early visual filters (e.g. disparity, velocity or orientation-tuned neurons) that integrate over the entire stimulus. If the contrast paradox is a result of single filter integration, it should result whenever a stimulus comprises mismatched contrasts *regardless of task*. If, however, it results from inherently binocular processing, as has been proposed (Legge & Gu, 1989; Kontsevich & Tyler, 1994), it should be unique to the stereoscopic task.

Methods:

Gabor patch pairs of matched or mixed contrast were combined either dichoptically (Fig. 1, top), as a motion sequence (middle) or as two halves of a vernier stimulus (bottom). Because previous work indicated that the contrast paradox phenomenon is spatial frequency dependent (Cormack et al., 1997), we measured offset sensitivity for both 1 cycle per degree and 4 cycle per degree gratings under conditions of equal and unequal contrast.

Stimuli were displayed on a linearized Apple 15 inch color monitor with mean luminance 38 cd/m2 and viewed from a distance of 200 cm. At this distance, with monitor resolution set to 640 by 480, each pixel subtended one minute of arc. Stereoscopic stimuli were displayed side by side on the monitor and were fused with the aid of a four mirror haploscope. A grid of black lines preceded the stereoscopic stimuli to provide a zero disparity reference. Each frame of the motion stimulus was presented for 145 msec with no blank interval between them. Stereo and vernier stimuli were presented for 145 msec. Motion and vernier stimuli were displayed in the center of the screen and viewed directly. Gabor patches were 256 pixels square, made by multiplying a vertical sine wave grating of 1 or 4 cpd with a circular gaussian envelope whose standard deviation was 43 pixels. Displacements were produced by changing the phase of the grating component of each Gabor patch while leaving the envelope position constant.

Thresholds were measured using a method of constant stimuli and a two alternative forced choice procedure in which observers identified the direction of displacement. Seven levels of disparity, displacement or vernier offset presented in pseudo-random order constituted a single block of trials, and 25 blocks were run in each session. Combinations of low and high component contrasts were intermixed so that each session yielded a threshold estimate for each combination. Psychometric functions were fit with a Weibull equation and threshold was defined as the displacement producing 82% correct performance in the task. Beta values from the Weibull fit were typically between 1 and 2. Three independent threshold measurements were made for each condition.

Results:

Results from all three tasks are shown for two observers in Figure 2. The minimum detectable offset is plotted against contrast, with data for the mixed contrast cases plotted at the geometric mean of the high and low component contrasts. For all three tasks, when contrast was increased from 10% to 40% in both components, discrimination was roughly constant or improved slightly. When contrast was increased in just one component, performance degraded considerably compared to equal low contrast. A comparison of the results for 1 cpd (top panels) and 4 cpd (bottom panels) reveals the spatial frequency dependence of the phenomenon, as has been shown previously (Cormack et al., 1997).

Insert Fig. 2 about here.

The magnitude of the contrast paradox effect for each task is plotted in Figure 3. Each bar indicates the elevation of the mixed contrast threshold relative to the matched, low contrast threshold. The right axis shows threshold ratios and the left axis shows their logarithms. Larger positive values indicate a larger contrast paradox. The data for 1 cpd targets (filled bars) show substantial threshold elevations with mismatched contrast, with the strongest effects occurring for the motion and stereo tasks. The data for 4 cpd show much less or no elevation. The spatial frequency dependence of the effect does depend somewhat on task. For example, of the three tasks, vernier showed the largest contrast paradox at 4 cpd but the smallest at 1 cpd.

Insert Fig. 3 about here.

Discussion:

When one component of a vernier, motion or stereo stimulus pair is increased in contrast, the overall signal strength is increased. Although the components become less similar and so might be less well matched in some sense, a formal analysis such as cross-correlation reveals an improvement in signal strength when just one half of the pair is increased in contrast. Given reasonable assumptions about noise, this means that the stimulus should become easier, not harder to localize.

For stereopsis, others have postulated mutually inhibitory interactions prior to binocular combination (Legge & Gu, 1989; Kontsevich & Tyler, 1994). This proposed interaction has the effect of weakening the low contrast target substantially, and thereby accounts for the overall reduced signal quality that leads to poor performance.

Can this same sort of explanation be applied to the motion case? It seems unlikely that the two frames of the motion stimulus undergo a mutually inhibitory interaction prior to their combination in directionally selective neural mechanisms. Whereas the stereoscopic stimuli are segregated into parallel monocular channels which may interact in this way, the motion stimuli are separated only by time.

For motion, a possible explanation might be masking of the low contrast frame by the high contrast frame. Likewise, one might propose that one component of the vernier target might mask the other. Masking, however, is just a term indicating that one stimulus has interfered with another and thus does little more than restate the results.

The larger question is whether the interference is of fundamentally the same type in all three cases, or whether three different types of interference produce these very similar results. The facts are that vernier, motion and stereoscopic discrimination tasks are conceptually similar, they show a similar contrast paradox, and the contrast paradox shows a similar frequency dependence. It would be most satisfying and parsimonious to explain all these phenomena with the same fundamental process, rather than appealing to mutual inhibition in one case, masking in another, etc. In all cases, two components of a stimulus are combined into a single mechanism whose function is to respond to matching inputs that are displaced across eye-of-origin (stereo), time (motion), or space (vernier). Modeling efforts have confirmed that a general process of contrast normalization, operating as a gain control mechanism in early visual filters, can produce the interactions we observe as the contrast paradox. However, this still does not account for the effect's enigmatic but characteristic spatial frequency dependence. Whatever the explanation, our results suggest that the contrast paradox is a general phenomenon and so may well be a natural consequence of how the visual system compares stimuli within a single filter.

References:

Cormack, L. K., Stevenson, S. B. and Landers, D. D. (1997). Interactions of Spatial Frequency and Unequal Monocular Contrasts in Stereopsis. Perception **26,** 1121-1135.

Halpern, D. L. and Blake, R. R. (1988). How contrast affects stereoacuity. Perception **17**, 483-95

Kontsevich, L. & Tyler, C. W. (1994). Analysis of stereothresholds for stimuli below 2.5 c/deg. Vision Research **34**, 2317-2329.

Legge, G. E. and Gu, Y. (1989). Stereopsis and contrast. Vision Research **29**: 989-1004.

Schor, C, Heckman, T, 1989 "Interocular differences in contrast and spatial frequency: Effects on stereopsis and fusion" Vision Research **29** 837-847

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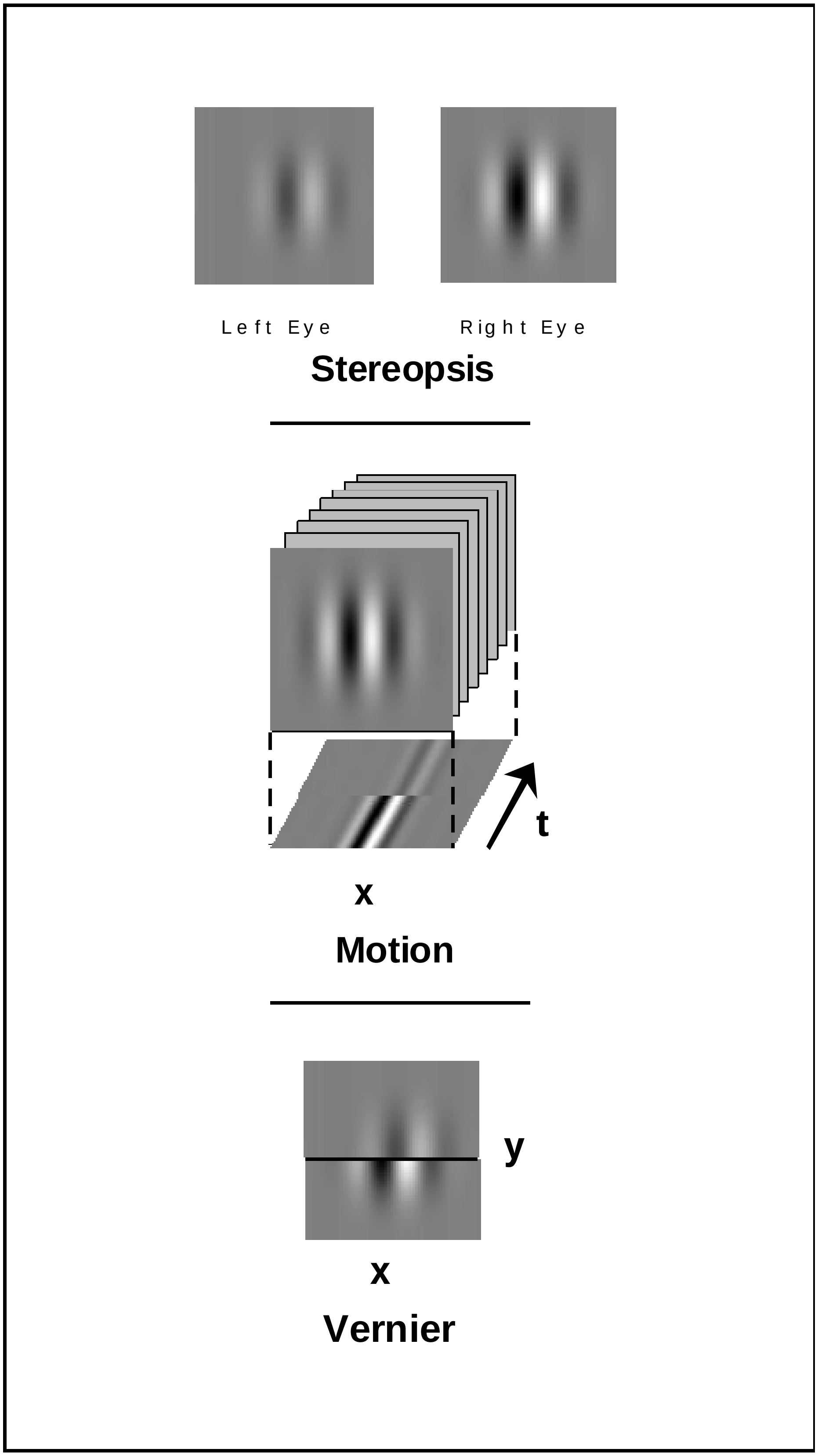
Figure captions

Figure 1: Gabor patches of high and low contrast were combined to measure offset detection in three tasks. The initial stereoscopic task that presented mismatched contrast to left and right eyes (top) was extended to two-frame motion (center) and to abutting vernier (bottom). Disparity, displacement or offset thresholds for the mismatched contrast stimuli were compared to thresholds for matched high and matched low contrast stimuli.

Figure 2: The contrast paradox phenomenon in stereopsis, motion detection and vernier offset detection. Results are shown for two observers at two spatial frequencies. As contrast is increased in both eyes from 0.1 to 0.4 ("matched"), performance is relatively unchanged or improves slightly. When contrast is increased in just one eye ("mixed"), performance suffers. The effect is larger at the lower spatial frequency. Data for the "mixed" condition are plotted at the geometric mean of the component contrasts. Each point shows the geometric mean of three threshold measurements. Error bars show +/- 1 standard error.

Figure 3. Data from Fig. 2 replotted as the elevation of mixed contrast thresholds relative to matched, low contrast thresholds. Bar height thus shows the magnitude of the contrast paradox for each task and spatial frequency. Error bars indicate +/- 1 standard error.


Left Eye
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Stereopsis
t
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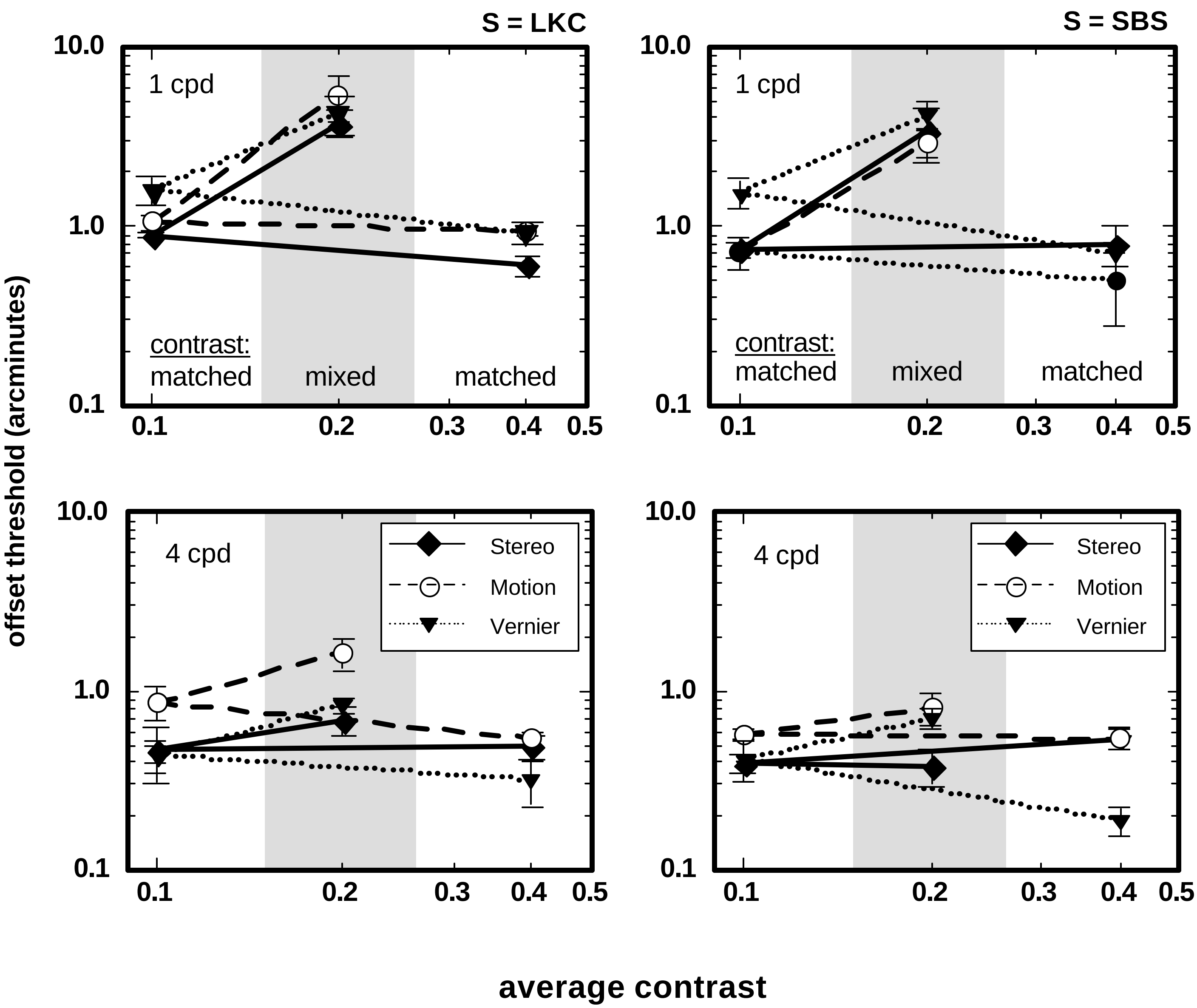
Vernier


S = LKC
S = SBS
1 cpd
4 cpd
contrast:
matched
mixed
matched
Stereo
Motion
Vernier
10.0
1.0
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0.2
0.3
0.4
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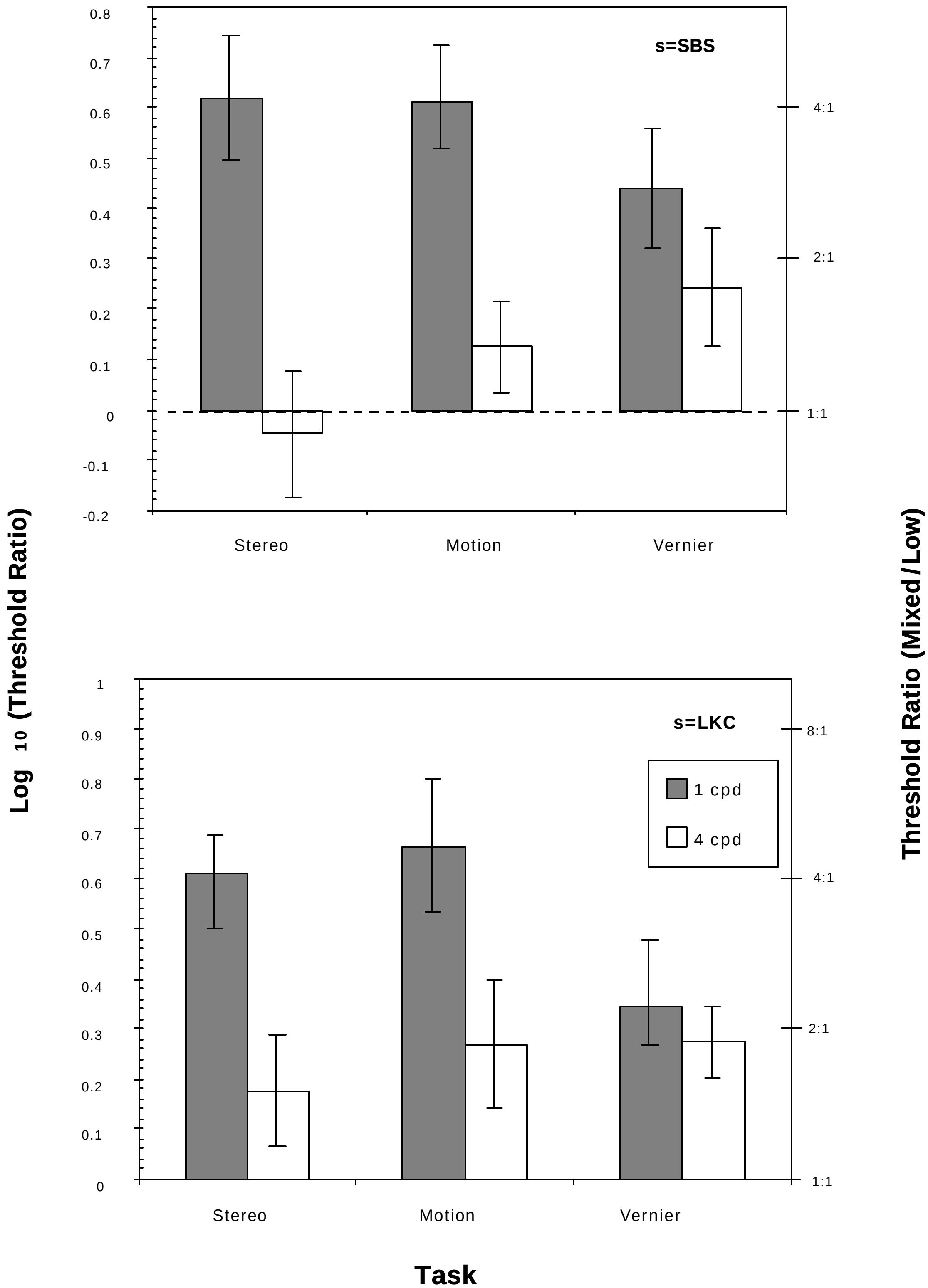
offset threshold (arcminutes)
average contrast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Stereo
Motion
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2:1
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0.7
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0
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s=LKC
1 cpd
4 cpd
8:1
1
0.9
Log 10 (Threshold Ratio)
Threshold Ratio (Mixed/Low)
Task