Spatial factors limiting stereopsis and fusion

By Clifton M. Schor

The appreciation of relative depth between two or more objects can be derived from the slightly different perspective with which our two eyes view the world. This perspective leads to the formation of both absolute and relative horizontal retinal image disparities. Absolute disparities are defined as the difference between the visual angle subtended by a target at the entrance pupils of the two eyes and the eye's angle of convergence. In contrast, relative disparity is independent of the angle of convergence or even the direction of gaze. It equals the difference in visual angles subtended by two targets at the entrance pupils of the two eyes.

Our sensitivity to those two forms of disparity is vastly different. We are able to detect several seconds of arc difference in the relative disparity subtended by two targets[1]. This keen sense of stereopsis earns it one of the highest ranks among the hyperacuities. In contrast, our sense of absolute disparity is amblyopic. If asked to

CLIFTON M. SCHOR is a professor of optometry and physiological optics at the University of California, Berkeley. This paper was presented as an invited paper at the 1986 OSA annual meeting.

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judge the distance of a single small light source in an otherwise darkened room, the target always appears at a distance of about 1 m, independent of its true distance. Gogle refers to this as specific distance tendency[2].

Only when a second target provides a frame of reference from which a relative disparity can be calculated is any depth appreciated, and even then, the absolute distance remains vague. Normally we are able to judge absolute distance in a less impoverished environment that contains familiar size cues and other monocular pictoral cues such as overlap, shadow, linear perspective, and texture gradients.

Convergence is another cue considered to aid in distance perception[3]. Through a process of triangulation, the point of intersection of the visual axes could provide distance information for a fused target. However recent reports[4] demonstrate otherwise. If a subject is allowed to track, with convergence eye movements, a small spot moving in depth in an otherwise darkened room, the target appears motionless.

Another example of the inability of convergence, by itself, to stimulate distance perception is the wallpaper illusion[5]. If a repetitive pattern is fused falsely, as a result of excessive convergence, the fused image appears to float in front of the page. This illusion is not the result of misreading depth from convergence. The illusion disappears if, for example, a repetitive wallpaper pattern is held close to the face and it is again fused with an error of convergence.

However, the illusion reappears if an unambiguous, nonrepetitive pattern such as a finger is held up between the observer's face and the falsely fused wallpaper. The finger subtends an unambiguous diplopic percept while the wallpaper subtends a falsely fused percept. The error in sensed absolute disparity of the wallpaper produces an error in sensed relative disparity between the finger and wallpaper, which in turn results in a perceived error of relative depth. Convergence error only serves to produce the error of sensed relative disparity; however, it does not directly cause the illusion.

The lack of utility of absolute disparity and convergence raises the question of how we can scale angular retinal image disparities into veridical perceived linear depth intervals. An inch in the saggital plane is perceived veridically over a range of viewing distances out to several meters, even though its retinal image disparity is reduced proportionally with the square of viewing distance[6]. Accordingly the visual process needs information about absolute distance in order to perceive relative depth veridically[3]. The recent de-emphasized role of convergence suggests that by default, monocular depth cues such as pictoral cues mentioned above must provide a major source of information for scaling disparity for the veridical sense of depth.

If absolute disparity is ineffective in stimulating absolute depth percepts, then what is its role? First and foremost, it assists relative depth judgement by stimulating vergence eye movements whose purpose is to null out absolute disparities and allow the optimal conditions for processing relative disparity. Absolute disparites also stimualte diplopia when they exceed Panum's fusional limit. Relative disparities, on the other hand, stimulate the percept of relative depth or stereopsis.

Classically the diplopia and stereo-thresholds have both been considered as constants. However recent studies have demonstrated that these thresholds vary markedly with target features including size, spatial frequency, spacing, motion, and field location. The most influential of these variables are the absolute and relative locations of targets in the visual field.

Stereo-sensitivity to a given angular relative disparity varies with the saggital distance of the stimulus depth increment from the fixation place. Sensitivity to depth increments is highest at the horopter or fixation plane, where the disparity of one of the com-

parison stimuli is zero[7-8]. This optimal condition for stereopsis was used by Tschermak as one of four criteria for defining the empirical longitudinal horopter[9]. The Weber fraction, describing the ratio of increment stereo threshold (arc sec) over the disparity pedestal (arc min) (3 "/min), is fairly constant with disparity pedestal amplitudes up to 2 deg. Stereoscopic depth is not perceived beyond this absolute disparity[8].

Unlike the reduction of stereosensitivity in the saggital plane, stereoacuity remains uniformly at its peak in the central 5 deg of the tangent plane about the fixation point[9]. Curiously, monocular vernier offset thresholds, measured with the same targets and at the same retinal eccentricities as used for testing stereopsis, are markedly elevated (reduced sensitivity), while tangential stereoacuity is unaffected by parafoveal retinal eccentricities.

It has been proposed that vernier sensitivity to spatial offset is a precursor to the formulation of retinal image disparity[10], that is, relative retinal image disparities are computed from differences between spatial separations seen by each eye; however, this is clearly not the case. A more likely computation of relative disparity comes from camparison of absolute disparities as described above[11]. Vernier acuity is apparently reduced by a central (nonretinal) process that does not limit fronto-parallel stereopsis.

Both the fronto-parallel and extra-horopteral stereothresholds are influenced by the spatial frequency of the fusion stimulus[12]. Stereo thresholds are lowest and remain relatively constant for spatial frequencies above 2.5 cycles/deg. Thresholds decrease proportionally with lower spatial frequencies. Even though stereo threshold varies markedly with target coarseness, suprathreshold disparities needed to match the perceived depth of a standard disparity of 40 arc min.

are independent of spatial frequency. This equivalence constitutes a form of stereo-depth constancy[13].

Similar variations in the diplopia threshold or binocular fusion limit are found by varying the coarseness of fusion stimuli[14]. Classical vertical and horizontal dimensions of Panum's fusion limit (PFL) are found with high spatial frequency targets, but the fusion limit increases proportionally with the spatial width of targets at spatial frequencies lower than 2.5 cycles/deg. When measured with

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high spatial frequency patterns, the horizontal radius of PEL is 15 min, and when measured with low spatial frequencies below .1 cycles/deg, the fusion range is enlarged to over 6 deg at the fovea.

The spatial dependence of stereopsis and fusion on spatial frequency results in the simultaneous perception of diplopia, fusion, and stereopsis in complex targets composed of a broad range of spatial frequencies. For example, leaves within the foliage of an extended limb of a tree can be seen diplopically, while clusters of leaves appear single[15]. Clearly a single dimension for Panum's area is incompatible with this observation.

Stereopsis and fusion are also influ-

enced by the relative position or spacing of targets in the visual field. The traditional studies of stereopsis, such as those conducted by Wheatstone, mainly consider the disparity stimulus in isolation from other disparities at the same or different regions of the visual field. It is said that disparity is processed locally in the limiting case, independent of other possible stimulus interactions, other than the comparison between two absolute disparities to form a relative disparity.

However, recent investigations have clearly illustrated that in addition to the local process, there are global processes in which spatial interaction between multiple relative disparities in the visual field can influence both stereopsis and fusion. These global interactions appear to influence phenomena such as the variation in size of Panum's fusional area, reductions and enhancement of stereo-sensitivity, constant errors or distortions in depth perception, and resolution of 3-D form that has been camouflaged with an ambiguous surface texture.

Three forms of global interactions have been studied. These are disparity gradients, disparity crowding, and disparity interpolation. The first of these, disparity gradients, depends upon spacing between disparate targets and the difference in their disparities. Taken together these two variables can be described in terms of a disparity gradient between two or more adjacent targets. The disparity gradient represents how abruptly disparity varies across the visual field. Several studies have shown that the binocular sensory fusion limit or diplopia threshold increases according to a constant disparity gradient of 1.0 as the spearation between adjacent fusion stimuli increases[16-17]. Thus the diplopia threshold is approximately equal to the separation between the test target and fixation point.

Like fusion, stereopsis also under-
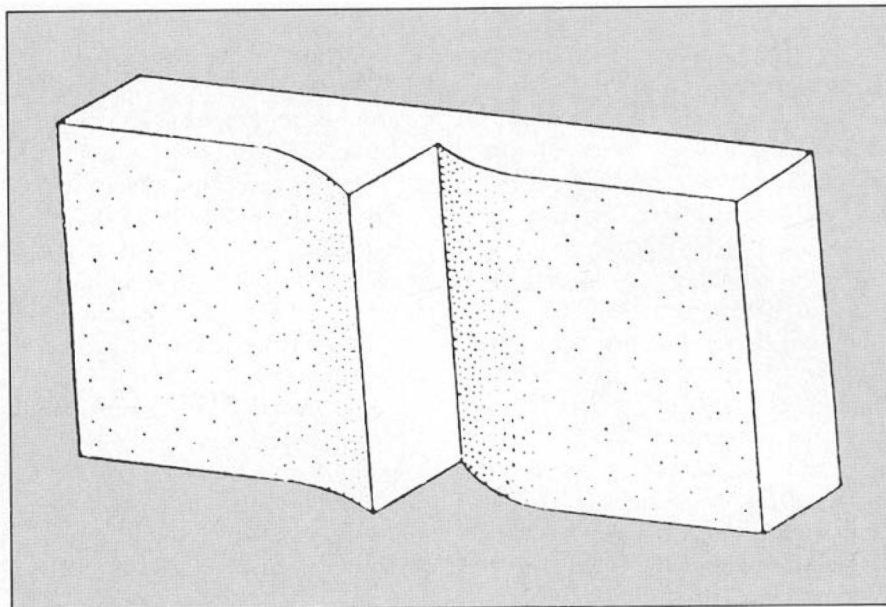
FIGURE 1. The gradual changes in depth of the textured surface are not perceptible when the only cut to distance is retinal image disparity. Rather, the target is seen as a step change in depth, which illustrates the principle of continuity.

goes global interactions with other stereo figures in the visual field. For example, stereo threshold reaches its minimum value at spatial separations of 15 arc min or 1/4 deg.[18] The second global interaction, crowding between disparate features, appears at smaller target separations and causes an elevation of stereo threshold[18-19] This may be an averaging effect resulting from an inability to resolve closeley spaced disparities.

A third form of global interaction is observed under conditions where disparity differences between neighboring regions occur too gradually to be detected, such as in the 3-D version of the Craik-Obrien-Cornsweet illusion (Fig. 1),[20] when stereo patterns are presented too briefly to be processed fully,[21-22] or when several equally probably but ambiguous stereo solutions are presented in a region neighboring an unambiguous disparity solution[23]. Under all of these conditions, the depth percept resulting

from the vague disparity is simialr to or continuous with the depth stimulated by the more visible portion of the disparity stimulus.

This illustrates the principle of depth continuity formulated by Julesz[24] and later by Marr and Poggio[25], which was recently shown to include the extension of depth to subjective contours in which no physical contour or disparity exists[26]. All of these examples support the rule that states that if some region of the visual field is fused binocularly while an ambiguous adjacent region is not, then the disparity solution for the ambiguous region will be one that minimizes the depth differences between the adjacent regions, i.e., the solution that results in the most gradual disparity gradient.
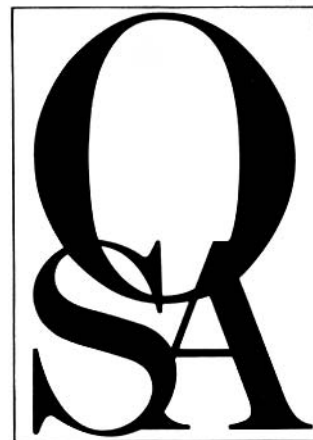
Conclusions

Collectively, the studies reviewed here indicate that certain stimulus pa-

rameters (i.e., absolute and relative spatial location) influence the range of absolute disparity that stimulates sensory fusion as well as the range and magnitude of relative disparity that stimulates stereoscopic depth perception. Panum's fusional areas are no longer described as fixed units of binocular correspondence; rather they have variable dimensions that accommodate both the size and spacing of the fusion stimulus. Similarly, stereo-sensitivity to relative disparity is influenced by the absolute or average disparity of the depth stimulus, as well as size and spacing between stereo targets. Further research will elaborate upon the global processes that underlie the flexibility of binocular sensory fusion and stereoscopic depth perception.

REFERENCES

1. G. Westheimer and S. McKee, "Stereoscopic acuity with defocused and spatially filtered retinal images," J. Opt. Soc. Am. 70, 772–778 (1980).
2. W.G. Gogle and J.D. Teitz, "Absolute motion parallax and the specific distance tendency," Percept. Psychophys. 13, 284–292 (1973).
3. H. Wallach and L. Floor, "The use of size matching to demonstrate the effectiveness of accommodation and convergence as cues to distance," Percept. Psychophys. 10, 423–428 (1971).
4. C.J. Erkenlens and H. Collewijn, "Eye movements and stereopsis during dichoptic viewing of moving random-dot stereograms," Vision Res. 25, 1689–1700 (1985).
5. W.H. Ittelson, "Binocular stereopsis," in Visual space perception visual space cues 123–127 (1960).
6. H. Ono and J. Comerford, "Stereoscopic depth constancy," in Stability and Constancy in Visual Perception: Mechanisms and Processes, W. Epstein, ed. (Wiley, New York, 1977), pp. 91–128.
7. C. Blakemore, "The range and scope of binocular depth discrimination in man," J. Physiol. 211, 599–622 (1970).
8. D.R. Badcock and C.M. Schor, "Depth increment detection function for individual spatial channels," J. Opt. Soc. Am. 2, 1211–1216 (1985).

9. C.M. Schor and D.R. Badcock, "A comparison of stereo and vernier acuity within spatial channels as a function of distance from fixation," Vision Res. 25, 1113–1119 (1985).
10. E. Ludvigh, "Direction sense of the eye," Am. J. Ophthalmol. 36, 139–143 (1953).
11. G. Westheimer, "Cooperative neural processes involved in stereoscopic acuity," Exp. Brain Res. 36, 585–597 (1979).
12. C.M. Schor and I. Wood, "Disparity range for local stereopsis as a function of luminance spatial frequency," Vision Res. 23, 1649–1654 (1983).
13. C.M. Schor and P.A. Howarth, "Suprathreshold stereo-depth matches is a function of contrast and spatial frequency," Perception, in press (1986).
14. C.M. Schor, I. Wood, and J. Ogawa "Binocular sensory fusion is limited by spatial resolution," Vision Res. 24, 661–665 (1984).
15. A.L. Duwaer, "Patent stereopsis and diplopia in random-dot stereograms," Percept. Psychophys, 33, 443–454 (1983).
16. P. Burt and B. Julesz, "A disparity gradient limit for binocular fusion," Science 208, 615–617 (1980).
17. C.M. Schor and C.W. Tyler, "Spatio-temporal properties of Panum's fusional area," Vision Res. 21, 683–692 (1981).
18. C.W. Tyler "Spatial organization of binocular disparity sensitivity," Vision Res. 15, 583–590 (1975).
19. G. Westheimer "Spatial interactions in the domain of disparity signals in human stereoscopic vision," J. Physiol. 370, 619–629 (1986).
20. S.M. Anstis, J.P. Howard, and B. Rogers, "A Craik-Cornsweet illusion for visual depths," Vision Res. 18, 213–217 (1978).
21. V.S. Ramachandran and J.I. Nelson, "Global grouping overrides point to point disparities," Perception 5, 125–128 (1976).
22. G.J. Mitchison and S.P. Mckee, "Interpolation in stereoscopic matching," Nature 315# 6018, 402–404 (1985).
23. L.L. Kontsevich, "An ambiguous random-dot stereogram which permits continuous change of interpretation," Vision Res. 26, 517–519 (1986).
24. B. Julesz, "Foundation of cyclopean perception," Univ. of Chicago Press (1971).
25. D. Marr and T. Poggio, "A computational theory of human stereo vision," Proc. Royal Soc. 204, 310–328 (1976).
26. V.S. Ramachandran and P. Cavanagh, "Subjective contours capture stereopsis," Nature 314, 527–530 (1985).