Notes and Comment

Does stereopsis have a fusional component?

ROBERT P. O'SHEA

Queen's University, Kingston, Ontario, Canada

There has been some recent discussion in this journal about fusion of stereoscopic stimuli that are rotated by small amounts around the line of sight, that is, cyclofusional stimuli (Kertesz, 1983a; O'Shea & Crassini, 1982). In both papers, it was agreed that cyclovergent eye movements could contribute to singleness of vision of the stimuli. With single-line stimuli, the contribution was asserted to be minor, and almost negligible (O'Shea & Crassini, 1982), whereas with complex stimuli, there was thought to be substantial cyclovergence (up to 70% compensation (Kertesz, 1983a). Kertesz (1983a) found our paper to be untimely, equivocal, and uninformative. I wish to dispel these impressions, and to address the implication by Kertesz that stereopsis involves fusion that is somehow different from the nonmotor component of cyclofusion.

Terminology

Part of the problem in this area has to do with the use by different researchers of the same terms for theoretically different constructs. To facilitate communication, I intend to define the terms I use. Three levels of terminology can be distinguished. The first names the *percepts* of binocular vision. The second designates the *processes* involved with the percepts. Finally, there are the *mechanisms* accomplishing the processes, and hence the percepts.

The percepts of binocular vision that I am concerned with are (1) singleness of vision, and (2) stereoptic depth perception. These percepts can be considered to be independent: stereoptic depth perception is possible with diplopia (Ogle, 1953) and, in fact, with stimuli that cannot be fused (Ramachandran & Nelson, 1976); singleness of vision does not presuppose stereoptic depth perception (e.g., inspection of dichoptic stimuli with no binocular disparity).

The associated processes bear the following labels: "vergence eye movements," "fusion," and "stereopsis." Vergence eye movements (noted by Euclid,

ca. 300 B.C., cited by Boring, 1942) bring the two retinal images of a single object in the visual world onto (as far as possible) corresponding retinal areas (Müller, 1826, cited by Boring, 1942). Fusion is responsible for singleness of vision of an object despite its two retinal images (attributed by Kaufman, 1974, to Kepler, 1604/1965). Stereopsis is the process leading to the experience of depth arising from binocular parallax afforded by the lateral placement of the eyes (Wheatstone, 1852). These processes are independent as defined, and arguments can be made for their theoretical independence. For example, vergence movements can be initiated by stimuli that are very different in form (Mitchell, 1970), and stereopsis is possible with such form differences (Ramachandran & Nelson, 1976). Fusion, however, does require quite close comparability of dichoptic stimuli (O'Shea, Note 1).

The nature and number of mechanisms that accomplish the above processes are matters of debate. It is sufficient for my purpose to recognize two things: (1) "vergence," "fusion," and "stereopsis" have been applied as labels to mechanisms, and (2) a logical distinction between processes does not necessarily imply that there are different mechanisms.¹ It could well be that a stereoptic mechanism accomplishes both the process of stereopsis (by definition) and of fusion (see Bishop, 1979).

Communication difficulties arise when people use the same terms to explain a percept (e.g., "fusion" for "singleness of vision"), a process or processes ("fusion" for "fusion and vergence"), and/or mechanism(s) (the fusion mechanism as incorporating vergence and stereopsis mechanisms). I offer the distinctions but no panacea; these terms have always been used interchangeably, and I know it would be futile to attempt to change current usage at this late stage.

With the distinctions in mind, I wish to propose a strict correspondence between processes and the percepts and that the processes are neural in nature. That is, stereoptic depth perception arises from a neural stereopsis process and singleness of vision arises from a neural fusion process. Vergence is the process whereby the retinal images are brought into close enough correspondence for these two neural processes to operate. Most authors would have no objection to the stereopsis process (e.g., see Bishop, 1979), but there may be less unanimity about the fusion process. For example, Kertesz has always asserted that the cyclofusional response leading to singleness of vision consists of two components: a motor (vergence) component and a nonmotor, sensory (fusion)

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component (Kertesz, 1971, 1983a). However, vergence cannot accomplish fusion. Even if the retinal images are brought into perfect registry (i.e., the vergence component of the fusional response is 100%), there is the problem that the resultant percept is not doubled in "intensity." This is a very ancient observation (recorded by Aristotle; see Breese, 1899), and modern thought is divided into two camps (see Dodwell, 1970, and Kaufman, 1974). Fusion theorists hold that there is a roughly equal, facilitatory contribution of each eye to the fused percept, while suppression theorists argue that there is an inhibitory relationship between corresponding retinal points so that parts of the image in one eye are suppressed.

Finally, it is necessary to apply the above terms to the situation in which the eyes are presented with stimuli that are rotated in opposite directions around the line of sight. These are cyclorotated stimuli. Vergence in response to such stimuli I call "cyclovergence." Singleness of vision with such stimuli has been called "cyclofusion," but this has also been used as a catchall to include the vergence process (Kertesz, 1983a). I will use "cyclofusion" to describe the neural process producing the percept of singleness of vision with cyclorotated stimuli. The question of whether there is also a separate cyclofusional mechanism (distinct from stereopsis and fusion mechanisms) is treated below. I will consistently use the terms as defined above. Table 1 provides a memory aid, and shows the large number of competing synonyms. With an understanding of the defined terms, it is possible to go on and consider the

seeming differences between Kertesz (1983a) and O'Shea and Crassini (1982).

Kertesz's Objections

Crassini and I provided a stereogram consisting of an upright cross rotated in opposite directions by 4 deg in each half-image. Subjects reported that with stereoscopic presentation, the near-vertical part of the cross was seen as single (fused) and tilted in stereoptic depth (with the top closer than the bottom, or vice versa, depending on the direction of rotation in the stimuli). However, the near-horizontal components were diplopic, with no associated depth (or, more correctly, they appeared to lie in the plane of the stereogram), and occasionally the whole or parts of one or the other component were briefly invisible (binocular rivalry). Our conclusion contained three elements which I will spell out because Kertesz (1983a) seems to have misunderstood them. We reasoned that as cyclovergence must rotate the near-vertical and near-horizontal components of the cross equally, it could not be responsible for the different respective percepts (element A). Hence, the fusion process must be responsible (element B). We then speculated that the greater fusional range around the vertical meridian was due to fusion being augmented by stereoptic units accepting a greater range of horizontal than of vertical disparities (element C) (Barlow, Blakemore, & Pettigrew, 1967).²

Kertesz (1983a) objected to our paper on three counts. The first was that a subjective technique had been used to discriminate vergence and fusion (non-

Table 1
Preferred Labels (in Capitals) and Current Synonyms of Theoretical Constructs
at Different Levels of Explanation of Cyclofusion

Level	Fusion	Depth
Stimulus	CYCLOROTATED STIMULI cyclofusion(al) stimuli	CYCLODISPARITY orientation disparity angular disparity
Percept	SINGLENESSE OF VISION fusion cyclofusion	STEREOPTIC DEPTH PERCEPTION stereoscopic depth stereopsis
Process	1. CYCLOVERGENCE fusional cyclovergence motor cyclofusion cyclorotatory (eye) movements cyclofusional (eye) movements cyclotorsion cyclofusion 2. CYCLOFUSION sensory cyclofusion nonmotor cyclofusion	STEREOPSIS depth perception stereoscopic depth perception
Mechanism	1. CYCLOVERGENCE MECHANISM 2. CYCLOFUSION MECHANISM	STEREOPSIS MECHANISM

Note—In Columns 2 and 3, the preferred label is given in all-capital letters, and the current synonym(s) are given in all-lowercase letters.

motor) components of cyclofusion while the relevant objective data from measuring cyclovergence were deemphasized. While this is true, Kertesz's ostensible concern that researchers will henceforth overlook the objective data and revert to subjective methods recognizes in our paper a persuasive influence which was never intended. Our aim was to provide a simple demonstration of the minor influence of cyclovergence which anyone could try with a minimum of equipment—to be confirmatory rather than definitive.

Perhaps what concerned Kertesz more was that we minimized the role of cyclovergence, which he now believes to be a substantial component of cyclofusion (Kertesz & Sullivan, 1978; Sullivan & Kertesz, 1978). A review of Kertesz's work is instructive here. In a number of early studies, Kertesz used marked scleral contact lenses and/or conjunctival landmarks to monitor cyclovergence in response to cyclorotated stimuli. With a supposed precision of better than 0.50 deg, no evidence of cyclovergence was found with either single- or multiline stimuli in a number of subjects (Kertesz, 1972, 1973; Kertesz & Jones, 1970). In later work, however, cyclovergence ranges of up to 6 deg in response to multiline cyclorotated stimuli were found, with the use of a search-coil technique (Kertesz & Sullivan, 1978; Sullivan & Kertesz, 1978) for one subject (Kertesz himself). In attempting to rationalize this result with the earlier work, Kertesz and Sullivan (1978) proposed that cyclovergence ability was acquired during the course of the experiment. Recently, Kertesz (1983b) concluded that for cyclovergence to be elicited, large (50 deg rather than 10 deg) complex stimuli are required. Hampton and Kertesz (1982) present objective evidence of no cyclovergence in response to single, near-vertical lines, similar to the stimulus we used, so our conclusion is not contradicted by objective studies.

Kertesz's (1983) second cavil was that our interpretation was equivocal, and I reject this. The first part of our conclusion (element A), that cyclovergence cannot explain the percept following stereoscopic presentation of the cross, is inescapable from the logic outlined above. As motor (vergence) and non-motor processes are defined by Kertesz (1983a) as the only members of the complete set of fusional processes, element B is strictly true. Our speculation about the mechanism (element C) is perhaps less tenable, but actually seems to agree with the "alternative" account offered by Kertesz. He seems to have overgeneralized on our behalf that "[a]ll fusion is neural in nature" (Kertesz, 1983a, p. 99), although we were careful to note that our demonstration "does not disallow a small amount of cyclovergence; the crucial point is that cyclovergence must affect each arm of the cross equally" (O'Shea & Crassini, 1982, p. 196).

The third objection was that our results told little about cyclofusion, as defined by Kertesz (1983a). That is, we made no attempt to quantify the vergence and fusion components of the response to cyclorotated stimuli. Rather, our conclusion was about the nature of cyclofusion as I have defined it. We implied that cyclofusion was an epiphenomenon. I examine the utility of the concept of cyclofusion below in greater detail.

Is Cyclofusion an Epiphenomenon?

As defined earlier, stereopsis and fusion are logically independent processes (although this is not to say that stereopsis and fusion are subserved by different mechanisms). Thus, it seems odd that Kertesz (1983a) can maintain that the "8-deg orientation disparity contained in . . . [our cross-] stimulus . . . is beyond the range of cyclofusional compensation" (p. 100), and yet "the vertical line is seen as being inclined and the horizontal line is seen as being diplopic" (p. 100). This implies that the vertical member is fused by some other fusional process, but not by cyclofusion. Let this other process be known as stereoptic fusion (not to be confused with the process of stereopsis, which gives rise to depth perception). Stereoptic fusion, then, has the following properties: it can fuse disparities other than those produced by a cyclofusional stimulus, and its fusional range is greater for horizontal disparities. It would be nice, on the grounds of parsimony, to have a single general fusional process rather than two independent processes implied by the labels "stereoptic fusion" and "cyclofusion."

In order to achieve parsimony, either stereoptic fusion or cyclofusion could be broadened to include the other. In the first case, stereoptic fusion becomes general fusion if it can fuse any disparity (including those accompanying cyclorotated stimuli) and has an expanded fusional range of horizontal disparities. This is a small change in the original definition above. The other advantage is that a ready stereoptic fusion mechanism has long been proposed: that fusion is accomplished by the stereopsis mechanism (see Kaufman, 1974).

To broaden the process of cyclofusion it is necessary to specify its nature, and herein lies a problem. It is difficult to find out just what is meant by cyclofusion. Generally, it is defined tautologically, which is not helpful: cyclofusion is the process whereby cyclorotated stimuli are fused. The name implies a general remapping of the retinal projections, that a cyclovergence is accomplished neurally (Kertesz, 1973; Kertesz & Optican, 1974). However, this is wrong, from Kertesz's own work. That is, cyclofusion can accomplish fusion of a region requiring a remapping in one direction and of an adjacent region requiring the opposite remapping (Kertesz & Optican, 1974; Sullivan & Kertesz, 1975).³ It could perhaps be de-

defined as a global process in which fusion is greater than that possible with local fusion of individual elements, when adjacent elements are consistent with a rotation of the visual field in that region. Kertesz's (1973) demonstration of enhanced cyclofusion with increased contour density would be consistent with this view, but a strong test of the global-local distinction has not been conducted. To return to the original task, it is difficult to broaden a concept as ill-defined as cyclofusion. If it cannot be shown that there is anything to cyclofusion over and above local fusions, then its value would be in serious doubt. As stereoptic fusion can encompass cyclofusion with a minor change, and it is unknown whether the reverse could apply, it seems more useful to work with the former until the latter can be validated. I wait with interest to have cyclofusion's apparent epiphenomenal status confirmed or dismissed.

Conclusion

The word "cyclofusion" has a number of meanings. It has been used variously to describe the percept of singleness of vision when cyclorotated stimuli are presented, the process whereby this percept is attained, and as a label for the mechanism of process. I have tolerated the first use, wished to restrict the second to the neural, nonmotor process of fusion, and questioned the third. A cyclorotated stimulus can be resolved into horizontal and vertical disparity components. Kertesz (1983b) has concluded that cyclovergence differs from vertical vergence in adhering to Hering's law of equal innervation. However, for cyclofusion as I have defined it, Kertesz (1983b) found it to be similar to (limited by?) fusion of vertical disparities in both its speed and dependence on stimulus size. If there is a global cyclofusional mechanism, such a resolution into vertical disparities may be inappropriate, but my contention is that it is unknown whether there is such a global cyclofusional mechanism. Finally, I hope I have shown that Kertesz's objections are largely spurious: our conclusions were consistent with the most-recent objective evidence, which Kertesz (1983a) accepts, and Kertesz's alternative explanation casts doubts on the likelihood of a global cyclofusional mechanism.

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NOTES

1. For example, a pair of scissors (the mechanism) can be used to cut paper (one process) and to make a noise while doing so (another process).
2. There is some debate about this. Bishop (1979) reviewed a substantial amount of his and others' work, which showed equivalent ranges of optimal horizontal and vertical disparities for binocular neurons in the cat visual cortex. However, Von der Heydt,

Adorjani, Hännny, & Baumgartner (1978) found a greater range of facilitatory neural binocular interactions for horizontal than for vertical disparities.

3. Bishop (1978) also established this with a simple cross figure similar to ours. His stereogram consisted of half-images with a long, thick vertical line, which required an incyclovergence of 11 deg for "fusion" by eye movements, and a short, thin horizontal line, which required an excyclovergence of 4 deg. Nevertheless, the whole cross was seen as single.

Note Added in Proof:

Recently, S. Krekling and S. Blika (Meridional anisotopia in cyclofusion, *Perception & Psychophysics*, 1983, **34**, 299-300) pointed out that the direction of rotation of the crosses in the

stereogram presented by O'Shea and Crassini (1982) was towards the vertical horopter (i.e., tilted away at the top). Such rotation would reduce the effective disparity of the vertical members, but not of the horizontal members, and so explain the fused and diplopic respective percepts. While this is undoubtedly important, it is a simple matter to eliminate it as a complete explanation of our stereogram. That is, fusion of the vertical members and diplopia of the horizontal members persist when the stereogram is inverted, despite the rotation now being away from the vertical horopter.

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