

Stereopsis and Binocular Rivalry

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Stereopsis and binocular rivalry appear to be incompatible. Rivalry involves suppression of input from one eye at each location in space and time, whereas stereopsis requires the combination of information from both eyes to yield a sensation of depth. This article presents a theory of the relationship of these phenomena. Evidence from previous work and from experiments reported here shows that (a) the pathways mediating stereopsis are separable from those mediating rivalry; (b) stereopsis and rivalry can coexist at the same point in space and time; (c) rivalry occurs inevitably, whenever visual stimuli are present, even if identical stimuli are presented to both eyes; and (d) stereopsis can be disrupted without disrupting rivalry and vice versa (termed *double dissociation*). On the basis of the evidence, it is proposed that rivalry and stereopsis involve independent and parallel pathways through the early stages of visual processing and that binocular perception is a simple combination (probably a weighted average) of the output of the pathways mediating stereopsis and rivalry.

Stereopsis and binocular rivalry, two of the central phenomena of binocular vision, are seemingly incompatible. In stereopsis, matched or nearly matched retinal images are combined to form a "cyclopean" image (Helmholtz, 1909/1924; Julesz, 1971). The cyclopean percept is identical to neither monocular image but requires contributions from both. Binocular rivalry is most easily demonstrated when each eye is presented with a different image. At each location in the visual field, one monocular image will be dominant and visible while the other is suppressed and unseen (Breese, 1899). Over time, the pattern of dominance and suppression will change. At any given point in space and time, the stimulus presented to one eye is seen while that presented to the other eye is lost to sight. The suppression of one monocular input would eliminate the basis for stereopsis. The fusion of the two inputs into a cyclopean image would eliminate the basis for rivalry.

How, then, do the two phenomena coexist in human vision? One class of theoretical solution is to deny the existence of one of these two. Verhoeff (1935, 1959), for example, held that binocular vision could be explained without allowing for the fusion of the two monocular images into a unique binocular image. At the present time, it is more common to argue that rivalry and stereopsis cannot *coexist* at the same point in space and time and that stereopsis takes precedence; that is, rivalry occurs when stereopsis cannot occur (e.g., Julesz, 1971, p. 23; Julesz & Tyler, 1976).

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This article will defend a different set of propositions:

1. Rivalry and stereopsis involve independent and parallel pathways through the early stages of visual processing.
2. Rivalry occurs whenever visual stimuli are present. It occurs if identical stimuli are presented to both eyes. It occurs during stereopsis.
3. Binocular perception is a simple combination (probably a weighted average) of the output of the pathways mediating stereopsis and rivalry.

One consequence of these propositions is to deny the existence of a special "fused" state in binocular vision if that fused state is defined by the absence of binocular rivalry.

The following four lines of evidence will be presented in defense of these propositions: (a) *separability*: evidence that the pathways mediating stereopsis are distinct from and parallel to those mediating rivalry; (b) *coexistence*: evidence that stereopsis and rivalry can occur at the same point in space and time; (c) *inevitability*: evidence that rivalry occurs whenever visual stimuli are present, even if the stimuli are the same in both eyes; (d) *double dissociation*: evidence that stereopsis can be disrupted without disrupting rivalry, and vice versa. Although any individual piece of the data might be compatible with a variety of models, taken as a whole the evidence suggests that rivalry and stereopsis are parallel processes in human vision.

Separability of Stereopsis and Binocular Rivalry

Early processing in human vision can be thought of as a series of sequential stages. (a) The system gathers information about the input stimulus. (b) "Assertions" about the stimulus are made on the basis of that information. (c) Finally, the various assertions are combined and reconciled into a single percept. Initially, information is gathered through a number of broadly tuned channels. Sets of channels exist for a variety of different stimulus dimensions, including size (e.g., Campbell & Robson, 1968; Wilson & Bergen, 1979), motion (e.g., Levinson & Sekuler, 1975), depth (e.g., Julesz & Miller, 1975), color (e.g., Boynton, 1979), and orientation (e.g., Caelli & Bevan, 1983). For a

general review of the concept of a channel see Braddick, Campbell, and Atkinson (1978). Monocular and binocular channels exist as well and are discussed in detail below.

Activity in a single, broadly tuned channel is ambiguous. The classic example is color where the individual cone mechanisms are the broadly tuned input channels. Activity in a single type of cone does not specify color. The outputs of two or more such channels need to be compared in order to make specific assertions about perceived color. A plausible model maintains that, at the second level of processing, outputs of broadly tuned channels are the inputs to labelled lines that respond maximally to a specific ratio between two or more channels (e.g., opponent color mechanisms—for reviews see Boynton, 1979; Hurvich, 1981).

Another salient feature of this information gathering is redundancy. Information about a single stimulus is gathered in many different ways. For example, an edge will be examined by a number of relatively independent channels, broadly tuned for several different size scales (e.g., Marr, 1982) or in different monocular and binocular channels. These assertions about orientation may differ from one another due to noise or, as will be discussed below, due to differential adaptation of the channels. At the third level of processing, the various assertions must be combined to yield a single perception of the input. In the edge example, the perceived orientation will be based on some average of all of the assertions about orientation made for that location in the visual field.

The sequential stages in visual processing can be described in more detail. The remainder of this section will consider the details of monocular and binocular processing. The evidence suggests that stereopsis and binocular rivalry are parts of two parallel and independent routes through the early stages of visual processing. Each route generates assertions that are combined into binocular, single vision.

Structure of Human Binocular Visual Pathways

In recent years, it has become possible to map out the psychophysical sequence of monocular and binocular stages in early visual processing. Taken together, these findings clarify the relationship of stereopsis to rivalry. Obviously, given two separate eyes, the visual pathways are monocular in their earliest stages. After the two monocular pathways converge onto binocular sites, four processes emerge: two monocular and two different types of binocular process. Evidence comes from experiments involving visual aftereffects. Exposure to one pattern can change the appearance of subsequently presented patterns. This change is known as a visual aftereffect. In the tilt aftereffect, for example, exposure to lines of one orientation changes the apparent orientation of other lines. Lines tilted to the left of vertical will make vertical lines appear tilted to the right (e.g., Gibson, 1937). Viewing contours moving to the right will make stationary contours appear to drift to the left (*motion aftereffect*—e.g., Wohlgenuth, 1911). Viewing a sine wave grating of a specific frequency will reduce sensitivity to other gratings of that frequency (*threshold elevation*—Blakemore & Campbell, 1969) and will alter the apparent spatial frequency of neighboring frequencies (Blakemore & Sutton, 1969).

In each of these cases, exposing one eye to an adapting pattern will produce an aftereffect that can be measured when the

other eye is presented with a test pattern (e.g., Blake, Overton, & Lema-Stern, 1981; Gibson, 1937; Kohler & Wallach, 1944; Wohlgenuth, 1911). This is known as *interocular transfer* (IOT) and is considered to reflect the activity of a binocular process that is active when one eye views the adapting pattern and when the other eye views the test pattern (Blake et al., 1981). A variety of control experiments rule out the possibility that IOT is the result of activity from the monocularly adapted eye feeding forward on to binocular processes. For example, Blake and Fox (1974) pressure blinded the adapted eye during testing of the unadapted eye. Removing input from the adapted eye did not alter IOT. The IOT is the result of adaptation of a binocular process that can be activated by either the left eye OR the right eye. This process will be referred to as the *binocular OR* process.

Interocular transfer is not complete. For example, after exposure of one eye, the tilt aftereffect in the contralateral eye is 70% to 80% as strong as it is in the adapted eye (Moulden, 1980; Wolfe & Held, 1981). Figures are similar for the threshold elevation effect (Blake et al., 1981). This reduction in the magnitude of the interocularly transferred effect reflects the existence of exclusively monocular processes at this level in the visual system. The reasoning is as follows: When the left eye is stimulated by an adapting pattern, adaptation occurs in two central processes. One of these is the previously described binocular-OR process. The other is a process that is activated by stimulation of the left eye. When the left eye is tested, both processes are again active and both are adapted, which means, in this case, that the assertions that each is making about orientation have been changed. Because both active processes are adapted, the aftereffect is at full strength. When the right eye is tested, the binocular-OR process is active—as is an exclusively monocular process responding ONLY to right eye stimulation. It has not been adapted. Here we have a situation where two processes are making different assertions about the orientation of a specific contour. This does not lead to perception of two contours or to competition between the differing assertions. Rather, the magnitude of the aftereffect appears to be a weighted average of the assertions. Thus, the unadapted “right-ONLY” process will reduce the magnitude of the aftereffect. This interpretation is consistent with a large body of aftereffect data (Blake et al., 1981; Wolfe & Held, 1981; Moulden, 1980) and is illustrated in Figure 1A.

The inferred existence of monocular-ONLY processes can be bolstered by a further aftereffect experiment. If each eye is exposed to a different orientation or direction of motion (Anstis & Duncan, 1983) or spatial frequency (Sloane & Blake, 1982), aftereffects of opposite sign should be measured when each eye is tested. Consider the motion aftereffect version. If the left eye is exposed to motion to the left and the right eye to motion to the right, there will be no net adaptation of the binocular-OR process. It will have received equal stimulation in both directions. The monocular-ONLY processes will have received adaptation in opposite directions. When each eye is tested, the weighted average of an adapted monocular-ONLY process and an unadapted OR process will yield an aftereffect with the sign of adaptation determined by the monocular process. In each of the experiments cited above, aftereffects of opposite sign are found in each eye.

One aspect of these results bears directly on the relationship

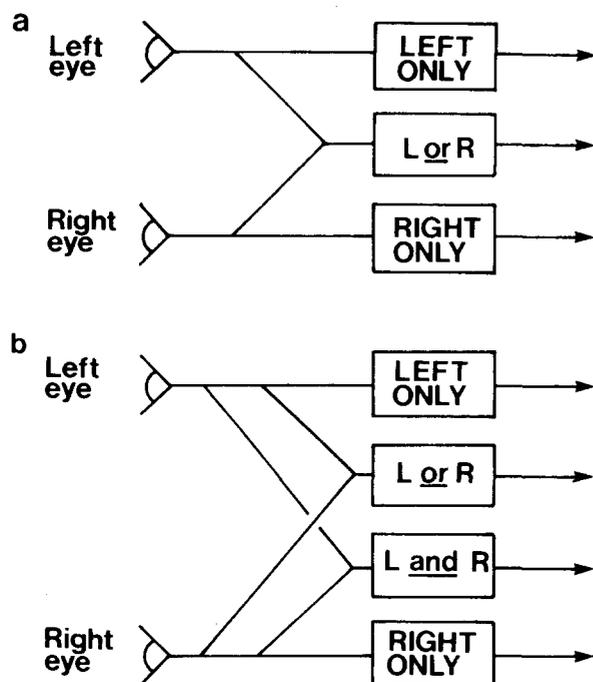


Figure 1. (a) Monocular and binocular processes as revealed by experiments on the interocular transfer of adaptation. (Model is taken from Blake, Overton, & Lema-Stern, 1981.) (b) Model of monocular and binocular processes as revealed by further adaptation experiments. (Information from the two eyes feeds four processes. Two are monocular, with one of these responding only to stimuli presented to the left eye and the other responding only to stimuli presented to the right eye. A third process responds to stimuli presented to either the left OR the right eye. Finally, the fourth process responds only when the stimuli presented to the left AND the right eye match one another [within the disparity limits tolerated by stereopsis].)

of stereopsis and rivalry. Consider the tilt aftereffect case. Following adaptation, one eye may see a vertical line as apparently tilted 1° clockwise, while the other eye may see the same line tilted 1° counterclockwise. These differences, if physically present in the stimulus, would produce a sensation of stereoscopic depth during binocular viewing. The line would appear tilted out of the frontal plane. No depth is seen when the differences in the monocular percepts are produced by adaptation. Sloane and Blake (1982) have reported a similar result with the spatial frequency shift paradigm. We may conclude from this that the outputs of the monocular-ONLY processes are not inputs to the stereopsis mechanism.¹

A fourth process is uncovered at this level in the visual pathway by aftereffect experiments. It is a binocular process that is active only when the left AND right eyes are presented with similar stimuli at the same time. Its effect can be seen in an extension of the basic IOT experiment. Suppose that, following exposure of the left eye, we test with both eyes open. Given only the three processes already described (see Figure 1a), we would conclude the following: The left-ONLY process would be adapted. The OR process would be adapted. The right-ONLY process would be unexposed. During binocular viewing, all three processes would be active, and the aftereffect would be based on a weighted average of the assertions made by all three.

It is easy to see that the magnitude of the aftereffect should fall between that measured with the left and the right eyes.

Instead, a series of tilt aftereffect experiments shows that the aftereffect is smaller in the binocular case than in the IOT case (Wolfe & Held, 1981, 1982). The reduction is explained by invoking a process that is not active or adapted during monocular adaptation but is active and adding its assertions to the determination of orientation during binocular testing. Such a process is "purely binocular." In logical terms, it is an AND gate, responding only if the left AND right eyes are stimulated. Evidence from a number of related experiments supports the existence of an AND process in the human binocular visual system (Wolfe & Held, 1981, 1982, 1983).

Stereopsis and the AND process share a number of features suggesting that stereoscopic information flows through a pathway containing the AND process. (a) Tilt aftereffects produced by adaptation to cyclopean random-dot stimuli are confined to the AND process. No monocular aftereffect can be measured after cyclopean adaptation (Wolfe & Held, 1982). Just as the outputs of the monocular-ONLY processes are not inputs for stereopsis, so the output of a stereopsis mechanism does not provide input to the adaptation of the monocular processes. (b) Neither stereopsis nor the AND process can function with low-contrast stimuli. (c) Both have similar spatial frequency tuning (Frisby & Mayhew, 1978; Wolfe & Held, 1983). (d) Though stereopsis can survive some blur of one image (Julesz, 1971), both stereopsis and the AND process are more disrupted by unilateral than by bilateral blur (Wolfe & Held, 1983). (e) Finally, physiological evidence suggests that stereopsis may be mediated by cells that do not respond to monocular stimulation (Poggio & Fischer, 1977; Poggio & Talbot, 1981).

Figure 1b summarizes the visual pathway to this point. Aftereffect evidence shows that four processes are generated out of inputs from the two eyes. They are left-ONLY, right-ONLY, binocular-OR, and binocular-AND processes. The binocular-AND process probably mediates stereopsis. The monocular-ONLY processes do not contribute to stereopsis, as evidenced by the failure of disparities generated by aftereffects to give rise to stereopsis. In the next section, evidence will be presented showing that the monocular-ONLY processes and the binocular-OR process provide the inputs to the rivalry mechanism.

Pathway for Binocular Rivalry

The four monocular and binocular processes of the preceding section describe the visual system at the level where adaptation

¹ There are exceptions to this general finding. For example, monocular color-contingent tilt aftereffects of opposite signs can be generated. Shattuck and Held (1974) report that these artificial binocular disparities can give rise to a depth sensation. It is not clear why this aftereffect should behave in an atypical fashion, though, as noted above, color is often the exception to simple rules of binocular vision. In this specific case, it is probably significant that most color-contingent aftereffects do not show normal IOT (e.g., Skowbo, Timney, Gentry, & Morant, 1975; White, Petry, Riggs, & Miller, 1978). Mack and Chitayat (1970) also adapted each eye to different stimuli. They created monocular orientation aftereffects by rotating the entire visual field of each eye by 5° with prisms. Aftereffects in the third dimensions were found; however, the binocular adapting conditions would include stereoscopic adapting stimuli. Furthermore, if the subject was not allowed to move freely, no stereoscopic aftereffect was found.

occurs. This section will review the evidence that rivalry occurs at a subsequent stage and that the outputs of the monocular-ONLY and binocular-OR processes provide the input to rivalry.

A number of studies have shown that rivalry does not interfere with the production of aftereffects (Blake & Fox, 1974; Lehmkuhle & Fox, 1975; Wade & Wenderoth, 1978) or with IOT (Blake & Overton, 1979; O'Shea & Crassini, 1981). These studies exploit the fact that, up to a ceiling, all aftereffects increase in magnitude as a function of the length of the adapting period. Rivalry blocks stimuli from perception. Does it block stimuli prior to the locus of adaptation? If an adapting stimulus is shown to one eye and a different pattern is shown to the other, the adapting stimulus will be "seen" only part of the time. Nevertheless, the resulting aftereffect is of the same magnitude as it would have been had the adapting stimulus been continuously perceived (Blake & Overton, 1979). The most plausible interpretation of these results is that the site of rivalry is subsequent to that of adaptation. It is not possible to argue that rivalry and adaptation occur in separate and parallel pathways. Any account of this sort would need to explain why the output of an adaptation pathway could not be seen when that eye was suppressed during rivalry.

The argument for a sequential arrangement of adaptation followed by rivalry is strengthened by the results of Blake and Overton (1979) and Sloane and Blake (1982). If two orthogonal sinusoidal gratings are undergoing rivalry, the grating with higher contrast will be seen for longer than the one with lower contrast. The effective contrast of a grating can be reduced by adapting to that grating (Blakemore, Muncney, & Ridley, 1971, 1973). Does this reduction, produced at the adaptation stage in the system, alter binocular rivalry? Sloane and Blake found that it did. If the left eye views a vertical grating and the right views a horizontal grating, preexposure of the left eye to that vertical grating will reduce its ability to suppress.

Furthermore, the dominance in rivalry of a vertical grating presented to the left eye will be reduced even if it is the right eye that views the vertical adapting pattern. This interocular transfer of the effect of adaptation on rivalry shows that rivalry must receive an input from the binocular-OR process. The fact that it makes a difference which eye is adapted shows that rivalry must receive input from the monocular processes as well.

Binocular adaptation has no more of an effect on rivalry than monocular adaptation. The only difference between direct monocular adaptation and binocular adaptation is the activation of the AND process during the binocular adaptation. However, because the AND process would not be active when orthogonal gratings were presented to the two eyes during the rivalry phase of the experiment, the fate of the output of the AND process is not definitely established by this finding. It could be that the AND process does affect the rivalry process in those cases when the AND process is active. We will turn to this question later.

Leaving aside the AND process for the time being, what can be said about the way in which three processes (left-ONLY, right-ONLY, and OR) provide input to the rivalry mechanism? Rivalry is a perceptual alternation between a left-eye view and a right-eye view. Consider the contents of the processes at the adaptation stage in the visual pathway when the left eye views a horizontal grating and the right eye views a vertical grating. The AND process is not activated by this input and can be ignored.

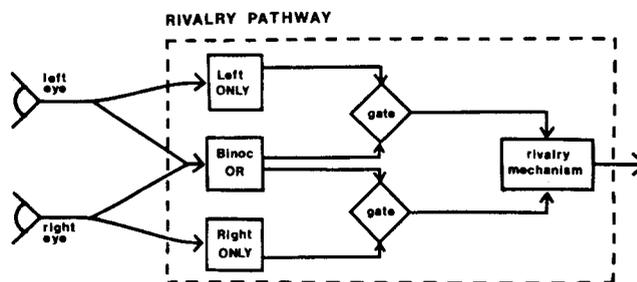


Figure 2. Pathway for binocular rivalry.

The left-ONLY process will be activated by a horizontal grating, and the right-ONLY, by vertical. The OR process will be activated by both gratings. Clearly, the vertical and horizontal components must be kept separate within the OR process because, under these stimulus conditions, no fused perception of a checkerboard or a plaid is ever seen under normal viewing conditions.

The orthogonal gratings can be kept separate because of the existence of orientationally specific channels. Within the OR process, the vertical grating will activate a vertical-specific channel, and the horizontal will activate a horizontal channel. The "plaid" problem recurs because the same pattern of activity would arise in the OR process if both gratings were presented to one eye. Therefore, a mechanism is needed that will produce a plaid percept when the gratings are presented to one eye and rivalry when the gratings are presented dichoptically.

One answer is to gate the output of the OR process by the outputs of the ONLY processes. These gates can be thought of as further AND gates. The input to rivalry from the right eye would come from those stimulus-specific channels that were active in the OR and the right-ONLY processes. In the preceding example, that would be a vertical grating. The left eye's input to rivalry would be a horizontal grating by the same logic. If both gratings had been presented to the left eye, the intersection of the OR and left-ONLY processes would have been both the vertical and horizontal channels, and a plaid would have been seen.² The model is illustrated in Figure 2.

Four points summarize this section: (a) Evidence from after-effect experiments suggests that rivalry occurs after the locus of

² Although the mechanism of binocular rivalry is not a topic for this article (see Walker, 1978, for a review), it is worth noting that by the time visual information reaches the locus of rivalry, the independence of stimulus-specific channels has been lost. At the locus of adaptation, it is possible to selectively adapt one spatial frequency channel and not another. However, in rivalry, all frequency components are glued together. Thus, if each eye is presented with a square-wave grating, the fundamental and, say, seventh harmonic of the grating presented to the left eye will never split apart and engage in separate patterns of rivalry with the stimulus presented to the right eye. The one curious exception may be color. Hastorf and Myro (1959) report that if a red form, A, is presented to the left eye and a green form, B, is presented to the right, form rivalry and color rivalry will be seen but may become decoupled. That is, the subject may report seeing a green A or a red B. I have found this phenomenon elusive in the lab. Nevertheless, to reiterate a point raised in Footnote 1, the monocular and binocular pathways for color seem to be different from those for achromatic patterns.

adaptation. (b) The work of Sloane and Blake (1982) supports this conclusion by showing that adaptation can influence rivalry. (c) Sloane and Blake's results also demonstrate that the outputs of monocular-ONLY and binocular-OR processes are at least part of the input to the rivalry mechanism. (d) To prevent stimuli presented to one eye from "leaking" via the OR process into the perception of the stimuli presented to the other eye, we must assume that the output of the OR process is gated in such a way that its activity progresses further into the system only if matching activity exists in the appropriate monocular-ONLY process.

The two inputs to rivalry are as follows: (a) the intersection of activity in the left-ONLY and binocular-OR processes and (b) the intersection of activity in the right-ONLY and binocular-OR processes. The output of the rivalry mechanism, under normal circumstances, is one of those two inputs.

Why is there an OR process at all? In binocular vision, it seems useless to have a binocular process that feeds into the two monocular inputs to rivalry and that has to be "corrected" by the monocular processes. One answer involves monocular vision. Ignoring the AND process, suppose visual neurons at this level in the system were all monocular, half responding to the left eye and half to the right. If one eye were closed or damaged, one half of the neurons would be without stimulation and useless. Neurons in an OR process, however, will continue to respond as long as either eye is working, allowing more than half of the neurons to be activated during monocular vision. The binocular-OR process may exist to make monocular vision better.

Pathway for Stereopsis

The rivalry pathway makes assertions based on the input from one eye at any point in space and time. However, there are times when the perceived position or color or motion of stimuli seem to result from the combination of the two monocular inputs. These "fused" percepts are products of the pathway for stereopsis. As will be discussed later, this fusion does not preclude the simultaneous occurrence of suppression in the rivalry pathway.

The pathway for stereopsis is organized to produce these fused assertions whenever the monocular inputs are sufficiently similar. Like the rivalry pathway, it is designed to take advantage of as much information as possible. The pathway is shown in Figure 3. As discussed above, stereoscopic information flows through the AND process at the level in the visual system where aftereffects are generated. The output of the AND process is combined with the output of the ONLY and OR processes in a gate of the same kind that combines the output of OR and ONLY in the rivalry pathway. That is, information from OR and ONLY enters the pathway for stereopsis only if it matches the information from the AND process.

What is the evidence? The magnitude of aftereffects during binocular viewing can be shown to be influenced by the state of adaptation in all four of the possibly adapted processes (Wolfe & Blake, 1985; Wolfe & Held, 1981, 1982, 1983). Could the information from ONLY and OR have its impact after binocular rivalry? This could be tested by differentially adapting the two eyes. During binocular testing, an oscillation should occur between left and right eye-adapted states. This should lead to a

bimodal distribution of aftereffect magnitudes during binocular viewing. A post hoc examination of the data from Wolfe and Held (1981) does not reveal any such bimodality. Both monocular processes seem to have simultaneous influence on aftereffect magnitude, suggesting that both have an influence on the stereopsis pathway.

Could that influence occur prior to the locus of stereopsis? As discussed above, dichoptic differences in perceived orientation or spatial frequency produced by adaptation do not yield stereopsis (Sloane & Blake, 1982; again, see Footnote 1). Therefore, it follows that any influence of ONLY or OR processes on the stereopsis pathway must occur after the locus of stereopsis.

The workings of this pathway can be illustrated with several examples. If the input to the left eye is a vertical grating and the input to the right is horizontal, the AND mechanism is not activated, and the entire pathway is silent. No contribution from OR or ONLY processes gets past the "gate" in Figure 3. If a single line is viewed with both eyes, the AND process is activated, and assertions about the position and orientation of that line will be influenced by all four processes. Within the stereopsis pathway, assertions about the position and orientation of the line will be a compromise between the monocular positions and orientations. This intermediate position has been taken as evidence for a separate "fusional" state (e.g., Blake & Camisa, 1978; Sheedy & Fry, 1979; Tyler, 1984), and indeed, the stereopsis pathway generates a fusion of the monocular inputs. The rivalry pathway will contribute to the final seen position, as will be discussed later.

If a cyclopean line is created in a random-dot stereogram, its seen position will be a pure product of the AND process and the stereopsis pathway. No influence of OR and ONLY processes will be seen via either pathway because the OR and ONLY processes cannot "see" the cyclopean contour (Wolfe & Held, 1982).

Performance on a variety of visual tasks is enhanced when both eyes are used. These include detection of stimuli and brightness summation (reviewed in Blake & Fox, 1973; Blake, Sloane, & Fox, 1981) and several perceptual and visual motor tasks (Jones & Lee, 1981). These phenomena probably reflect the contribution of the stereopsis pathway, as all of them require a fairly close match between the monocular inputs. For example, when dichoptic patches are of similar luminance, brightness summation will produce an intermediate perception. If the two patches are very different, rivalry will be seen (e.g., Levelt, 1965).

To summarize, the stereopsis pathway always conveys the information gathered by the AND process. It also conveys information from the OR and monocular-ONLY processes when that information is compatible with the AND information.

Coexistence of Binocular Rivalry and Stereopsis

The message from the psychophysical dissection of the binocular visual pathways is quite clear. At the level in the system where adaptation has its effects, stereoscopic information is handled by a purely binocular AND process that cannot respond to superthreshold monocular stimuli. Rivalrous stimuli are handled by different binocular-OR and monocular-ONLY processes. The outputs of these various processes form two pathways, here labeled *stereopsis* and *rivalry*. The two functions are, then, separable. This does not prove, however, that they can

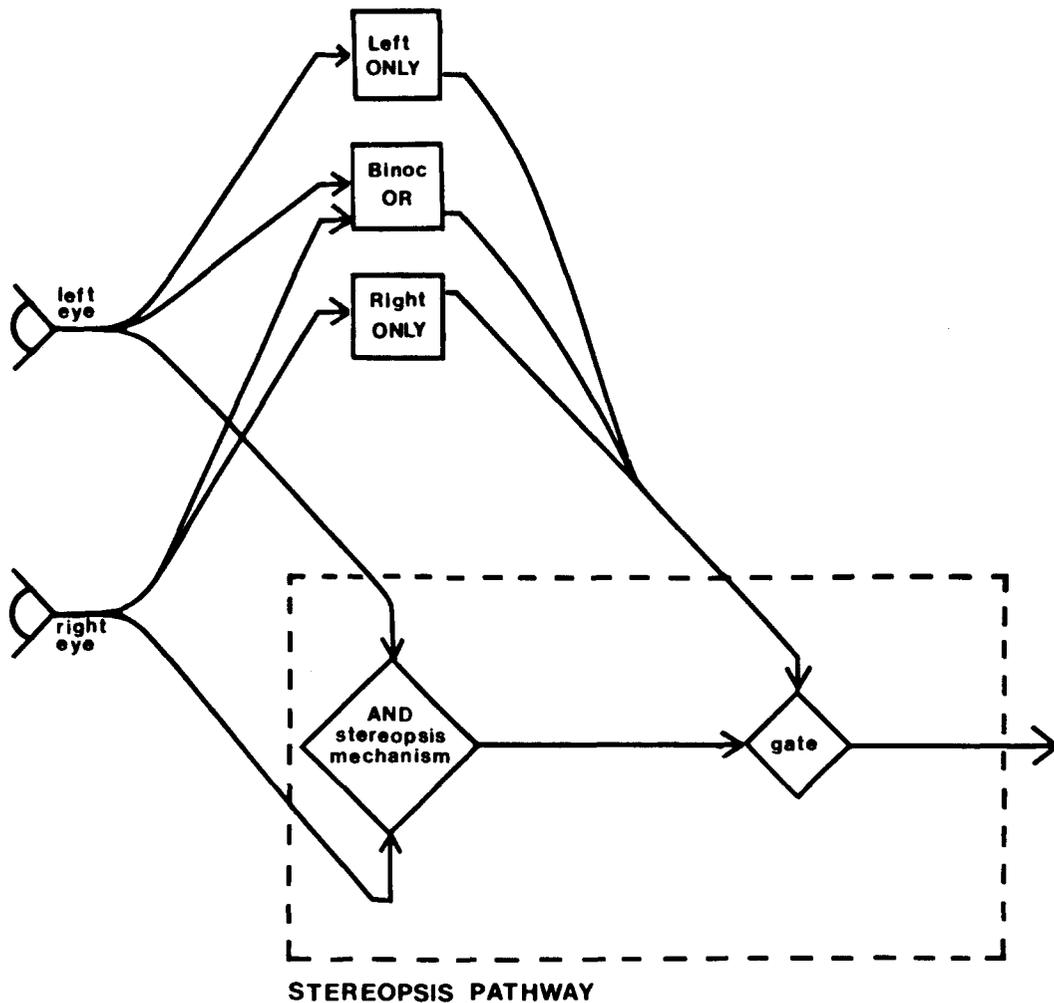


Figure 3. Stereopsis pathway. (Data of Wolfe & Held, 1983, suggest that stereopsis is mediated via the AND process. There is, however, a contribution to the pathway from the monocular-ONLY and binocular-OR processes.)

both be active at the same time and place as asserted at the outset. The following section presents evidence that activity in the stereopsis pathway need not block the perception of rivalry and vice versa.

A substantial body of psychophysical data shows that stereopsis and binocular rivalry are not mutually exclusive in the human visual system. Asher (1953) produced a series of demonstrations showing the cooccurrence of the two phenomena. An example is his account of the appearance of a stereoscopic view of an arch first shown by Wheatstone. Asher noted that one could see through the arch in one monocular view but not in the other. When viewed in the stereoscope, subjects saw the arch in stereoscopic depth. However, one of the two monocular views of the space under the arch dominated in perception. The percept might alternate between the two views, but no intermediate condition was seen. Asher used a series of examples of this sort to bolster his view that binocular vision was essentially monocular, with stereoscopic depth mapped onto the dominant monocular image.

Similar phenomena had been noted with real three-dimen-

sional objects by Washburn and Manning (1934). In looking at a solid cube, they noted that the two eyes had different views of the side slanting back out of the frontal plane. In terms of the two dimensional projections on the retinae, the image of the side was thinner in one image than in the other. They found that the apparent length of the side during free, binocular viewing was derived from either the thin or the thicker monocular image and was not of some intermediate width. Subjects could be trained to monitor the alternations in perception between the two views. These alternations were reminiscent of those seen in rivalry.

These observations illustrate the coexistence of rivalry and stereopsis. However, it is an oversimplification to think that a stereopsis mechanism simply adds depth to one of the monocular images. Under some circumstances, in particular when binocular disparities are small, a contour will be seen in neither monocular location, but in an intermediate locus (e.g., Helmholtz, 1909/1924; Hering, 1920/1964; Sheedy & Fry, 1979; Verhoeff, 1933; though see Kaufman & Arditi, 1976, for a contrary view). Even when it assumes this intermediate state, the final

binocular percept is not a strict or constant average of the two monocular views. Sheedy and Fry (1979) found that different people had different average binocular percepts, whereas Verhoeff (1933) found that the specific binocular location could be manipulated by changing monocular luminance.³ Furthermore, the binocular percept can vary as a subject views the stimulus (Tyler, 1984). The binocular percept is not merely a monocular view with depth. The stereopsis pathway can provide position information as well. The seen position of a contour is a compromise between the outputs of the rivalry and stereopsis pathways. A more extensive discussion of this claim will be presented later.

There are other cases where quite different monocular images can give rise to stereopsis while also producing rivalry. Helmholtz (1909/1924) illustrated this with a pair of line figures, one with black lines on a white ground, the other white on black. The pair could be fused to yield stereoscopic depth while producing the binocular "lustre" that is the usual rivalrous result of putting a dark field in one eye and a light field in the other. This situation has been further analyzed by Levelt (1965) and Levy and Lawson (1978). Some more complicated pairs with matching contours and mismatched contrasts will not yield stereopsis. For example, reversed-contrast random-dot stereograms do not yield an impression of depth (Julesz, 1971). In most simpler cases, differences in contrast yield rivalry, whereas similarities in contour in the same figure support stereopsis.

What is true for dichoptic differences in contrast is true for dichoptic differences in color. Coexistence of color rivalry and stereopsis has been reported a number of times. Treisman (1962) using classical stereograms and Ramachandran and Siram (1972) using random-dot stereograms have noted that color rivalry may be seen during viewing of anaglyphic stereograms. So, for example, if one looks at a random-dot stereogram (e.g., Julesz, 1971), the cyclopean contour will be seen, superimposed on a mosaic of red and green regions produced by color rivalry. At any specific location, one may perceive an exclusively monocular color and a cyclopean figure that arises from the interaction of the two monocular inputs.⁴

Julesz and Miller (1975) have shown that rivalry and stereopsis can coexist in space if the inducing stimuli are separated in spatial frequency. They took random-dot stereograms and bandpass filtered them to create stereograms containing only a narrow range of spatial frequencies. If they then added noise to the input to one eye, they could get simultaneous rivalry and stereopsis if the noise was in a different spatial frequency band. If the noise contained the same frequencies as the stereogram, stereopsis was disrupted. Even if the stereopsis and rivalry mechanisms are independent, stereopsis will be disrupted when masking noise is added to the filtered stereograms in the same spatial frequency band. The noise will interfere with the matching process that is basic to stereopsis, regardless of what a rivalry mechanism is doing. If the stereopsis mechanism cannot find matches between the left- and right-eye inputs, there will be no stereopsis.

Mitchell (1969) reports a striking experiment that may be explained in terms of the Julesz and Miller results. A vertical line presented to one eye and a horizontal line presented to the other will, of course, produce binocular rivalry. If there is an offset between the positions of their centers, qualitative stereopsis is also possible. A crude stereoscopic match in the low spatial

frequency range probably accounts for this example of coexistence.

Parametric measures of stereoscopic accuracy in the presence of rivalry have been provided by Ogle and Wakefield (1967). In their task, the subject set a line to the perceived midpoint of a region defined by two other lines. The lines could be displaced into the third dimension by the introduction of disparity. The task was performed under a variety of conditions, including several varieties of form rivalry, color rivalry, and fusion. Stereoscopic accuracy was unaffected by any type of rivalry.

Demonstration: "Trinocular Vision"

Most of these illustrations of coexistence are subject to reinterpretation. For example, consider Washburn and Manning's (1934) observation that the side of a real cube appears in one of its monocular views in spite of the stereoscopic appreciation of its shape. It could be that the front face of the cube is seen via the stereoscopic pathway. The side of the cube generates disparities too large for stereopsis and so, unseen by the stereopsis pathway, it reaches perceptual awareness via the rivalry pathway. In Mitchell's (1969) experiment, rivalry and stereopsis probably occur in different spatial frequency ranges (as proposed by Julesz & Miller, 1975).

To bolster the case that rivalry and stereopsis coexist, consider the following situation, here labeled *trinocular vision*. The left eye is presented with a vertical grating, and the right eye, with a horizontal one. This, of course, produces rivalry. Now a random-dot stereogram is added binocularly. Viewed in isolation, the stereogram gives rise to an oblique, cyclopean grating. All gratings are square waves of 3 cpd. When all three are superimposed, the cyclopean grating should suppress the monocular gratings if the output of the rivalry mechanism can be blocked by the output of the stereopsis mechanism. At the very least, a form of "trinocular rivalry" should ensue in which complete intersections between cyclopean and monocular contours are not seen, just as complete intersections between the orthogonal, monocular contours are not seen in binocular rivalry. However, observers all agree that trinocular rivalry does not occur. The monocular contours engage in binocular rivalry. The cyclopean contours do not interact in any way. They are simply superimposed on the ongoing rivalry. The sign of disparity does not matter.

A couple of notes about this demonstration are in order. Robert O'Shea (personal communication, August 1985) has independently invented a similar display with similar results. The

³ Sheedy and Fry object that Verhoeff's finding may be contaminated by cyclotorsional eye movements, though Kertesz and Jones (1970) report no measurable eye torsion under similar stimulus conditions.

⁴ Evidence from color rivalry depends, of course, on the existence of color rivalry. Some people do not see color rivalry in these situations. Instead, they experience color fusion (e.g., Hering, 1920/1964). For them, the demonstration will not work. Furthermore, there is evidence that color rivalry and form rivalry may be separable. Hastorf and Myro (1959) found that a red object presented to one eye will rival with a different green object presented to the other. The forms and the colors, however, may become dissociated so that the color in the left eye and the object in the right may be seen at the same time.

demonstration as described here is obviously similar to the observation that stereopsis occurs in anaglyphic stereograms in spite of continuing color rivalry. The present example is more useful than the color rivalry case because, as previously noted, color behaves in a consistently odd manner in binocular experiments and some individuals do not see color rivalry. The point in either example is the same. Even though the rivalry pathway is delivering to perception only the stimulus presented to one eye, the stereopsis pathway is delivering a cyclopean contour at the same place and time. The creation of that contour requires integration of input from both eyes.

The bars of the cyclopean grating are defined by depth, but it cannot be objected that rivalry and stereopsis are occurring in two different depth planes. Half of the cyclopean grating lies in the zero disparity plane of the monocular gratings. The cyclopean edge of a bar is a step from the zero disparity plane to some disparity. If cyclopean contours could rival with or suppress monocular contours, the contours in this demonstration are in the right place to do so.

One final point: In producing this demonstration, it is important to use relatively low-contrast monocular gratings. High-contrast gratings mask the monocular stimuli that give rise to the cyclopean contour. If the cyclopean contour cannot be seen, its interactions or lack thereof cannot be examined.

In sum, there is substantial evidence that rivalry and stereopsis can coexist. However, although coexistence is a necessary part of the evidence for the hypothesis outline at the outset, it is not sufficient. Beyond claiming that stereopsis and rivalry can occur at the same place and time, the hypothesis maintains that stereopsis cannot occur alone, that rivalry is occurring whenever visual stimuli are present. The next section presents evidence for the inevitability of rivalry.

Inevitability of Binocular Rivalry

The propositions listed at the outset of this article require that rivalry always occur during apparent fusion and stereopsis. The somewhat ambiguous evidence on this point is drawn largely from detection experiments. During the rivalry seen when two eyes view different stimuli, detection thresholds are elevated by 0.3 to 0.5 log units for stimuli presented to the suppressed eye (e.g., Wales & Fox, 1970). To determine if rivalry occurs during fusion, researchers have looked for evidence of this threshold elevation during fusion. This is not simple, because even if rivalry is occurring, the observer cannot tell which eye is dominant in any spot at any given time because both eyes are looking at the same thing. Fox and Check (1966a, 1966b), Blake and Camisa (1978), and Blake and Boothroyd (1985) have found that monocular detection thresholds during fusion are the same in each eye and are as good as the thresholds measured in the dominant eye during rivalry. Makous and Sanders (1978) find that average performance is not as good during fusion as it is in a dominant eye. Makous and Sanders (1978) monitored what they believe to be rivalry during stereopsis. They found that the appearance of bars in depth alternated over time between left-eye and right-eye views (see Washburn & Manning, 1934; discussed above). When the left-eye view was reported, thresholds in the left eye resembled those in a dominant eye during rivalry, and thresholds in the right eye were sup-

pressed. When the right-eye view was reported, this pattern of results reversed.

The differences between the findings with identical stimuli may be due to variations between subjects (Sanders, 1980), methodological differences, or to the difficulty of obtaining clear answers to this particular question with this particular method. Furthermore, the failure to find evidence for suppression in detection experiments can be explained in terms of the model presented here. For example, Blake and Boothroyd (1985) report that, during rivalry between orthogonal gratings, reaction times for monocular contrast decrements are slow for suppressed stimulus and fast for the dominant stimulus. When both eyes view the same vertical grating, all reaction times are fast. They conclude that there is no suppression when the stimuli are identical. However, when the stimuli are identical, the stereopsis pathway will be stimulated. The decrement in one eye will perturb or eliminate the stimulus to that pathway and may be detected regardless of the status of dominance and suppression in the rivalry pathway.

In the following experiment, a different approach is used. The results support the conclusion that rivalry does occur during the viewing of identical stimuli.

Experiment: Abnormal Fusion Following Real Fusion

There are circumstances under which binocular rivalry does not occur. One of these can be used to detect rivalry during the binocular viewing of identical stimuli. Rivalry can be disrupted by presenting stimuli intermittently. A number of investigators have reported that normally rivalrous stimuli will appear abnormally fused if briefly presented (e.g., Hering, 1920/1964; for a brief review see Wolfe, 1983a). Wolfe (1983a) has shown that the "abnormal fusion" phenomenon depends strongly on the timing of the presentations, whereas there is very little effect of other stimulus parameters like spatial frequency or luminance. If the dichoptic stimuli are simultaneously flashed for less than about 150 ms, and if the interval between successive flashes is greater than 150 ms, the stimuli will appear to fuse. Apparently, it takes more than 150 ms to activate the rivalry mechanism and more than 150 ms for the mechanism to become inactive if it is active.

For the present purpose the important feature is that abnormal fusion does not occur if the rivalry pathway is already active. Suppose, for example, that rivalrous stimuli are viewed for several seconds. If these stimuli are removed and another pair is flashed for less than 150 ms, abnormal fusion of the second pair is not seen. They are seen as abnormally fused only if a blank interval of longer than 150 ms follows the initial, rivalrous pair. Abnormal fusion, therefore, is an indicator of the activity of the rivalry mechanism. If the rivalry mechanism is inactive, then briefly presented stimuli show abnormal fusion. If rivalry is active, then abnormal fusion is not seen, with test stimuli presented within 150 ms following the offset of the rivalrous stimuli. We looked for abnormal fusion following presentation of perceptually rivalrous and perceptually fused stimuli. If rivalry does not occur when identical stimuli are viewed with both eyes, then abnormal fusion should occur immediately after the offset of those stimuli. If the identical stimuli activate the rivalry mechanism, then the results for those stimuli should be the same as the results for perceptually rivalrous stimuli.

Method

Procedure. The methods were similar to those used in previous studies of abnormal fusion (Wolfe, 1983a). Subjects were shown dichoptic, orthogonal gratings in a 10-ms flash and were asked to rate their appearance on a scale from 0 (*rivalrous*) to 5 (*fused*). Details of the rating scale method are given in Wolfe (1983a). In this experiment, the 10-ms test flash was preceded by 2 s of "preexposure" to one of four binocular stimuli listed below: (a) rivalrous orthogonal gratings of 8.5 cpd, mean luminance 200 cd/m-sq; (b) fused vertical gratings of 8.5 cpd, mean luminance 200 cd/m-sq; (c) fused blank fields of 40 cd/m-sq; (d) fused stereogram (classical, not random dot). The complete sequence for one trial was as follows: 2-s preexposure followed by a variable dark inter-stimulus interval (ISI), followed by the 10-ms test flash. The test stimuli were orthogonal, 3.8 cpd gratings, mean luminance 200 cd/m-sq. All stimulus fields were 2.6° in diameter. All gratings were square-waves of contrast greater than 95%. Nine interstimulus intervals between 0 ms and 1,000 ms were used. Subjects saw and rated each combination of preexposure and ISI five times. All trials for a single preexposure stimulus were run in a block. The ISI was random within a block. Stimuli were presented in a Scientific Prototype binocular tachistoscope.

Subjects. There were five subjects in each preexposure condition. Three subjects were tested in all four conditions. Four other subjects were tested to reach the desired five subjects per condition. All subjects had or were corrected to 20/20 acuity or better in each eye. All had good stereopsis as assessed by the Randot test. In each condition, three subjects were naive. The remaining two were the author and a research aide.

Results

In the absence of a preexposure stimulus, the average rating for a 10-ms flash is 4.6 (Wolfe, 1983a). That is, the orthogonal gratings appear to be convincingly fused. As shown in Figure 4, this is not the case following preexposure to either fused or rivalrous stimuli.

The five trials at each ISI were averaged for each subject. Because the pattern of results was similar across subjects, data were averaged across subjects. Standard deviations for across-subject averages are never greater than 1.2. Most are less than or equal to 1.0. (Although standard deviations must be used with some caution with rating scale data, they do give a feeling for the degree of variability across subjects.)

All preexposure patterns produce a similar pattern of results. For short ISIs, there is no evidence of abnormal fusion. Abnormal fusion does not reach the levels seen without preexposure until 200 ms to 500 ms after the preexposure stimulus has been extinguished. (A similar time course for the decay of the effects of monocular preexposure is found in Wolfe, 1984.)

Discussion

The rivalry mechanism is inactive in the absence of stimulation. Presented against the background of this inactivity, briefly flashed stimuli will abnormally fuse. The results of the present experiment indicate that the rivalry mechanism is activated by fused stimuli just as it is activated by rivalrous stimuli. It makes no difference if dichoptic gratings are presented to subjects in orthogonal, rivalrous orientations or in the same, fused orientations. It does not matter if the stereopsis mechanism is activated. Wolfe (1984) showed that it does not matter if only one eye is activated. In all of the conditions, the rivalry pathway is activated. Even a circular patch of light activates the rivalry

mechanism. In this last case, we cannot say that light alone is sufficient to activate the rivalry mechanism. The circular patch field was 2.6° in diameter. The edge of the field may have activated the rivalry mechanism. Of the conditions tested, only darkness fails to produce rivalry.

Though further experiments are needed to pin down the minimal conditions for the activation of rivalry, these results bolster the argument that rivalry continues even when it is not perceptually evident. This does not deny the existence of fusion if we define fusion as a product of the stereopsis pathway. It does deny the existence of a special fused state defined by the absence of binocular rivalry. These results argue against the hypothesis that the rivalry mechanism is suppressed when the stereopsis pathway is active. Binocular rivalry is the inevitable result of any visual stimulation of more than 150 ms duration. It is a default state for visual processing.

Double Dissociation of Stereopsis and Rivalry

As a final line of evidence in favor of the hypothesis that rivalry and stereopsis lie in independent pathways in human vision, we turn to a version of a classic neuropsychological paradigm for determining if two functions are structurally independent: "double dissociation" (Pribram, 1954, though credit is shared with H. L. Teuber). If Manipulation A disrupts Function X but not Function Y, and Manipulation B disrupts Y but not X, the functions are said to be doubly dissociated and, thus, independent. Although double dissociation shows independence, it is not the case that a failure to find such a dissociation proves nonindependence. For example, it would obviously be possible to disrupt both stereopsis and rivalry by severely reducing or eliminating input from one eye. Such a demonstration, even if more subtly arranged, would not lead to any conclusions about common central mechanisms of rivalry and stereopsis beyond the trivial statement that both mechanisms require two functional eyes.

In neuropsychological studies, the manipulation is usually a brain lesion, an unacceptable methodology in the present case. However, it is possible to independently disrupt stereopsis and rivalry by noninvasive means. Abnormal fusion, discussed above, is a disruption of binocular rivalry. If stereopsis is examined under similar temporal conditions, it is not disrupted.

Experiment: Stereopsis Under Conditions of Abnormal Fusion

Method

Procedure. On each trial, subjects viewed one of two stereograms. Each consisted of two black squares subtending 0.65° at the 44-cm viewing distance. The squares were arranged vertically, with 1.20° separating their centers. A set of surrounding lines in the frontal plane provided an aid to fixation and convergence. One square in each stimulus had a crossed disparity of 700 min. The other square had an uncrossed disparity of the same amount. In one of the two stimuli, the upper square had crossed disparity. In the other, the lower square had crossed disparity. The subjects' task was to state if the upper or the lower square was "standing in front" of the image plane. Under continuous illumination, this is an error-free task for subjects with normal stereopsis.

The stimuli were flickered at 3 Hz for 2 s per trial. The on period was 10 ms. The off period was 300 ms. With stimuli that are rivalrous under continuous illumination, these temporal conditions produce convinc-

ing abnormal fusion (Wolfe, 1983a). Fifty forced-choice trials were run for each subject. Stimuli were presented in random order.

Subjects. Five subjects were tested. All had stereopsis of at least 50 s as assessed by Randot and Army Orthorator tests. Three were completely naive. The author served as a subject, as did a research aide.

Results

Subjectively, the task is trivially easy. The sensation of stereoscopic depth is clear and unimpaired. No subject made more than two errors in 50 trials. Three subjects performed perfectly. The squares tended to look like horizontal rectangles because of the abnormal fusion of the two offset squares.

Discussion

Clearly, a temporal manipulation that disrupts the normal function of the rivalry mechanism does not disrupt the stereopsis mechanism. Wolfe (1984) has shown that abnormal fusion of rivalrous stimuli is not dependent on the spatial pattern used, making it unlikely that this particular stimulus is unaffected by the flicker. Furthermore, the result cannot be explained by arguing that a difficult rivalry task is being compared with a simple stereopsis task. Both tasks are simple. Under these temporal conditions, orthogonal gratings appear to be clearly fused.

If the ISI is shortened to less than 150 ms, the same gratings appear to be clearly rivalrous.

A variant on this experiment can be carried out with a three-line stereogram. Three thin lines are presented to each eye. The center line has a horizontal disparity. The disparity is such that under normal viewing conditions, a subject reports seeing three lines, one in depth. If the stimuli are flickered, depth can still be seen. It is more difficult than in the conditions described above probably because of the reduced visibility of the thin lines during a brief exposure. Interestingly, a careful observer can see all four lines and stereoscopic depth during the flicker. This apparent reduction in the size of Panum's area is somewhat at variance with Mitchell (1966). He did not see four lines under similar, though not identical, conditions. He did find that Panum's area could be shrunk under some circumstances. It may be that stimulus conditions in the present experiment make the gap between the two central lines easier to see.

In this experiment, the experience is similar to Ogle's (1952) condition of stereopsis without single vision. Ogle had subjects view three-line stereograms of different disparities. When the disparity was small, three lines were seen with the center line in depth. As the disparity increased, the singleness of vision broke down. Four lines were seen. Nevertheless, depth was still experienced on the center lines. When the disparity was still larger,

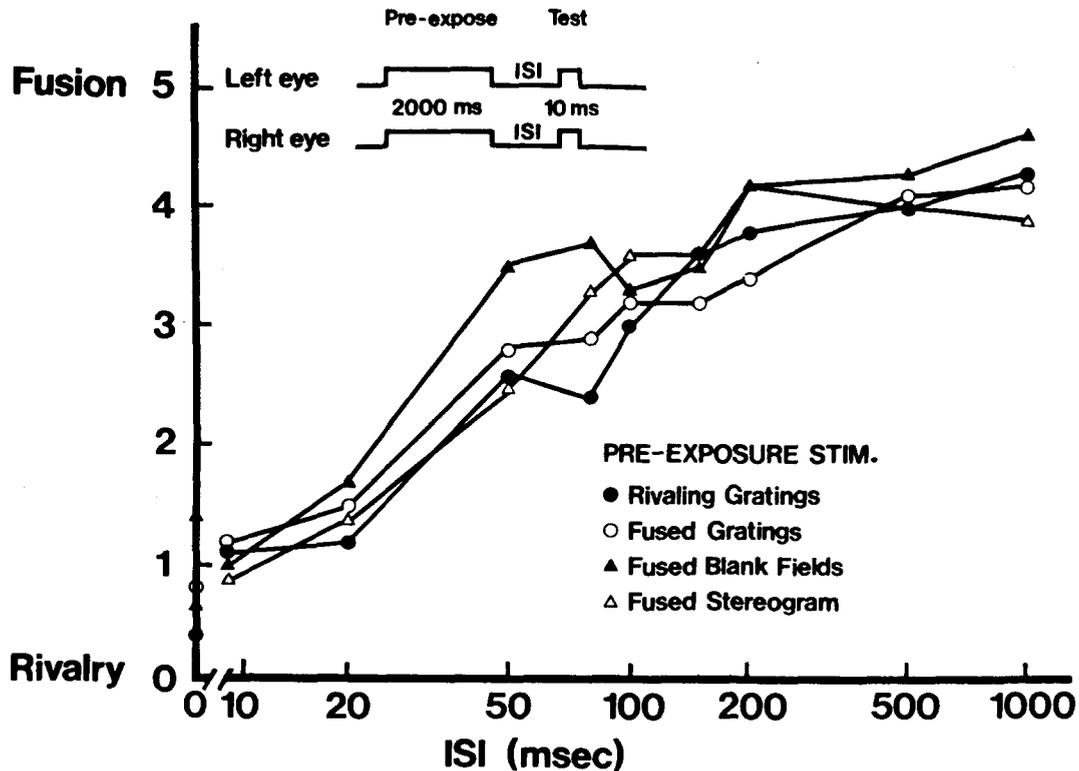


Figure 4. Appearance of flashed, orthogonal, dichoptic gratings as a function of time after the offset of a 2-s binocular stimulus. (Briefly flashed dichoptic stimuli will abnormally fuse even if they ordinarily produce rivalry. This is only true if the rivalry pathway is inactive prior to the flash as it is in the dark. Following 2 s of binocular rivalry, it takes about 200 ms of darkness for activity in the rivalry pathway to decline and for abnormal fusion to return. The same result is found when the initial stimuli are fused or even stereoscopic. Fused stimuli activate the rivalry pathway.)

stereopsis failed and simple diplopia reigned. Stereopsis with diplopia has been a puzzle. It is readily explained in the present model. Rivalry and stereopsis have different spatial properties. When two lines are close together, one may suppress the other (e.g., Kaufman, 1963) while, at the same time, the disparity produces stereopsis. When the lines are further apart, they exceed the reach of the spread of suppression in the rivalry mechanism, and so two lines are seen. However, the separation does not exceed the maximum tolerable disparity for the stereopsis mechanism, so depth is seen. Finally, at greater separations, the limits of both pathways are exceeded and pure diplopia results.

Returning to the abnormal fusion situation, the flicker breaks down the mechanism of dominance and suppression that normally causes one of the two central lines to be suppressed for small disparities. Both lines are seen. The temporal conditions do not disrupt stereopsis, so depth is seen. Here it is stereopsis and abnormal fusion that coexist.

Nature provides the case where stereopsis is disrupted while binocular rivalry remains. A significant group in the population is "stereoblind." They lack the ability to use disparity as a cue to depth. There are a variety of conditions that can cause this. The most common is strabismus, a misalignment of the eyes. If the eyes are not aligned during a critical period after birth, stereopsis may fail to develop. Most stereoblind individuals have one strongly dominant eye with some degree of amblyopia in the other eye. When roughly equivalent stimuli are presented to each eye, they will perceive the stimulus in the dominant eye. In many cases, the weaker eye of a stereoblind subject can be made perceptually dominant if a high-contrast pattern is presented to that eye and lower contrast pattern is presented to the other eye. If the stimuli are properly balanced, an alternation of dominance will be experienced. Although it has been suggested that this rivalry may be abnormal (e.g., Smith, Levi, Manny, Harwerth, & White; 1985), a regional pattern of dominance and suppression does occur in most such individuals (Jampolsky, 1955; Burian & von Noorden, 1974; Schor, 1977).

The abnormal fusion paradigm provides some evidence that the dominance and suppression seen in stereoblind subjects is mediated by the mechanism that produces binocular rivalry in normal subjects. Faced with dichoptic, orthogonal gratings, stereoblind subjects will generally report seeing only the grating in the dominant eye. If the gratings are flashed, these subjects often report seeing the abnormal fused plaid or checkerboard pattern seen by normal subjects under similar temporal conditions (Wolfe, 1983b). The temporal requirements for abnormal fusion appear to be the same in normal and many stereoblind subjects. Thus, the same conditions that disrupt rivalry in normal subjects disrupt dominance and suppression in stereoblind subjects. As in normal subjects, the status of the stereopsis pathway is unaltered. In normal subjects, the temporal conditions for abnormal fusion do not disrupt stereopsis. In stereoblind subjects, disrupting their standard patterns of dominance and suppression and producing abnormal fusion does not produce stereopsis.

The disruption of stereopsis seen in stereoblind subjects can be mimicked in normal individuals by optically blurring the input to one eye (Harwerth and Smith, 1985; Wolfe & Owens, 1979; D. Heath, personal communication, June 1985). This artificial anisometropia does not appear to disrupt the rivalry mechanism. The unblurred eye becomes dominant. However,

alternation between stimuli in each eye continues. Thus, in normal and stereoblind individuals, rivalry can exist even if stereopsis is disrupted.

The requirements of the double dissociation paradigm have been satisfied. Rivalry can be disrupted without disrupting stereopsis and vice versa. This is further support for the theory that the rivalry and stereopsis pathways are separate and parallel.

General Discussion: Binocular Single Vision

The pathways for rivalry and stereopsis are separable. Nevertheless, rivalry and stereopsis can coexist and indeed must coexist because it appears that rivalry occurs inevitably whenever visual stimuli are present for more than 150 ms. Rivalry and stereopsis are independent processes. They interact only after both processes have gone to completion, and then they interact in a cooperative, not a mutually inhibitory, fashion. For purposes of this article, the final product of the stereopsis and rivalry pathways is binocular single vision. The data presented and discussed here are consistent with the theory that binocular single vision is a fairly simple merging or averaging of the outputs of the two parallel pathways. Just as assertions made about the same contour by, say, the left-ONLY and binocular-OR processes are averaged to produce an input to the rivalry mechanism, so assertions about the same contour made by the stereopsis and rivalry pathways are averaged when both are available.⁵ The full model is shown in Figure 5. In most cases, the combination of the two pathways will be impossible to notice. For all real-world contours in the frontal plane or, more accurately, on the horopter, the assertions made by the rivalry pathway will be identical to those made by the stereopsis pathway. As many suppression theorists (e.g., Verhoeff, 1935, 1959) note, if rivalry replaces a perceived stimulus from the left eye with an identical one from the right, there is no change to be observed. If we now add to that another identical stimulus from the stereopsis pathway, there is still no noticeable change.

Off the horopter, the system is elegantly designed so that the two pathways seek different sources of information. For all stimuli lying outside of Panum's area (and outside the region of stereopsis with double vision), the stereopsis pathway makes no assertions. It is silent and, in those areas of the visual field, the assertions made by the rivalry mechanism alone give rise to perception. Diplopia is seen in those cases where the two disparate monocular images of a single physical object or contour are both dominant at the same time. This is most easily seen when a single object, for example, a finger, is present outside of Panum's area in an otherwise blank field. If the monocular images of the finger are more than about a degree apart, they cannot suppress each other (Kaufman, 1963). Being much more salient than the blank field in the corresponding location in the other eye, each monocular "finger" will be dominant in rivalry, and diplopia will be the perceived result.

Within Panum's area, we have a situation where slightly different assertions are made about the same contours by the two pathways. The stereopsis pathway will assert that a contour

⁵ Julesz and Tyler (1976) proposed that rivalry and stereopsis are separate mechanisms and that their outputs are averaged. However, in the same paper, they propose that the two are mutually inhibitory, a position at variance from the theory presented here.

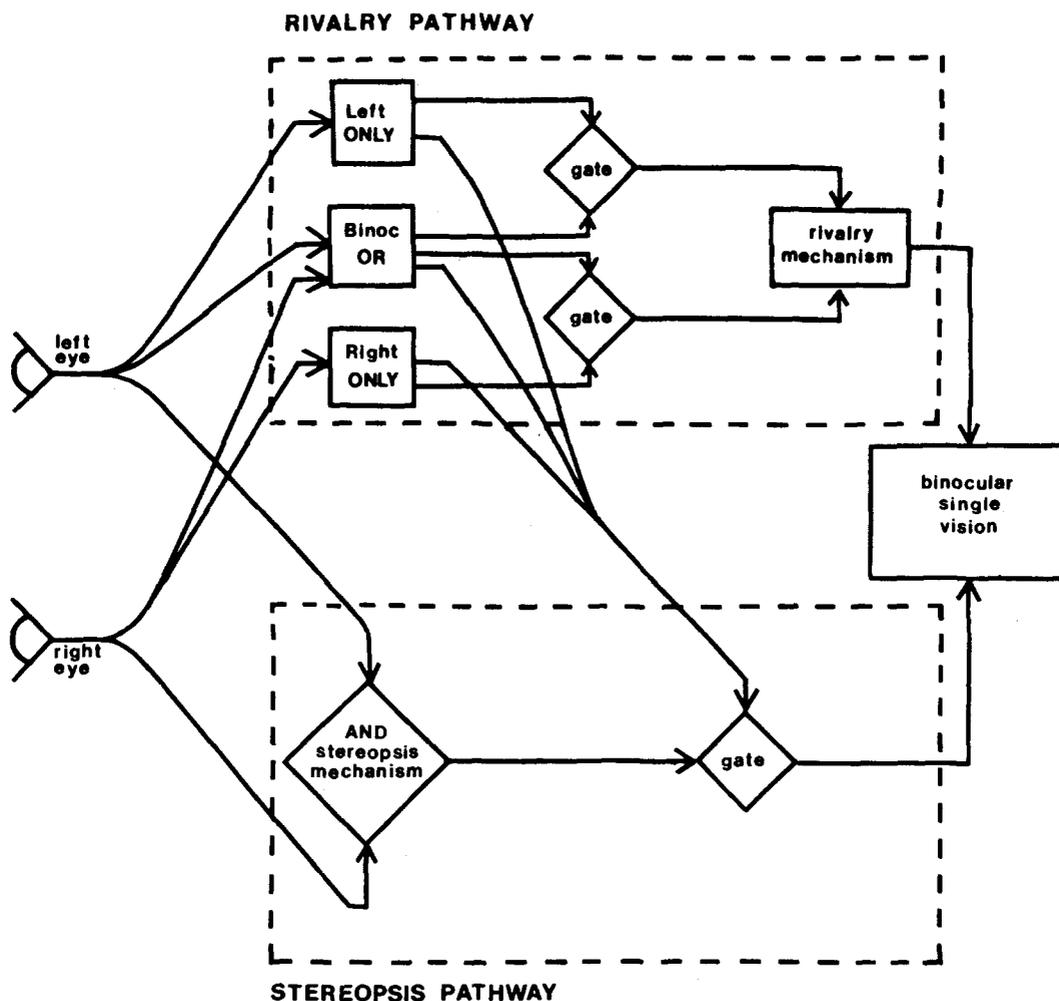


Figure 5. Pathways producing human binocular single vision. (Stereopsis and rivalry pathways are essentially parallel. Their outputs are simply combined to produce what is perceived as binocular single vision.)

is to be seen at an average position between that in either retinal image. The rivalry pathway will deliver an assertion corresponding to a choice between one or the other of those images. The seen position of that contour is a compromise between the pathways (e.g., Sheedy & Fry, 1979). Seen position does not usually appear as a simple average of the two monocular images. It seems to be biased toward one of the views (Sheedy & Fry, 1979), and if observed for some length of time, that bias may shift (Makous & Sanders, 1978; Tyler, 1984). Makous and Sanders used these alternations as a measure of the alternations of a continuously active rivalry mechanism. This could be tested by examining fluctuations in seen position under conditions that have known effects on alternations in rivalry (e.g., contrast in Blake, 1977, or brightness in Kaplan & Metlay, 1964). If the deviations from a simple average position are caused by the output of the rivalry pathway, then the manipulations of that pathway should have predictable effects on seen position of stereoscopic contours. Verhoeff (1933) found that changing brightness did alter the perceived binocular position, but the experiment should be repeated in light of newer data.

Under real-world conditions, these fluctuations of seen posi-

tion will be largely unnoticed. They can be seen in the lab manifested as lines that are not perfectly straight or intervals that are not evenly bisected. The real world usually lacks any metric against which to measure these small and fleeting disagreements between the pathways.

Having divided the search for visual information between these two parallel pathways, the visual system does not insist on agreement between them. If the stereopsis pathway has ferreted out oblique contours while the rivalry pathway is attempting to resolve the simultaneous occurrence of vertical and horizontal, the visual system will perceive both of these conclusions as in the trinocular vision demonstration. In this way, the system as a whole does not waste information uncovered by one of its parts.

This model has interesting implications for the study of brightness summation. There has long been considerable interest in the experimental situation wherein a patch of one luminance is presented to one eye while another luminance is presented to the other (see reviews by Blake & Fox, 1973; Blake et al., 1981; and Levelt, 1965). The resulting apparent brightness is almost never a simple average of both retinal inputs. Accord-

ing to this model, this should not be surprising. Assertions about two contourless patches of light will be combined several times in the pathways shown in Figure 5. Some averaging will occur in the binocular-OR process. Some may occur in the AND process. Further averaging will occur in creation of the inputs to rivalry and in the contribution of OR and monocular-ONLY assertions to the output of the AND process. Finally, the assertion about brightness made by the entire stereopsis pathway will be averaged with the assertion that emerges from binocular rivalry. One can see why brightness averaging equations involving only two monocular terms do not explain all of the binocular summation data (a similar point has been made by Anderson & Movshon, 1981).

Conclusion

No single mechanism can extract from the visual world more than a fraction of the information needed to see. A mechanism that can detect vertical contours cannot detect all of the other orientations. A mechanism that can find information about features of one size is insensitive to features of different sizes. The visual system has dealt with this fact by creating sets of parallel pathways. Each pathway examines the visual input and informs later processing stages of its findings. In binocular vision, the visual system is faced with two types of stimulation. In one case, the inputs to the two eyes are similar and may contain the information for stereoscopic depth perception. In the other, the two eyes receive different input. As in other situations, the human visual system has evolved with two parallel pathways that between them extract the needed information from the input. Binocular single vision arises from the outputs of these two pathways.

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