

## Research Report

### VARIETIES OF BINOCULAR INTERACTION IN HUMAN VISION

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**Abstract**—Binocular processing was investigated using a quantitative, process-oriented metatheory of response times. The analyses are not confined to particular distributional assumptions or specific models. Upper and lower performance boundaries for probability summation in parallel processing are defined and compared with observed distributions of reaction times using a variety of dichoptic stimuli. Performance that exceeds the upper bound strongly suggests facilitatory convergence between the two eyes (binocular channel summation). Performance below the lower bound suggests that inputs to the two eyes are processed serially. The results indicate that binocular channel summation in subjects with normal stereo vision requires targets of the same luminance polarity (paired increments or decrements) in corresponding retinal locations. When corresponding retinal locations are stimulated with opposing luminance polarities (increment to one eye, decrement to the other), performance is consistent with probability summation, indicating that parallel ON and OFF pathways remain segregated at least to the level of binocular fusion. Further analyses of data from a stereo-blind observer suggest serial processing of binocular inputs.

A primary goal of cognitive and perceptual theorizing is to model processing architectures that underlie human performance. The resulting models often consist of elementary operations, filters, and processing stages that can be arranged in series or parallel. Recent theoretical work has provided a variety of analytical diagnostics capable of distinguishing between serial processing, parallel processing, and a variety of hybrid architectures (e.g., Townsend & Ashby, 1983; Townsend & Nozawa, 1995). This work has been most intensively developed within the realm of the time course of processing, with reaction times (RTs) as the dependent variable.

A central assumption is that execution of a task invokes component processes whose durations can be represented by random variables. This assumption finds ample justification in the observed variance of RTs and the patterns of activity within sensory pathways. Theoretical accounts of response accuracy also rely on stochastic processes (e.g., signal detection theory), but there is little by way of empirical or theoretical treatments that bridge the transition from low- to high-accuracy situations (see, however, Link & Heath, 1975; Thomas 1971).

The present report applies state-of-the-art stochastic RT modeling techniques to binocular interactions in human vision, with specific reference to interactions between ON and OFF pathways. These complementary pathways first appear at the level of the bipolar cells, and their role in visual processing has been the subject of physiological studies made possible by the discovery of a pharmacological agent that selectively inactivates the ON pathway (Slaughter & Miller, 1981). Cells with apparently normal receptive field characteristics have been found in central visual structures following inactivation of retinal ON cells, indicating that at least some visual neurons rely entirely on OFF sig-

nals for their afferent supply (Horton & Sherk, 1984; Schiller, 1982; Schiller, Sandell, & Maunsell, 1986; Sherk & Horton, 1984).

We wished to determine whether evidence of independent ON and OFF signals could be obtained up to the level of binocular fusion in humans by analyzing interactions between ON signals in one eye and OFF signals in the other eye. The receptive fields of ON center cells have an excitatory central region and an inhibitory surround. OFF center cells possess inhibitory receptive field centers and excitatory surrounds (e.g., Kuffler, 1952; Werblin & Dowling, 1969). As a result, ON center cells respond best to an appropriately positioned luminance increment, and OFF center cells respond best to an appropriately positioned luminance decrement. Performance associated with presentations of an increment to one eye paired with a decrement to the other eye should provide a paradigm for studying patterns of convergence between ON and OFF signals in binocular vision.

Westendorf and Fox (1974) found that detection accuracy for dichoptic presentations of opposite-polarity signals is near levels predicted by statistically independent detectors of the signals presented to each eye alone. On this basis, they rejected an *energy summation* model in which energies provided to the two eyes are summed. They also rejected an inhibitory interaction model, which was suggested by the observation that sustained viewing of opposite-polarity stimuli at suprathreshold intensities produces binocular rivalry.

The detection models used to evaluate probability summation required an assumption that the left- and right-eye channels were stochastically independent. It is noteworthy that the present approach does not require this assumption. Indeed, we illustrate how variations in the degree of stochastic dependence between parallel channels modulate performance levels predicted by a probability summation model. The performance bounds described here define the range of performance that is compatible with a generalized notion of probability summation. Within those bounds, the predictions change according to the degree of stochastic dependence between monocular pathways.

It is often not appreciated that accuracy results alone typically say little about underlying perceptual architecture. For instance, stochastic independence in the accuracy for detecting two stimuli is compatible not only with parallel, stochastically independent processing; it is also formally compatible with a serial processing architecture in which information is accrued independently over the two channels and assessed in exactly the same manner as in a parallel architecture. This type of mimicry has been overcome by recent advances in the stochastic theory of psychological processes.

Our design evaluates integration of luminance increments and decrements for both corresponding and noncorresponding retinal locations (where the signals are not fused in cyclopean vision). The results in normal observers are compared with those obtained from a stereo-blind subject. The use of RTs places the emphasis on the time course of stimulus processing over a complete sensorimotor circuit: one that begins within each eye and ends with a motor response. Thus, it is essential to develop a rigorous definition of channel independence that is amenable to empirical analysis in this context.

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### APPLICATION OF THE STOCHASTIC MODELING TECHNIQUES

Consider a situation in which *ON* and *OFF* pathways originating from either eye can be activated selectively. How might one determine whether the information conveyed over these pathways remains independent or becomes integrated? There are now known to be several logically separate types of channel independence, each with its own implications for information processing (Colonius, 1990; Colonius & Vorberg, 1994; Townsend, 1984; Townsend & Ashby, 1983; Townsend & Colonius, in press; Townsend & Nozawa, 1995). Assume that information accumulates in an individual channel until a criterion is reached and a "detection" response is released. The two channels operate in parallel, so processing can begin synchronously, but may finish asynchronously. A fine-grained type of independence, termed stochastic independence, occurs if the marginal probability distribution of times-to-criterion on each channel equals its distribution conditioned on the time to reach criterion on the other channel. If there is cross talk, the conditional time for one channel to complete processing (reach its criterion) will in general depend on when the other channel reaches its criterion, thus defeating stochastic independence. Stochastic dependence could result from interactions between monocular pathways, which actually may occur as early as the lateral geniculate nucleus (e.g., Rodieck & Dreher, 1979). It certainly is a salient feature of the visual cortex.

A coarser kind of independence is called *context invariance*.<sup>1</sup> This notion requires the somewhat weaker stipulation (relative to stochastic independence) that the marginal distribution on reaching criterion on one channel remains constant across intensity levels of stimulation in the other channel (Colonius, 1990). In the present situation, context invariance means that the marginal distribution on completion times is constant on one monocular channel, whether or not a signal is presented to the other eye. Note that context invariance allows stochastic dependence, as long as the overall marginal probability distribution is unaffected by the distribution of completion times on the other channel.

Stochastic independence and context invariance are logically independent notions: Either could obtain in the absence of the other. It is true that one might ordinarily expect a failure of stochastic independence to lead to a failure of context invariance or vice versa, but that is not necessary.

The pertinence for the present study is that the first parallel channel to complete processing can in principle terminate processing of the system as a whole. We refer to this processing termination rule as the *OR decision rule*, models of parallel processing using the *OR* decision rule as *race models*, and the predicted performance as *probability summation*. Given the relatively weak assumption of context invariance, race models have a very strong upper bound. Thus, if binocular processing conforms to a race model, there is a limit on how fast RTs to

binocular signals can be relative to monocular RTs. Systems in which stochastic independence holds will conform to this boundary, but the limit is more general than that, for the boundary applies regardless of any stochastic dependencies. We call this upper bound the *fast race boundary* in order to differentiate it from another bound defining the slowest RTs producible by race models, which we term the *slow race boundary*.

Of course, alternative processing architectures are possible. For example, a system in which the outputs from both eyes are combined within a binocular channel prior to the decision stage can produce performance that exceeds the fast race boundary. This processing architecture is generally referred to as channel summation, and in the present context has been called binocular channel summation. The fast race boundary provides a powerful diagnostic tool for distinguishing race models from channel summation architectures because performance that exceeds the bound strongly implies channel summation (e.g., Hughes, Reuter Lorenz, Nozawa, & Fendrich, 1994; Hughes, Nozawa, & Kitterle, 1996; Miller, 1982, 1986; Nozawa, Reuter-Lorenz, & Hughes, 1994). Situations in which parallel processing approaches the slow race boundary have in general been rare, but did occur in the present context (also see Hughes, Nozawa, & Kitterle, 1996). We now turn to a brief development of these two boundary conditions.

Irrespective of statistical dependencies, race models state that the probability that the observer detects either the left-eye or the right-eye stimulus by time  $t$  is given by the probability that the stimulus delivered to the left eye was detected by  $t$ , plus the corresponding probability for the right eye's stimulus, minus the probability that both stimuli were detected by  $t$ . Expressed in terms of cumulative density functions, race models state:

$$P(D_B \leq t | S_{LE} \& S_{RE}) = P(D_L \leq t | S_{LE} \& S_{RE}) + P(D_R \leq t | S_{LE} \& S_{RE}) - P(D_R \cap D_L \leq t | S_{LE} \& S_{RE}),$$

where  $D_B$ ,  $D_L$ , and  $D_R$  represent the time needed to detect a stimulus presented binocularly, to the left eye, and to the right eye, respectively, and  $S_{LE}$  and  $S_{RE}$  refer to stimuli presented to the left eye and right eye, respectively. The last term on the right side of this equality is the joint probability (that both monocular stimuli were detected by  $t$ ). According to the elementary laws of probability theory, the joint probability of the co-occurrence of two statistically independent events equals the product of the probabilities of the two individual events. Thus, if context invariance and statistical independence apply, this formula is identical to one in which the probabilities can be taken from the monocular stimulation conditions.

$$P(D_L \leq t \text{ OR } D_R \leq t | S_{LE} \& S_{RE}) = P(D_L \leq t | S_{LE} \& \overline{S_{RE}}) + P(D_R \leq t | \overline{S_{LE}} \& S_{RE}) - (P(D_L \leq t | S_{LE} \& \overline{S_{RE}}) \times P(D_R \leq t | \overline{S_{LE}} \& S_{RE})). \quad (1)$$

Equation 1 predicts the cumulative RT distribution for detecting dichoptic signals based on the cumulative RT distributions obtained using the component monocular signals, assuming statistical independence between the channels originating from the left and right eyes, so we call it the *independent race model prediction*. If statistical independence does not hold, the joint probability is still a quantity on the interval between 0.0 and 1.0. Hence, if context invariance is satisfied, we

1. The previous term for this constraint has been "context independence." However, as a reviewer suggested, what is really occurring (or not) is a type of invariance, not probabilistic independence. Although we are reluctant to introduce new terminology, this concept is just now appearing in the empirical literature, so this may be a propitious time for a logical alteration. Interestingly, context invariance is logically identical to a combination of pure insertion (e.g., Ashby & Townsend, 1980; Sternberg, 1969) and marginal selective influence (e.g., Townsend & Schweickert, 1989).

can permit any degree of statistical dependency, and it still follows that race models conform to the following expression:

$$P(D_L \leq t \text{ OR } D_R \leq t | S_{LE} \& S_{RE}) \leq P(D_L \leq t | S_{LE} \& \overline{S_{RE}}) + P(D_R \leq t | \overline{S_{LE}} \& S_{RE}). \quad (2)$$

Equation 2 is the fast race model inequality (Miller, 1982, 1986; Townsend & Nozawa, 1995), and it represents the upper limit of performance for separate parallel processing using the OR decision rule (Colonius, 1990).

A second bound sets the lower (i.e., slower) limit on parallel race models (Colonius, 1990). It was first introduced into the psychological literature by Grice, Canham, and Gwynne (1984) and is defined in the present context by the maximum of the cumulative distribution functions of the two monocular signals.

$$\text{Max}\{P(D_L \leq t | S_{LE} \& \overline{S_{RE}}), P(D_R \leq t | \overline{S_{LE}} \& S_{RE})\}. \quad (3)$$

We refer to this lower bound as the slow race boundary. Notice that the slow race boundary is slower than the independent race prediction:

$$\begin{aligned} &\text{Max}\{P(D_L \leq t | S_{LE} \& \overline{S_{RE}}), P(D_R \leq t | \overline{S_{LE}} \& S_{RE})\} \\ &\leq P(D_L \leq t | S_{LE} \& \overline{S_{RE}}) + P(D_R \leq t | \overline{S_{LE}} \& S_{RE}) \\ &\quad - (P(D_L \leq t | S_{LE} \& \overline{S_{RE}}) \times P(D_R \leq t | \overline{S_{LE}} \& S_{RE})). \end{aligned}$$

The speed of parallel processing could fall below the slow race bound if signals presented to each channel had a devastating effect (probabilistically) on the processing speeds (a result of extreme limitation in capacity; see Townsend & Nozawa, 1995). Alternatively, performance that falls below the slow race bound is compatible with a serial processing architecture (cf. Townsend & Nozawa, 1995). Consider a situation in which an observer has two eyes, but can access only one eye at a time. He selects the left eye with a probability of  $p$  and selects the other eye with a probability of  $(1 - p)$ . If the cumulative distribution functions for monocular targets presented to the left and right eyes were identical, then performance of such a monocular observer would equal the slow race limit (which in this circumstance would be identical to either of the monocular cumulative distribution functions). If the monocular cumulative distribution functions were not equal, however, the mixture would be less than  $\text{Max}\{P(D_L \leq t | S_{LE} \& \overline{S_{RE}}), P(D_R \leq t | \overline{S_{LE}} \& S_{RE})\}$ , and performance would be slower than the slow race boundary.

We now have several answers to the question of how these probabilistic notions of neural information processing can be applied to human performance. The fast and slow race expressions set upper and lower limits for parallel race models, so parallel processing using the OR decision rule must fall within the shaded region depicted in Figure 1.

If context invariance holds (as is likely for dichoptic stimuli, at least at the level of retinal processing), then violations of the fast race bound provide strong disconfirmation of the OR decision rule, thereby providing robust evidence of binocular channel summation. In a complementary fashion, violations of the slow race bound can occur in a parallel race system only if there are massive failures of context invariance (of a mutually inhibitory type). Otherwise, among relatively simple architectures, such failures imply serial processing.<sup>2</sup>

Our strategy is now clear. First, we assumed that ON pathways can be selectively activated by luminance increments, and OFF pathways can be selectively activated by luminance decrements.<sup>3</sup> Figure 2 pro-

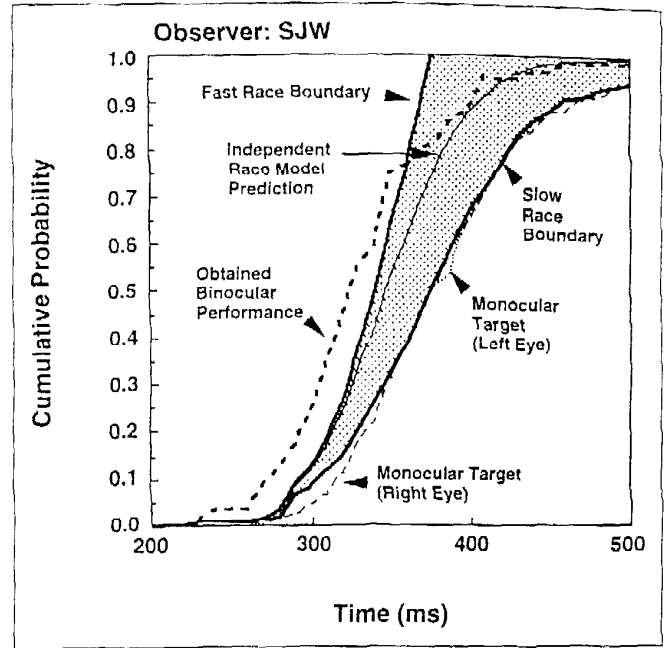


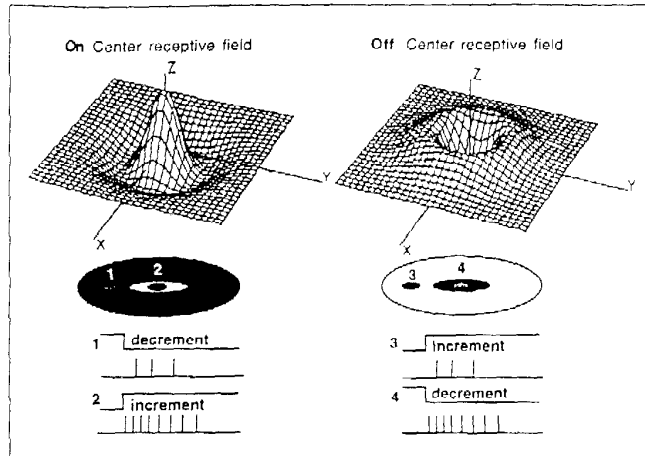
Fig. 1. Illustration of the fast race and slow race boundaries, portrayed in terms of cumulative distribution functions. The shaded region represents the range of performance that is consistent with parallel race models. These are the actual boundaries computed for data obtained from an observer who participated in the present experiment.

vides a schematic illustration of responses expected for ON and OFF center ganglion cells when small spots of light were incremented and decremented. The more robust responses should govern visual performance, especially when RT is the dependent variable. Thus, we expected that ON center cells provide the primary signal for detecting luminance increments, and OFF center cells provide the primary signal for detecting luminance decrements. Powerful supporting evidence for this assumption is provided by Schiller et al. (1986).

As stereo vision depends on neurons with binocular receptive fields, we evaluated performance under a variety of viewing conditions, including both monocular and binocular signals. For example, to

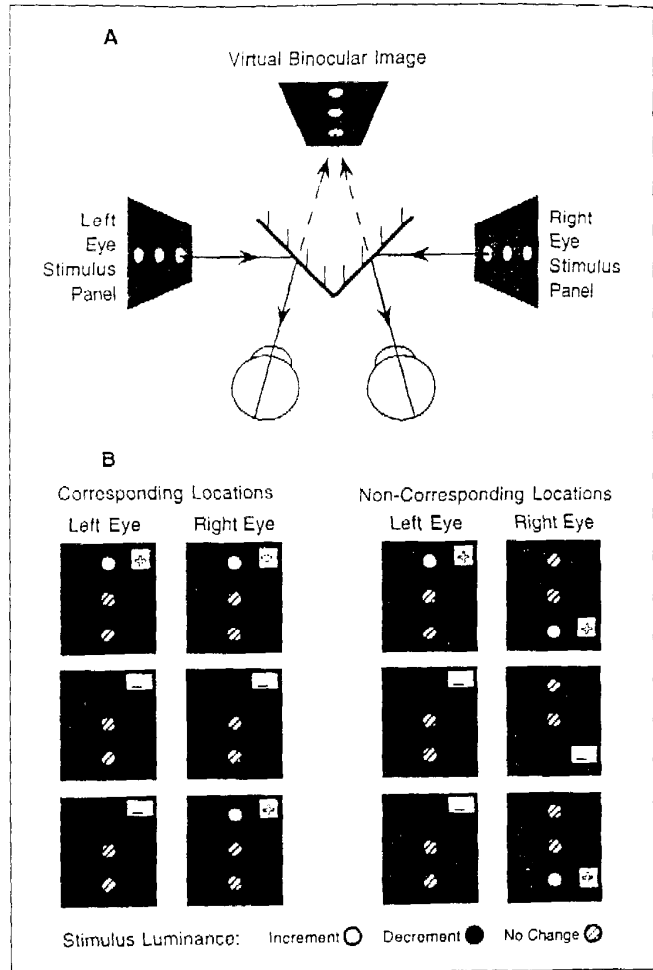
2. See Schweickert (1978) or Townsend and Schweickert (1989) for more complex architectures that a priori appear unlikely in the present context.

3. The justification for this assumption is as follows. Because the target stimuli are of such a small size (0.165° in diameter, described in Methods), they are expected to be inefficient in stimulating the surround mechanisms of concentric center-surround receptive fields. For example, although a luminance increment that happens to fall within the surround mechanism of an OFF center ganglion cell could produce an excitatory effect in that cell, the discharge expected would be very weak because the size of the surround mechanism is large relative to the size of the target. In contrast, spatially restricted luminance increments are expected to effectively drive those ON center cells whose receptive field centers correspond to the target location, because the spatial weighting function of the center mechanism is much stronger than that of the surround. Thus, although an increment in the luminance of a small spot might produce a weak response in several OFF center cells, it would produce a more robust response in ON center cells.



**Fig. 2.** Schematic of ON and OFF center receptive fields of retinal ganglion cells, and their expected responses to change in the standing luminance of a small spot of light. The top panel shows the two-dimensional weighting function of each class of cell as the difference of two Gaussians. The middle panel shows the spatial extent of inhibitory (black) and excitatory (white) subregions. Superimposed are stimuli projected onto the centers and surrounds of the receptive fields. The bottom panel depicts hypothetical responses to these stimuli: the "ticks" represent action potentials, and upward and downward displacements represent increments and decrements in brightness, respectively. From left to right, the diagrams show weak excitation of the ON cell in response to a decrement located in the receptive field surround (1), strong excitation of the ON cell in response to an increment located in the receptive field center (2), weak excitation of the OFF cell in response to an increment in the receptive field surround (3), and strong excitation of the OFF cell in response to a decrement in the receptive field center (4). Because both cell types have partially overlapping receptive field locations that cover the entire visual field, any stimulus should fall within both the center and the surround mechanisms of individual cells of both types, so any change in the luminance of a small spot should produce responses in both types of cells. The greatest response should always be obtained by stimulation of the center mechanism, however.

search for interactions between ON and OFF pathways, we presented a luminance increment to one eye and a luminance decrement to the corresponding location of the other eye. We compared performance in this condition with performance when binocular signals were presented at corresponding locations and the same luminance polarity. This latter condition was expected to produce evidence of a channel summation architecture (e.g., Blake, 1982; Blake & Cornack, 1979; Blake, Martens, & DiGianfilippo, 1980). When binocular stimuli in either matched or unmatched luminance polarity were presented at stereo disparities that were so large that fusion was not possible (so the stimulus presented to each eye was separately visible), we expected to see performance consistent with probability summation. Finally, because stereo-blind observers probably lack binocular neurons, such observers should not show evidence of the channel summation architecture under any of these conditions (e.g., Blake, 1982; Blake & Cornack, 1979; Blake et al., 1980; Levi, 1985). Indeed, in view of evidence that some stereo-blind observers see out of only one eye at a



**Fig. 3.** Apparatus and examples of the stimulus conditions. Shown in (a) is a schematic of the mirror haploscope that permits independent presentation of visual targets to the two eyes. Examples of the different combinations of binocular stimuli used in the experiment are shown in (b). Plus and minus signs denote luminance increments and decrements, respectively.

time (e.g., Burian & von Noorden, 1974, p. 310), we predicted we might actually see evidence of serial processing.

### METHODS

Luminance increments and decrements were presented dichoptically or to either eye alone using a mirror haploscope. The apparatus and stimulus conditions are summarized in Figure 3. At the optical distance of 70 cm, the fused images consisted of three vertically aligned luminous sources (0.165° in diameter, center-to-center spacing of 1.23°). The six stimuli (three viewed by the left eye, three by the right) consisted of light-emitting diodes (LEDs) that were independently controlled by 16-bit digital-to-analog converters. The middle LEDs were yellow (constant luminance of 1.94 cd.m<sup>-2</sup>) and served as a fixation point. Visual signals consisted of increases or decreases in the prevailing luminance of one (monocular trials) or two (binocular trials) of

the possible target LEDs. The target LEDs were red, and their steady-state luminance was set at  $21.8 \text{ cd.m}^{-2}$ .

There were two levels of luminance decrement ( $-12 \text{ cd.m}^{-2}$  and  $-21.8 \text{ cd.m}^{-2}$ ) and two levels of increment ( $+21 \text{ cd.m}^{-2}$  and  $+192 \text{ cd.m}^{-2}$ ). The dependent measure was simple RT to signal the occurrence of any change in steady-state luminance in any of the four target LEDs. These luminance changes were presented for 1 s to ensure that the responses were based on the initial change in luminance (all RTs were shorter than 1,000 ms). Single targets were presented to either the left or the right eye, and double targets were always presented dichoptically (one stimulus to each eye). Dichoptic signals were presented in both corresponding and noncorresponding retinal locations. In the case of noncorresponding dichoptic stimuli, the vertical separation of  $2.46^\circ$  precluded binocular fusion, so the stimuli appeared as two distinct targets. In the case of opposite-polarity signals presented at corresponding locations, the stimuli were seen as an increment, a decrement, or simply a "disturbance" in the luminance of a single target, depending on the stimulus magnitude presented to each eye. All possible binocular combinations of the magnitude and polarity of luminance changes were presented; examples are illustrated in Figure 3b. The probability of either a monocular or a binocular trial was .44 (12% catch trials). The various monocular and binocular stimulus combinations were all equiprobable and presented in a random sequence.

The results are based on 7,200 trials in each of 5 observers. Four of these subjects had normal stereo vision. The 5th subject was stereo blind, as a result of a condition of childhood strabismus.

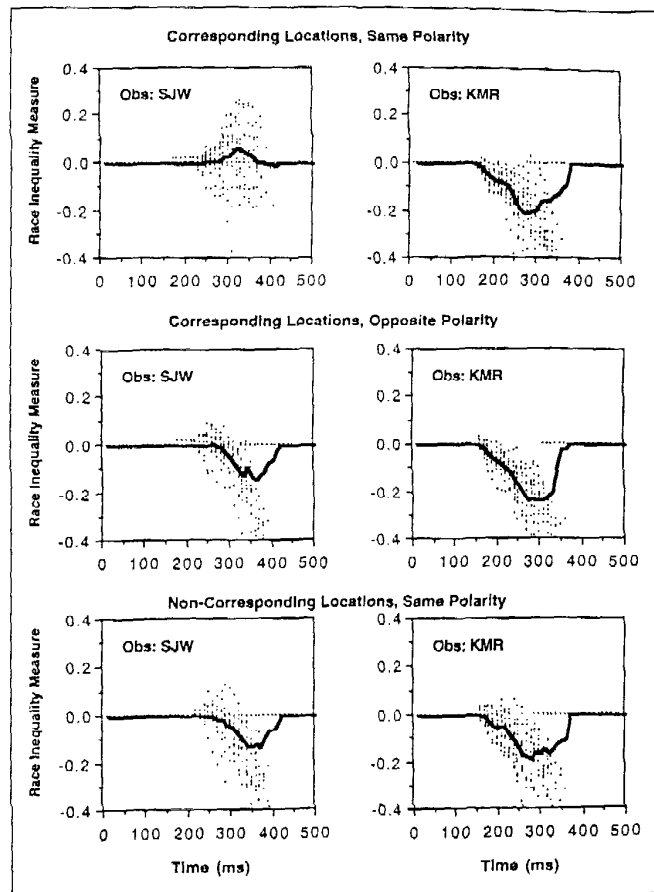
## RESULTS

### Parallel Channel Summation

Figures 4 and 5 illustrate model fits of the fast race boundary. The sum of two monocular cumulative distribution functions is subtracted from the cumulative distribution function obtained in the corresponding binocular condition, so violations of the boundary are represented by positive values in these graphs. Figure 4 compares the results for a normal (S.J.W.) and a stereo-blind (K.M.R.) observer. The only conditions that produced substantial and reliable violations of the fast race boundary in the normal observer were those in which matched-polarity targets (two increments or two decrements) were presented to corresponding locations of the two eyes (top panel of Fig. 4). For this observer, performance when opposite-polarity targets were presented at corresponding locations (middle panel) was comparable to performance when signals fell on noncorresponding retinal locations (bottom panel). S.J.W.'s performance in both of these latter conditions is similar to the stereo-blind observer's performance. Figure 5 illustrates the averaged data for 4 stereo-sighted observers. The overall trend in these results is quite consistent: Binocular channel summation is observed only in individuals who have stereo vision, and depends on presentation of stimuli of the same luminance polarity at corresponding retinal sites.

### Independent Race Model for Separate Parallel Channels

The failure to find evidence of binocular channel summation using targets of opposite luminance polarities suggests that ON and OFF pathways remain segregated up to the level of binocular convergence. Next, we compare these results to predictions assuming independent



**Fig. 4.** Evaluation of the race model inequality in a stereo-sighted observer (S.J.W.) and a stereo-blind observer (K.M.R.). Positive values represent violations of the inequality (performance that exceeds the fast race boundary). The heavy lines represent the average values as a function of time. Robust violations of the inequality are completely lacking in the stereo-blind subject, indicating a lack of binocular channel summation. Evidence for binocular channel summation in observer S.J.W. is confined primarily to conditions in which dichoptic flashes were presented in the same polarity at corresponding locations. Performance when opposite-polarity flashes were presented at corresponding locations closely approximates that obtained by stimulating noncorresponding locations; this finding strongly suggests a lack of binocular channel summation under these conditions.

probability summation (Equation 1). Because performance that violates the race model inequality naturally violates the independent race model as well, we restricted our race model analyses to those conditions that failed to provide evidence of binocular channel summation.

Again, the model fits are evaluated by subtracting predicted levels (right-hand expression in Equation 1) from the obtained binocular cumulative distribution functions. Figure 6a illustrates the independent race model fits for all 16 combinations of opposite-polarity targets presented at corresponding locations in the 4 normal observers. The fits of the same conditions to the slow race bound (Expression 3) are shown in Figure 6b. Figure 6c illustrates the independent race fits using same-polarity signals at noncorresponding locations. In general,

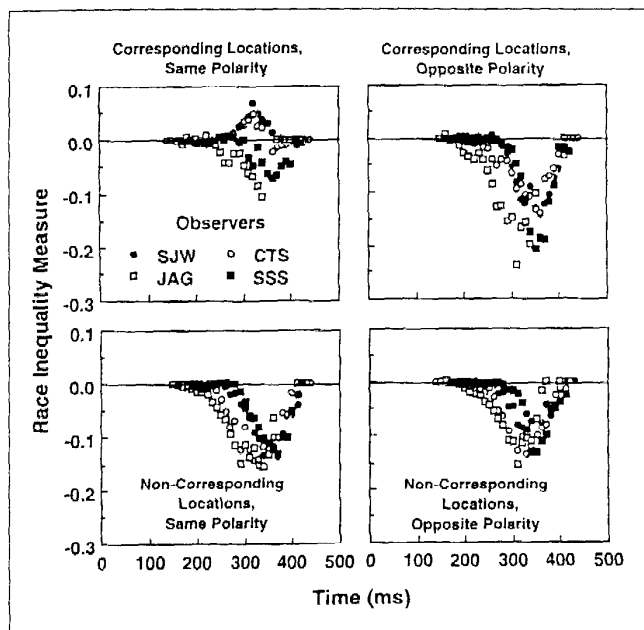


Fig. 5. Evaluation of the race model inequality in each of 4 stereosighted observers for four conditions of dichoptic stimulus presentation. Positive values represent performance that exceeds the fast race boundary.

observed performance was slower than the independent race prediction, but rather faster than the slow race boundary. Thus, opposite-polarity targets presented at corresponding retinal sites appear to activate separate parallel channels in the two eyes, and detection times conform to the OR decision rule. The striking similarity between the data for opposite-polarity signals at corresponding locations and same-polarity signals at noncorresponding locations (Figs. 6a and 6c) argues against the operation of any interocular suppression (i.e., binocular rivalry) between the mechanisms that respond to increments and decrements. If context invariance holds equally for all conditions, the tendency for the data points to fall slightly below levels expected by independent parallel mechanisms is more likely the result of positive dependencies between the left- and right-eye channels. Limited-capacity parallel processing could also produce such results (Townsend & Nozawa, 1995).

### Serial Processing by the Stereo-Blind Observer

We return now to the binocular interactions that characterized the stereo-blind observer. Analysis of the results for matched-polarity signals at corresponding retinal points (ordinarily associated with binocular channel summation) shows that the data are in fact well below the independent race prediction. Indeed, they are precariously close to the slow race boundary, which is defined as the maximum value of the monocular cumulative distribution functions at each point in time. In many instances, the performance of our stereo-blind observer clearly fell below this limit. Illustrations are provided in Figures 7a and 7b, where it is evident that binocular performance was slower than the faster of the two monocular conditions. These results would be obtained if the observer were to randomly select a channel (i.e., either

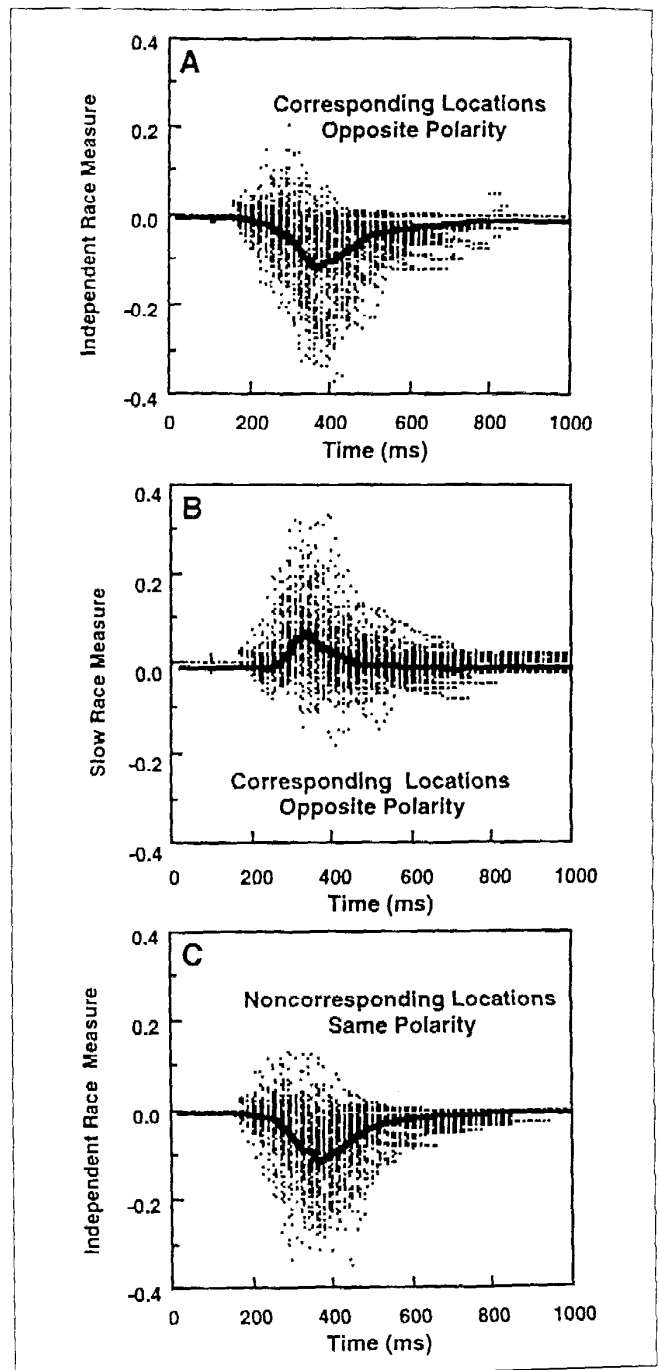
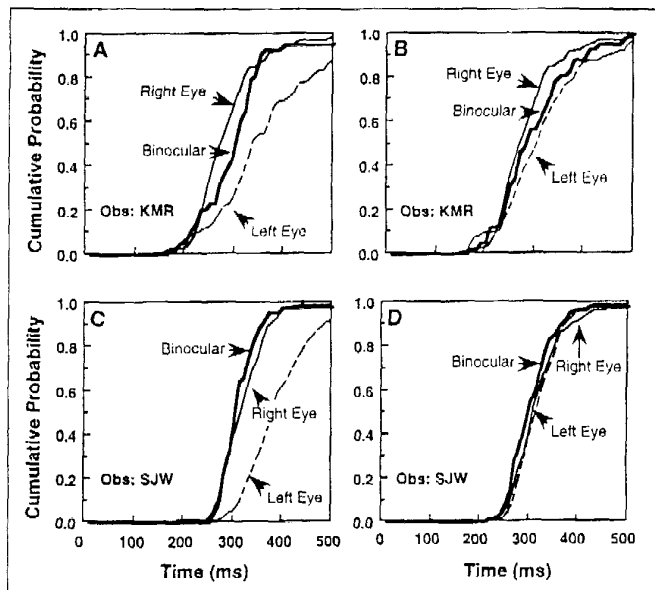


Fig. 6. Evaluation of the independent race model prediction (a and c) and the slow race bound (b). The heavy lines show the mean values. Obtained performance is clearly consistent with the race model prediction, although generally below the level predicted by independent parallel channels.

the left or the right eye) on any given trial and process only the activity on that channel. Note that performance would match the slow race boundary if the observer were always able to select the faster of the



**Fig. 7.** Comparisons between monocular and binocular performance in a normal observer (S.J.W.) and a stereo-blind observer (K.M.R.). In each case, the monocular targets were of the same luminance polarity, presented at corresponding retinal sites. Note that binocular performance in the stereo-blind observer falls below the faster of the individual monocular conditions. These data represent violations of the slow race boundary, suggesting serial processing of the binocular signals.

two ocular channels. The fact that binocular performance frequently fell below the slow race bound suggests that on some trials, processing must have been confined to the slower of the two input channels.

## DISCUSSION

The present theoretical analyses illustrate how race models of parallel processing are consistent with a range in RT performance, and the empirical results demonstrate that binocular interactions span much of that range. The fast race boundary lies at one extreme, and violations of this bound strongly imply binocular channel summation. This architecture depends on stereo fusion of signals of the same luminance polarity. At the other extreme lies the slow race boundary. RTs slower than this bound were observed only in the stereo-blind observer and are compatible with monocular processing of binocular signals.

Consistent with the general interpretations offered by Westendorf and Fox (1974), our analysis indicates that race models apply to the results for opposite-polarity flashes. These channels maintain their functionally independent states. Our interpretation in terms of independent ON and OFF pathways is consistent with physiological findings (e.g., Schiller et al., 1986; Sherk & Horton, 1984) and human adaptation data (Burton, Nagshineh, & Ruddock, 1977; DeValois, 1977). Nevertheless, an interesting sidelight that is perhaps deserving of further study was the moderately limited capacity of performance in these conditions.

What might be the processing advantage conferred by what at first glance appears to be the early establishment of apparently redundant ON and OFF mechanisms? In agreement with Schiller et al. (1986),

we suggest that these complementary pathways may function to permit rapid detection of local changes in luminance of either polarity by encoding increments and decrements in terms of increased activity within functionally separate parallel pathways.

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