Binocular Integration of Two-Flash Information

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Abstract

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The extent to which temporal resolution is improved by viewing a stimulus display binocularly rather than monocularly increases with the similarity of the displays presented to the two eyes. This was confirmed with respect to stimulus intensity. Two-flash thresholds were assessed a) in one filtered eye, b) in the other unfiltered eye, and c) binocularly with one filtered and one unfiltered eye. Thresholds were measured using 16 randomized staircases. A binocular advantage of 12% occurred under conditions of equal luminance. As the discrepancy in luminance increased, this advantage weakened and finally a binocular disadvantage was found at the highest filter level. The probability summation model was found to over-predict the binocular advantage at the lower filter levels, and the amount of over-prediction was quantified in a manner comparable to other studies involving probability summation. A combinatorial rule was produced which fits the data at the lower filter levels. The binocular disadvantage was explained in terms of a luminance-dependent weighting effect, whereby the filtered eye can adversely affect the binocular two-flash threshold.

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BINOCULAR INTEGRATION OF TWO-FLASH INFORMATION

Introduction

In normal vision the two eyes interact to produce a single, binocular, image. The nature of this interaction varies depending on the viewing conditions, and has been the subject of considerable study. There have been cases in which binocular sensitivity is far superior to monocular sensitivity (Peckham and Hart, 1960; Thomas, 1954), cases where binocular sensitivity is inferior to the better of the two monocular sensitivities (Levelt, 1965; Engle, 1969), and many in between (Sherrington, 1906; Fry and Bartley, 1933). There is even a case in which binocular sensitivity is inferior to either monocular sensitivity (Tyler, 1971). Much research has been devoted to determining the effect of different viewing conditions on the type of interaction produced. The research reported here deals with determining the type of interaction produced by interocular differences in luminance with two-flash stimulation, and addresses the broader issue of how the visual system binocularly integrates temporal information.

The two-flash threshold, the necessary off period between two flashes in order for both flashes to be detected, has not been the topic of as much research as other varieties of temporal resolution tasks. Flicker fusion, for example, is the frequency of flicker necessary for the flickering light to be perceived as steady. A train of flicker can be of any length, and as the length gets shorter the flicker becomes more and more like a two-flash stimulus; a flicker train of two is a two-flash stimulus. Two-flash thresholds, then, are a limiting case of flicker fusion thresholds.

Binocular interactions have not been heavily investigated with respect to two-flash thresholds, whereas binocular flicker has been somewhat more extensively studied. Fortunately the relationship between two-flash and flicker thresholds has been elucidated, so the results of binocular flicker experiments can, with only moderate caution, be applied to binocular two-flash investigations.

The relationship between flicker and two-flash thresholds was looked at by Roufs (1972), who found a constant relationship between the two. The two conditions in his experiment were identical in all respects except for the two-flash versus flicker aspect. The relationship between S, Roufs' measure of sensitivity to flicker, and F, sensitivity to two-flash stimuli, was shown to be:

$$\log S/F = 0.4$$

This relationship was found to hold over a broad range of background luminance conditions. The finding of a constant relationship should not be surprising, given that the two-flash paradigm is a limiting case of the flicker paradigm, but one must bear in mind that the two procedures are not identical. For example, one could miss an occasional off period in flicker and still detect flicker; there is only one off period to detect in the two-flash paradigm. Since there are many opportunities to detect an off period in flicker, the probability of detecting at least one is fairly high. There will be a more detailed discussion on the summation of detection probabilities later. For now it is sufficient to say that one must exercise caution in comparing flicker to two-flash experiments, but such comparisons can be made.

Even so, the amount of information concerning the binocular integration of flicker information is limited, so we must search further afield, to binocular brightness with steady state stimulation, in order to place binocular two-flash thresholds in an adequate context.

Binocular Brightness

The general nature of binocular interaction was first investigated by comparing the brightness of an object seen binocularly with the brightness of the same object seen monocularly. This type of experiment can be performed by merely closing one eye, noting the brightness of the visual field, and then re-opening the eye and again noting the brightness. The two brightnesses are the same. If the binocular view had been made up of two unequally luminous monocular views, for example had a filter been placed in front of one eye, the binocular brightness would have been intermediate between the two monocular brightnesses. This phenomonon, that two eyes can yield a dimmer percept than one of the eyes contributing to that binocular percept, is known as "Fechner's Paradox", because it contradicts the simplistic view that information from the two eyes is added together. Binocular brightness interaction was investigated by Sherrington (1904, 1906), who found that the binocular brightness is somewhat, but not much, above the average of the two monocular brightnesses. In this study comparisons between monocular and binocular brightnesses were made by comparing the brightness of a current binocular stimulus with that of a remembered monocular stimulus.

De Silva and Bartl~~ey (1930)~~ and Fry and Bartley (1933) used procedures involving the simultaneous comparison of binocular and monocular steady state brightnesses. Rather than having their subjects rely on memory, these investigators had both the binocular and the monocular stimuli visible at the same time. De Silva and Bartley allowed subjects to vary the intensity of the monocular stimulus until its brightness equalled that of the binocular stimulus. Fry and Bartley allowed the intensity of the lamp illuminating the binocularly viewed stimulus to be adjusted. In both cases the monocular luminance had to be higher, by up to 50%, than the binocular luminance in order for the two to have the same brightness.

That this binocular advantage was not found in Sherrington's steady state brightness experiment discussed above was explained by De Silva and Bartley. They said this was due to inaccuracies in measurement inherent in the successive presentation method used by Sherrington, relying as it does on human memory to make the brightness comparison. Another factor accounting for the difference in results, discussed by Levelt (1965), was the unreliability of measures of brightness matching; such matching is subject to high between-session variability.

Levelt performed a similar experiment in which he had his subjects make successive, rather than simultaneous, brightness matches. This method has the advantage of allowing the two stimuli being compared to fall on the same retinal location, but it relies on memory for the comparison. The luminance of the binocular comparison stimulus was controlled by the experimenter, as was one of the luminances of the binocular test stimulus. The subject adjusted the other binocular test luminance until the two stimuli were equal in brightness. The results indicated that the binocular brightness is a function of the average of the two monocular luminances, a finding in agreement with Sherrington (1906) and at odds with De Silva and Bartley (1930) and with Fry and Bartley (1933). After discussing some methodological criticisms in the latter's experiments, Levelt pointed out that the simultaneous procedure always yields a binocular advantage and the successive procedure does not. This fact is explained by Levelt's interpretation of another part of his study.

Levelt repeated his experiment adding one more variable: contrast. The amount of contour and contrast in the visual field of one eye was increased, and the same brightness matching procedure was performed. In this case the binocular brightness was not a function of the average of the two monocular luminances, but of a weighted average, the weight being determined by the amount of contrast in each eye's visual field. Expressed mathematically:

$$W_R E_R + W_L E_L = C$$

where W_R and W_L are the weights, dependent on the amount of contour and contrast in each eye's visual field, E represents the monocular brightness, and C is the binocular brightness. The sum of the two weights must equal unity. Contrast was measured by the presence or absence of a number of disks that constituted the stimuli.

In normal vision the two eyes see more or less the same scene, therefore they have similar amounts of contour and contrast in the visual fields and thus have equal weightings in the binocular percept. This was the case for Sherrington's subjects. In Fechner's Paradox there is also equal weighting. Although one eye is filtered, both eyes see the same scene, and nowhere does the filter reduce luminance to an undetectably low level. Thus the same amount of contrast is in each visual field, although luminance is unequal. The binocular brightness is thus an average of the two monocular luminance levels.

The binocular advantage found in studies employing the simultaneous comparison method is explained, not by a contrast-dependent weighting effect on the binocular brightness, but by such an effect on the monocular brightness. The simultaneous comparison method involves each eye being exposed to the binocular stimulus and one eye, for example the right eye, also being exposed to the monocular stimulus. Even when judging the luminance of the right eye monocular stimulus, the left eye has the contour and contrast of the binocular stimulus in its visual field; this is not a truly right eye monocular task. In the weighted average that determines the brightness the left eye will still play a part. Thus the right eye's monocular brightness is really a binocular brightness, and is a function of the weighted average of the monocular stimulus luminance and the luminance of the corresponding part of the left eye, which is the background luminance. This "monocular" brightness, then, is lower than the previously measured binocular brightness, due to a contrast-dependent weighting effect and not due to a binocular advantage. In the successive comparison method, used by Sherrington and Levelt, the contour and contrast in the left eye's visual field tends towards zero while the brightness of the right eye monocular stimulus is being judged, so the left eye's weighting also tends towards zero.

This model fitted most of Levelt's data, the exception being the binocular brightnesses formed by extremely disparate monocular illuminations; the model broke down where there was a luminance ratio of eight to one or greater. In these cases the model does not account for the binocular advantage that tended to occur.

Engle (1970) replicated Levelt's study finding similar results, but he proposed a different model to describe the data, and defined contrast in a more rigorous manner. Engle defined contour and contrast using an autocorrelation function. For each point in the visual field the absolute deviation of the luminance of that point from the average luminance was taken. The sum of each deviation multiplied singly by every other deviation is the definition of the contour and contrast. This allowed the weights to be made proportional to the amount of contour and contrast, such that the right eye's weight divided by the left eye's weight equals the right eye's contrast divided by the left eye's contrast.

This model of binocular integration is:

$$C^2 = (W_R B_R)^2 + (W_L B_L)^2$$

where C is the binocular brightness, W_R and W_L are the weights, and B_R and B_L are the monocular luminances. When each weight is squared the sum of the two must equal unity.

The validity of this model was tested by predicting Fry and Bartley's and Levelt's data using their luminance configurations (Engle, 1969). The concordance with respect to Levelt's data was almost perfect, and with respect to Fry and Bartley's was very good. Of particular interest is the fact that the model correctly predicted Levelt's disparate monocular illumination data, that which Levelt said was unpredictable.

The Engle model also fits well data of the same kind generated specifically to test the model. The binocular integration of brightness information, then, seems to be mediated by a weighted averaging mechanism based on the contour and contrast in the visual fields.

Binocular Flicker

Sherrington (1906) first studied temporal binocular interactions with his experiments on critical fusion frequency

(CFF). CFF is the frequency of intermittence at which a flickering light is first perceived as steady, and is usually expressed in flashes per second. Interested in studying binocular summation, Sherrington measured CFF in three conditions: monocular, binocular in phase and binocular alternating flicker. The alternating condition consisted of a right eye on period corresponding to a left eye off period, and vice versa. Sherrington reasoned that with perfect summation the alternating condition would appear at all frequencies as a steady light. He found, however, that flicker could be seen in the alternating condition and CFF was lower than in the other two conditions. For the alternating condition the CFF occured at 57.8 flashes per second, for the monocular condition, 63.6 flashes per second, and three percent higher, at approximately 65.5, for the binocular in phase condition. The existence of an alternating CFF led Sherrington to conclude that there was not perfect summation in the visual system; that the light energy input to the two eyes was not simply added together. He also concluded that the sensitivity of the two eyes was not summated either, despite the consistent 3% binocular in phase advantage over the monocular CFF. Sherrington concluded that there was no physiological interaction between the two eye's sensitivity to flicker; that the two eyes worked independently, and that the 3% difference found was too small to be relevant. However, Blake and Fox (1973) analysed Sherrington's data using a sign test and found significance at the .01 level. As well, many later researchers have found larger, significant binocular advantages in flicker perception.

Ireland (1950) reported a significant 5% binocular superiority using 24 subjects. Baker (1952a, 1952b, 1952c & 1952d), in a series of experiments, found an 11% binocular advantage. Similar results were found by Vernon (1934), Crozier and Wolf (1941), Perrin (1954) and, using sinusoidal flicker, Cavonius (1979). A similar binocular advantage was found for two-flash thresholds by Pearson and Tong (1968).

Thomas (1954) extended this investigation to conditions of unequal as well as equal luminance. Thomas used flickering stimuli of 2.2 and 6 degrees of visual angle, and dark adapted subjects. Under equal luminance an examination of the data revealed an approximate 15% binocular advantage, with an attenuation of this advantage as the luminance disparity increased. As the luminance disparity reached roughly 0.25 log units the binocular advantage disappeared and thereafter a binocular disadvantage was found. As Thomas put it " ... a steady dim light in one eye decreases the sensitivity of the other eye for the detection of flicker". The lower luminance eye is presumably perceiving a dim, non-flickering light; the luminance is too low to allow flicker resolution. This conclusion is supported by Lipkin's (1962) findings that a steady light to one eye lowers the CFF of the other eye.

Thomas, as well as the other researchers discussed above, did not use an important statistical control procedure first proposed by Pirenne (1943). Before Pirenne it was reasoned that, in the absence of any binocular interaction, the binocular sensitivity would be equal to the greatest of the two monocular sensitivities.

Pirenne showed that this is not the case. The CFF, as used by all the researchers thus far mentioned, is the frequency of flicker where the probability of flicker detection is 50%. This is the classic definition of a threshold. If it is assumed that the two eyes act independently, and that binocular detection will occur if either or both of the eyes independently detects flicker, then the binocular detection probability will be predicted by the probability summation of the two monocular detection probabilities.

To illustrate probability summation, consider a situation in which, at frequency "x", each eye has a detection probability of 29%, and therefore a 71% chance of missing the flicker. The binocular probability of missing the flicker is the intersection of the two monocular probabilities of missing the flicker; .71 multiplied by .71, or .50. Thus frequency "x" is the binocular CFF, for at frequency "x" the binocular detection probability is 50%. Since the monocular 29% detection probabilities were at frequency "x", their 50% detection probabilities, or CFFs, must have been at a frequency that is easier to detect, indicative of poorer temporal resolution. (The higher detection probabilities occur at the easier to see, that is lower, frequencies.) In the absence of binocular interaction, that is given monocular independence, the binocular CFF would be lower than the monocular ones, according to the equation:

$$Pb = 1 - (1 - pR) * (1 - pL)$$

where Pb is the binocular detection probability, Pl is the left eye's detection probability and Pr is the right eye's detection probability.

Pirenne tested this equation in a flash detection experiment and found the equation to be a good predictor of binocular performance. Unfortunately information concerning the procedures used, for example the number of subjects involved, were not included in his report, so the confidence one can put in his findings is unknown. The important contribution, however, was the recognition that probability summation plays a role in detection thresholds.

The question is raised as to the role played by probability summation in the binocular advantages found by the host of researchers referred to above. Unfortunately all of these researchers either collected or reported their data in such a way that only the various CFFs are available, rather than a complete set of detection probabilities. While each CFF corresponds to a 50% detection probability, this is not enough to allow a test of the hypothesis that some factor other than probability summation is at play in binocular flicker detection. Ideally both the CFF and a table of detection probabilities would be presented.

Matin (1962) performed an experiment designed to allow the testing of the probability summation hypothesis. Matin presented one flash to each eye and varied the time interval between the two flashes, and found that, with an interval of less than 100 ms, the chances of seeing either or both flashes was greater than the probability summation of the monocular flash detection probabilities. A similar conclusion, as well as the use of a refinement of the probability summation model to deal with forced choice paradigms with more than two choices, came from Thorn and Boynton (1974). The argument, which was first made by Blackwell (1963) concerns the role of catch trials. Catch trials are trials where no stimulus is presented, and are used to determine the influence of factors other than sensitivity on the threshold. For the non-catch trials, the obtained probability of seeing is due to the frequency of detecting the flash plus the frequency of a correct guess. Using the frequency of "detection" of the catch trials, the frequency of a correct guess can be removed from the probability of detection of the non-catch trials. This can only be done where catch trials are used, and only need be done where guessing might be a factor.

Binocular integration in excess of probability summation has been the conclusion of many studies dealing with the probability summation of thresholds, for reviews see Blake and Fox (1973) and Blake, Sloane and Fox (1981).

One study dealing directly with probability summation in binocular flicker perception is that of Peckham and Hart (1960). The probability of seeing for each eye and both eyes was measured for a stimulus alternating between five-percent above and five-percent below the brightness of the background. The rate of alternation, or flicker frequency, was varied, and measurements were taken at each frequency. At each frequency the two monocular probabilities were summated probabilistically to produce a set of predictions of binocular performance, given the assumption of independence. A graph of binocular versus probabilistically predicted detection probabilities at each frequency indicated that only at the highest detection probabilities, 80% and higher, were the binocular data inferior to the predicted data. Binocular superiority was established and increased as the detection probability decreased, leading Peckham and Hart to conclude that the binocular superiority occurred mostly at the subliminal level.

This binocular superiority occured at most detection probabilities, including the 50% detection probability. Since this is the definition of the threshold we can say that a binocular advantage was found at the threshold, and that therefore these findings agree with those from the studies in other areas discussed above. One minor failing here is that the data were not expressed in terms of thresholds or CFFs, but in terms of detection probabilities at each frequency. This makes it difficult to compare this data to that from other experiments, where results were expressed in CFFs. What is needed is a method of accurately obtaining the threshold from a table of probabilities, such a method would facilatate comparisons between studies where results were expressed in different ways.

Statement of the Problem

It is unfortunate that none of these studies extended the probability summation paradigm to flicker thresholds under conditions of unequal luminance, as in Thomas's experiment. The binocular disadvantage he found under high luminance disparity conditions clearly cannot be explained by probability summation, but it would be interesting to trace the size of the deviation from probability summation across luminance disparities. The works of Matin (1962) and of Thorn and Boynton (1973) both indicate that the role of factors other than probability summation occur only when the lag between the right and left eye stimulus is shorter than 100 ms. A general finding concerning binocular advantages is that they are greatest when the two monocular stimuli are very similar (see Brown, 1965).

As a preliminary look at the issues raised above, especially the binocular integration of temporal information, the following research was performed. Something like a two-flash replication of Thomas's experiment was conducted. Different luminance levels were presented to the two eyes, and measurements were taken in such a way as to allow the prediction of probability summation to be tested. To make the results of this study comparable to other studies in the two-flash and even flicker literatures, the probability summation prediction was formed in such a way as to be expressed as a threshold. The intent of this research was to determine: a) whether a two-flash version of Thomas's binocular disadvantage exists, b) the effect of luminance disparity on the binocular advantage, and c) the formation of a mathematical description of the monocular contributions to the binocular two-flash threshold.

Method

Stimuli and Apparatus

The stimuli were flashed points generated by a PDP-11/10 computer interfaced through D/A converters with a Hewlett-Packard 1310A CRT equipped with a fast decaying, burn resistant P15 phosphor. The points were viewed through Wratten gelatin neutral density (N.D.) filters. As can be seen in Figure 1, which presents the temporal distribution of luminance for one trial, the test point was extinguished for one second, reappeared for 10 ms, disappeared during the ISI, and finally reappeared, to remain on until a response was produced. The subject's task was to indicate whether two flashes were detected. The trials were separated by an intertrial interval of at least one second, determined by the subject.

Subjects

The three subjects had either 20/20 or corrected to 20/20 visual acuity, and they consisted of the experimenter and two paid participants. Two subjects were male, one was female, and all were between 20 and 25 years of age.

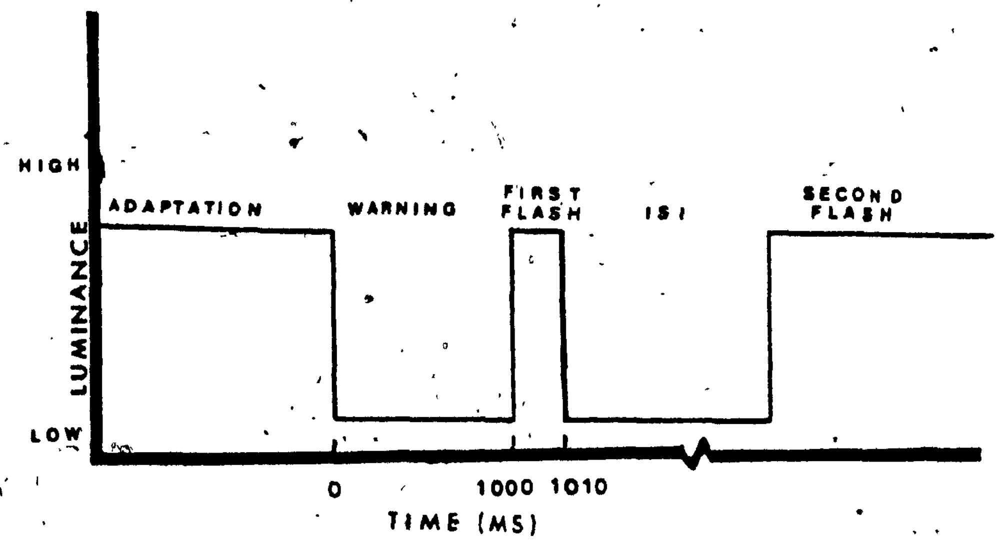

Figure 1. The temporal distribution of luminance for one trial.

Procedure

To assess the monocular contributions to binocular temporal resolution, two-flash thresholds were assessed in three conditions: a) monocular viewing through a variety of neutral density filters, b) monocular viewing with the other eye, through a fixed neutral density filter, and c) binocular viewing with one eye under the various filter conditions and with the other eye always under the same, fixed, filter condition. The entire procedure was performed twice, each eye being variably filtered once and steadily filtered once. Eleven filter levels, from 1.0 to 2.0 log units N.D., and a 2.2 N.D. filter level were used. A further 2.4 N.D. level was used for subjects who still felt comfortable with the task at a 2.2 N.D. filter. It was found that very high standard errors, and therefore unreliable data, occurred when the subject no longer felt comfortable with the task. This discomfort occured very near the point where the stimulus could not even be distinguished from the background, so the unreliability of the data was assumed to be due to subjects responding more or less randomly.

The eye for which the luminance level did not change was filtered with a 1.0 filter, the least dense filter level ever used. Thus the disparity in filter levels between the eyes varied from zero to 1.2 or 1.4 N.D. The variably filtered eye and the binocular conditions were both run under each filter level, and the unchanging eye was run only under a 1.0 filter level. Each filtered condition was performed twice, and the unchanging condition was performed at least 18 times throughout the experiment. Thus the total number of conditions for each subject was two times the number of filter levels plus one.

The entire experiment took several weeks for a subject to complete. Each day the procedure was as follows: two sessions, each consisting of a combination of one filter level and one ocular condition, were run in immediate succession, followed by a break of at least one hour. Each session lasted approximately 25 minutes. Another two sessions were run, followed by the break, and so on. Two, three or four such pairs of sessions were run each day. This was done in random order, subject to two constraints. First, each session had to occur as many times in the first position of the pair as in the last, and second, every day the unchanging condition had to appear at least once.

Each session was run in the same way. The two-flash threshold was assessed at 16 retinal locations, eight forming a circle, centered at the fovea, whose radius was 2.5 degrees and eight forming a five degree radius circle (see Figure 2). A foveal point was always visible and was fixated. A practice session preceded each actual session.

Practice trials began with a double flash from the top 2.5 degree point. On each trial, both for the practice trials and for those in the experiment proper, only the point to be tested and the foveal fixation point were presented. The off period between the two flashes of the test point, or interstimulus interval (ISI), was set by the experimenter to be well below the

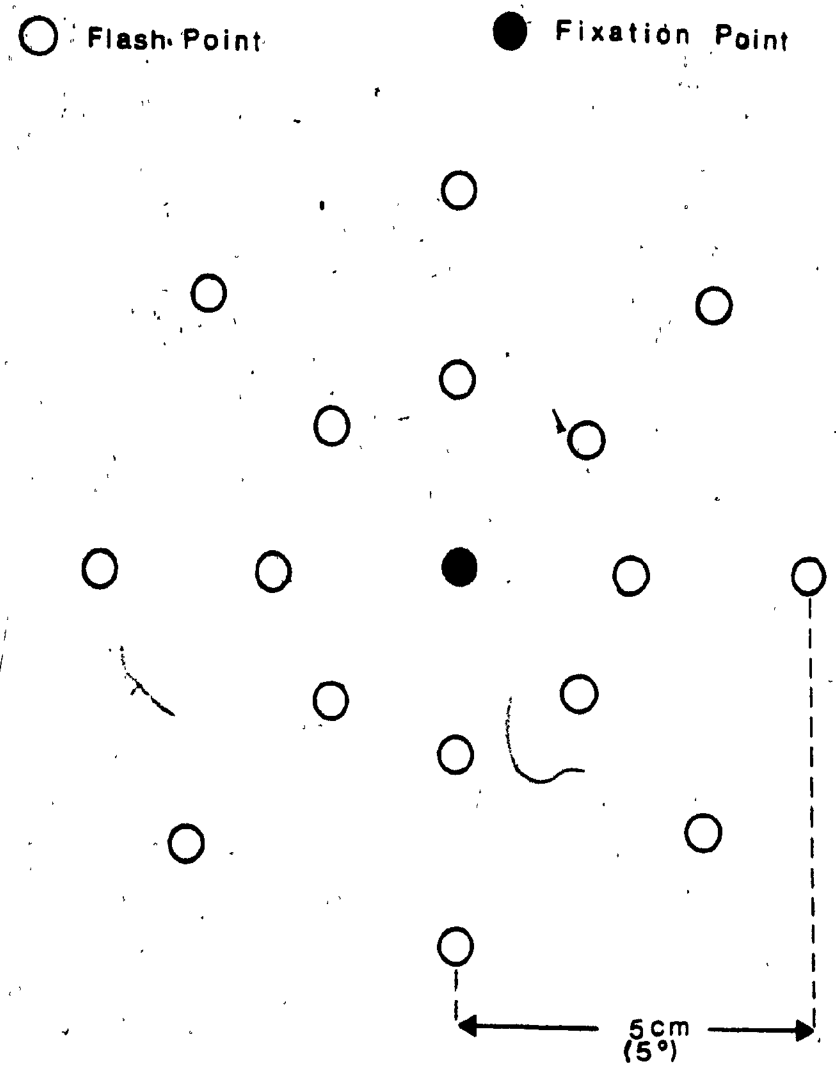

Figure 2. The full stimulus array: Fixation point and all flash points.

threshold, that is, too brief to be detected. On the next trial the I.S.I was increased by 4 ms, and the trials were continued until the subject reported the presence of the two flashes. This procedure was then repeated using the next point, going clockwise around the 2.5 degree circle. This went on until it was decided that a reliable threshold could be estimated, and the subject felt comfortable with the task. The average of all detected ISIs was taken as an estimated threshold, to be used in determining the starting point in the experiment proper.

During the actual experiment the threshold was assessed using 16 randomized staircases (Cornsweet, 1962), one for each retinal location. For each staircase the method was as follows: the first ISI was either eight ms above or below the threshold estimated during practice. If the subject produced a "YES" or "SAW IT" response, by pressing one of two response keys, the next ISI was four ms shorter, therefore harder to see. Had the response been "NO" the next ISI was four ms longer. The third ISI was shorter if the second response was "YES" and longer if the second response was "NO". Thus each ISI was either four ms longer or shorter than the previous one based on the response to that previous ISI. Data from this method tends to home in on the subject's threshold. (See Figure 3 for a single staircase example.)

The subject may have made several "YES" responses in succession, followed by a "NO" response. Upon the "NO" response the direction of change of the ISI reversed, it went from getting shorter to growing longer. Upon the next "YES" response there was another reversal. The staircase procedure continued until five

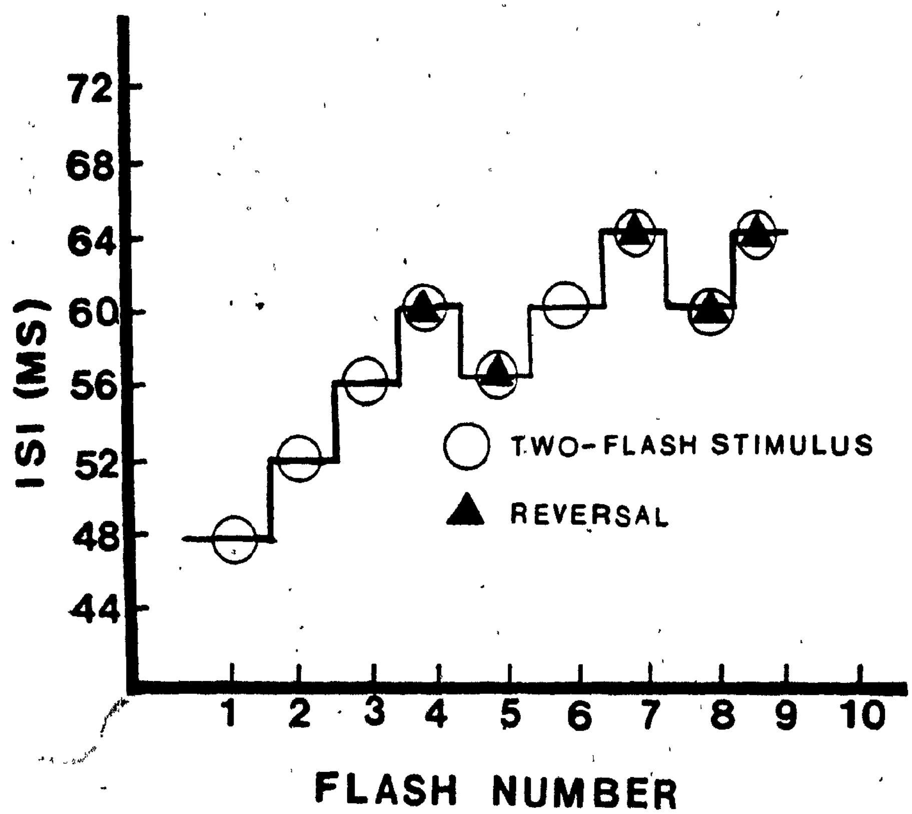

Figure 3. A single staircase example of the staircase method.

such reversals occured.

A single staircase example is diagrammed in Figure 3. With an estimated threshold of 56 ms the first flash appeared with a 48 ms ISI. Suppose this flash was not detected, nor were flashes at 52 or 56 ms. At 60 ms the flash was seen, and the direction of change reversed. The next flash, at 56 ms, was missed so the direction was reversed again. Further reversals occured at 64, 60 and 64 ms. The average of all five reversals, 60.8 ms, would be taken as the subject's "two-flash threshold".

In the above example five reversals occured within nine flashes. If it is assumed that this is an average number of flashes, for all 16 points there were 144 flashes. All 144 flashes occured in random order, with the obvious exception that the absolute order of each set of nine flashes was preserved. This means that it was virtually impossible for the subject to predict the ISI of any given flash.

In order for the stated location of the flash to correspond to its retinal location it was necessary to ensure that fixation was maintained on the fixation point. The importance of maintaining fixation was stressed to each subject, and before true data collection could begin all reported that fixation was easy to maintain. To test fixation subjects were exposed to an array of 30 points, each flashed in random order. One point was located such that, with the left eye occluded and if fixation was maintained, that point fell in the blind spot. The subjects consistently failed to see that point flash while seeing all the others. It was concluded that subjects were capable of maintaining fixation throughout the experiment and that, since the importance of it was understood, subjects did so.

The subjects spent, in total, between 80 and 120 hours seated 57 cm from a CRT with their heads supported by a chin rest. Light adaptation was maintained throughout each testing session with the presentation of ambient light to the peripheral visual field. The luminance of this adapting light ranged from 7.95 to 5.58 cd/m^2 across the central 50 by 50 degree visual field. Since the filters were sufficiently distant from the eye that ambient illumination could scatter across the entire visual field, it is argued that different filter levels did not result in any state other than light adaptation. Even under the highest filter level, the filtered eye was not dark adapted.

Results

Data Analysis Procedures

The average of all the reversals is the conventional measure of threshold when using the staircase procedure. This yields a point corresponding to approximately a 50% detection probability. Such averages were obtained for each session, such that the filtered eye and the binocular "eye" both had one averaged threshold for each filter level. The unchanging eye had one overall average, for the 1.0 N.D. filter level.

However, to test the prediction of the probability summation model, the prediction being that the binocular threshold is described by the probability summation of the two independent monocular thresholds, a different form of analysis was required.

The probability summation of C and D, expressed mathematically, is unity minus the product of qC times qD, where qC and qD indicate unity minus the probabitiy of C and D, respectively. In our terms, the probability summation of two eyes is unity minus the product of the probability of the right eye not seeing the flash times the probability of the left eye not seeing the flash. This is expressed mathematically as:

$$pB = 1 - (qC \times qD)$$

where PB is the probablistically determined binocular detection probability, that is, the probability summation of C and D.

To use this equation detection probabilities, and not thresholds, are required. The threshold is defined as the 50% detection probability, so the object is to find the 50% point predicted by probability summation and compare it with the obtained binocular threshold. To do this one must first express the two monocular thresholds in terms of detection probabilities.

Rather than taking the average of the five reversals, a table of how often each ISI was detected and missed was produced (see Table 1). To illustrate how this table was produced, consider the single staircase example illustrated in Figure 2. The reversals occured at 60, 56, 64, 60, and 64 ms. Since the second reversal was lower than the first, it can be concluded that the first flash was below 60 ms. (At 60 ms. the direction of ISI change reversed. Since it was going down after the reversal it must have been coming up before the reversal.) Therefore at 60 ms the subject saw the flash, and at 56 ms the flash was missed. It was also missed at 60 and seen at 64 ms. Finally the flash was missed at 60 and seen at 64 ms.

In summary, at 56 ms the flash was presented once and missed once. At 60 ms there were three presentations, only one of which was seen, at 64 ms both were seen. This was done for all 16 staircases to produce one table. Such tables were combined within each monocular session. Finally the table was converted to show the detection probability and number of presentations at each ISI (see Table 1).

The next step was to summate probabilistically the right and left eye detection probabilities for each ISI and obtain, by regression, the ISI at which the summated detection probability

Table 1

Examples of Detection Probability Calculation

One Retinal Location			One Retinal Location		
ISI	"SAW"	"MISSED"	ISI	Number of Presentations	Detection Probability
64	2	0	64	2	1.00
60	1	2	60	3	0.33
56	0	1	56	1	0.00

Collapsed Across Sixteen Retinal Locations

ISI	Number of Presentations	Detection Probability
68	2	1.00
64	6	0.67
60	9	0.55
56	17	0.53
52	10	0.50
48	4	0.25
44	1	0.00

was 50%. There are two problems with this approach, however. First, one cannot be equally confident in the accuracy of the detection probabilities for all ISIs; some were based on one presentation, some on hundreds. The solution adopted was to conduct a weighted regression analysis, with each ISI's weight being determined by the number of presentations at that duration. (See Appendix A for a discussion of weighted regression.)

The second problem deals with curve fitting. One would expect a graph of ISI against detection probability to be described by an ogive, as are most similar psychophysical functions. A near ogive was found in most of the actual (as opposed to probabilistically predicted) data, but with a fair amount of scatter. One would not expect the predicted data to be ogive shaped (see Appendix C), but rather a more complex shape. A straight line function would best be handled by linear regression, an ogive by a linear or quadratic function. It is a problem, then, to decide between linear, quadratic or even higher order regression. The solution is to do a trend analysis to determine the relative strengths of the linear, quadratic and higher order components, as discussed in appendix B. The highest order component to be statistically significant, at an alpha level of .05, determined the order of the function assumed to best fit the data, and was therefore used in the regression analysis. In the event that none of the components were statistically significant, the one that obtained the highest F ratio determined the order of the regression analysis.

To test the validity of this approach the regression predicted 50% point was determined for all of the actual data, that is, the data on which the conventional method had already been applied. These regression determined points were shown to be close to the conventionally determined thresholds found for the same data (see Appendix A). Since one can be fairly sure of the validity of the conventional, staircase determined thresholds, and the regression method yielded similar results for the actual data, one would expect the regression predicted 50% points to be equally valid when derived from probabilistically predicted data.

There was one case in which the regression approach was abandoned. At the higher filter levels it sometimes occured that for each ISI presented during the steadily filtered condition the corresponding detection probability at that ISI for the variably filtered condition was zero (see Figures C3 and C6). That is, the ISI that was the easiest to detect with a steady (1.0) filter level was never detected with a denser filter. Thus, for every ISI for which this occurred, the calculation involved summating the steady filter detection probability with a zero probability for the variably filtered condition. Since the probability summation of probability "a" and zero equals probability "a", in these cases the probability summation predicted probabilities were identical to the steadily filtered monocular probabilities. The best estimate of the probability summation threshold in this case, then, is not determined by the regression method but by the mean of the reversals from which the steadily filtered probabilities were derived. In these cases performance should be determined by the most sensitive eye alone, and thus the conventional method of means was used on this monocular data to determine the probability summation predicted thresholds.

A further potential problem concerns the possibility of shifts in subject criteria influencing the data. Such criterion shifts can be divided into three categories: those occuring within sessions, those occuring within days (i.e., between sessions), and those occuring between days. Within session shifts should have no systematic effect on the pattern of the data, due to the randomized nature of the staircase procedure. For potential between session shifts, it was found in pilot work that the only shift of this kind involved thresholds being higher in the second of a pair of sessions than in the first. To control for this effect each session occured once in the first and once in the second position of a pair of sessions. Pilot work indicated that the hour break between each pair of sessions proved enough to eliminate the effect of this shift, such that the first session after each break was effectively the same condition as the first session of each day.

Between days shifts presented the next potentially serious problem. Each day at least one unchanging filter level eye was run, so that at least one of a series of nearly identical conditions was run each day. In the absence of between days criterion shifts one would expect the only difference between thresholds from these conditions to be due to between session shifts; thresholds from the second half of a pair of sessions would be higher than those from the first half. While between session shifts have been controlled for by collapsing first and second session data, only after the effects of these shifts have been eliminated, that is, only when the mean of the first session thresholds equals the mean of the second session thresholds, can this data be used to indicate the between days shifts.

The effects of between session shifts were eliminated, not only from the unchanging filter data, but from all of the data in this experiment. The average of all unchanging filter level data from the first sessions was subtracted from that from the second sessions. The result represented the average effect of the between sessions criterion shift. This effect was eliminated from all the data by adding half of this result to all first session data and subtracting the same amount from all second session data. Not only did this correct all of the data for between sessions shifts, but it also eliminated the only non-between days effects from the unchanging filter data.

The magnitude of a between days shift could now be detected in the unchanging filter data. Should the unchanging eye's threshold be 2.5 ms lower for day three than for the average day, this can be taken as the extent to which day three's criterion is different from the average criterion. This difference in criterion should affect all thresholds measured that day by about 2.5 ms. Thus, to correct day three's thresholds for day three's different criterion, 2.5 ms would be added to each threshold gathered that day.

To correct for between days shifts, the average (or only) unchanging filter threshold for each day was subtracted from the overall unchanging filter average. The result of this subtraction is a measure of how much that day's criterion moved that day's threshold below the average day's threshold. This difference was added to all the filtered data for that day, eliminating the effect of between days criterion shifts. Therefore, of the three types of criterion shifts, within session shifts were controlled, between days shifts were corrected, and within days-between session shifts were both controlled and corrected. Table 2 displays some uncorrected and corrected thresholds for subject MZ. Note that the magnitude of the correction rarely exceeded 4 ms, so the criterion shift problem discussed above was not serious, and that the correction procedure has not greatly changed the configuration of the data.

Table 2

Corrected versus Uncorrected Data

Right Eye			Binocular		
Filter Level	Uncorrected Threshold	Corrected Threshold	Filter Level	Uncorrected Threshold	Corrected Threshold
1.0	79.85	83.91	1.0	71.18	73.71
1.1	81.58	82.74	1.1	79.13	74.47
1.2	95.08	93.46	1.2	73.90	73.71
1.3	93.60	96.86	1.3	75.73	79.31
1.4	101.20	101.05	1.4	68.78	77.15
1.5	100.95	105.59	1.5	73.45	77.00
1.6	108.45	105.61	1.6	69.93	72.81
1.7	139.10	135.26	1.7	73.75	74.91
1.8	120.10	118.71	1.8	76.08	78.93
1.9	106.35	108.52	1.9	85.95	83.69
2.0	114.63	119.92	2.0	86.00	88.02
2.2	156.45	158.19	2.2	75.10	72.92
2.4	198.80	200.13	2.4	72.25	72.34

Data Presentation

Each subject performed the experiment twice; once with the left eye under the unchanging filter condition, and once with the right eye under that condition. There are then six sets of data, each set consisting of: a) a monocular threshold for the unchanging filter eye, b) a series of monocular thresholds for the other, changing, filter eye, one for each filter level, c) a series of binocular thresholds, one for each filter level, and d) a series of thresholds predicted by probability summation, one for each filter level. The probabality summation thresholds are produced from the two monocular data sets, and are predictions of what the binocular data set would be, given that the visual system operates as assumed by the probability summation model.

Table 3 contains the averaged data for all six sets, and Figure 4 displays the data graphically. The equivalent tables for individual subjects are found in Appendix E. The standard errors are the standard errors of mean of the reversals from which the thresholds were derived, in most cases this means 960 reversals. Multiple T tests were performed to see where the monocular steadily filtered threshold differed significantly from any other threshold. The alpha level was set at .01 for each set of 13 comparisons. Any binocular threshold marked by an asterisk is significantly lower than the steadily filtered eye's threshold, and thus shows a binocular advantage, and any variably filtered monocular threshold marked by an asterisk is significantly higher than the steadily filtered eye's threshold. The binocular data marked by daggers is significantly higher than the steadily filtered monocular data, that is, the dagger marks a binocular disadvantage. There are no comparisons made with the predicted data, as this data does not yield a comparable variance.

As is seen most clearly in Figure 4, the effect of increasing the filter level on the monocular threshold is to raise that threshold. This is not surprising in view of the similar rise found by Thomas (1954) in flicker fusion thresholds, and Ireland (1950), and Boynton (1961) both referred to such a rise. The effect of increasing one of two monocular filter levels on the binocular threshold is to raise that threshold, but in a much less pronounced manner. Up to a 1.5 N.D. filter level there is found a significant binocular advantage. This is most easily seen in Table 4, and is confirmed by a linear regression of the binocular data in that table, which shows that at a filter level of 2.00 the binocular threshold equals 65.35, the steadily filtered monocular threshold. At filter levels above 1.8 a binocular disadvantage begins to be seen, and this disadvantage reaches significance at the 2.4 filter level.

The probability summation prediction of the binocular data is clearly inaccurate; the predicted thresholds are far too low. Only at the high filter levels, where both the binocular and the predicted thresholds approach the steadily filtered threshold, are the two sets of thresholds similar (see Table 5 and Figure 4). If the binocular thresholds are a function of the two monocular thresholds, the function is not one of probability summation.

Table 3

Thresholds Collapsed Over all Six Data Sets

Steadily Filtered Eye			Variably Filtered Eye		
Filter Level	Threshold	S.E.	Filter Level	Threshold	S.E.
1.0	65.35	0.160	1.0	64.95	0.568
			1.1	67.49	0.569
			1.2	66.58	0.571
			1.3	75.37*	0.661
			1.4	75.65*	0.666
			1.5	78.32*	0.714
			1.6	85.09*	0.866
			1.7	89.02*	0.966
			1.8	89.21*	0.971
			1.9	89.75*	0.985
			2.0	99.86*	1.267
			2.2	133.42*	2.292
			2.4	151.25*	1.599

Binocular			Probability Summation	
Filter Level	Threshold	S.E.	Filter Level	Threshold
1.0	57.18*	0.402	1.0	46.69
1.1	57.41*	0.402	1.1	49.02
1.2	59.01*	0.407	1.2	47.21
1.3	62.10*	0.433	1.3	53.55
1.4	58.57*	0.405	1.4	50.24
1.5	61.03*	0.421	1.5	52.09
1.6	62.98	0.444	1.6	52.11
1.7	63.07	0.445	1.7	55.26
1.8	64.21	0.463	1.8	51.65
1.9	66.98	0.513	1.9	54.82
2.0	65.37	0.482	2.0	57.21
2.2	63.71	0.455	2.2	65.09
2.4	69.45†	0.381	2.4	64.41

* For the variably filtered eye, this indicates significance above the unchanging eye.
For the binocular condition this represents significance below the unchanging eye.
† This represents significance above the unchanging eye.

The 2.4 filter level threshold averages were calculated using only data from subjects A.M. and M.Z., subject D.L. was not tested at a 2.4 filter level.

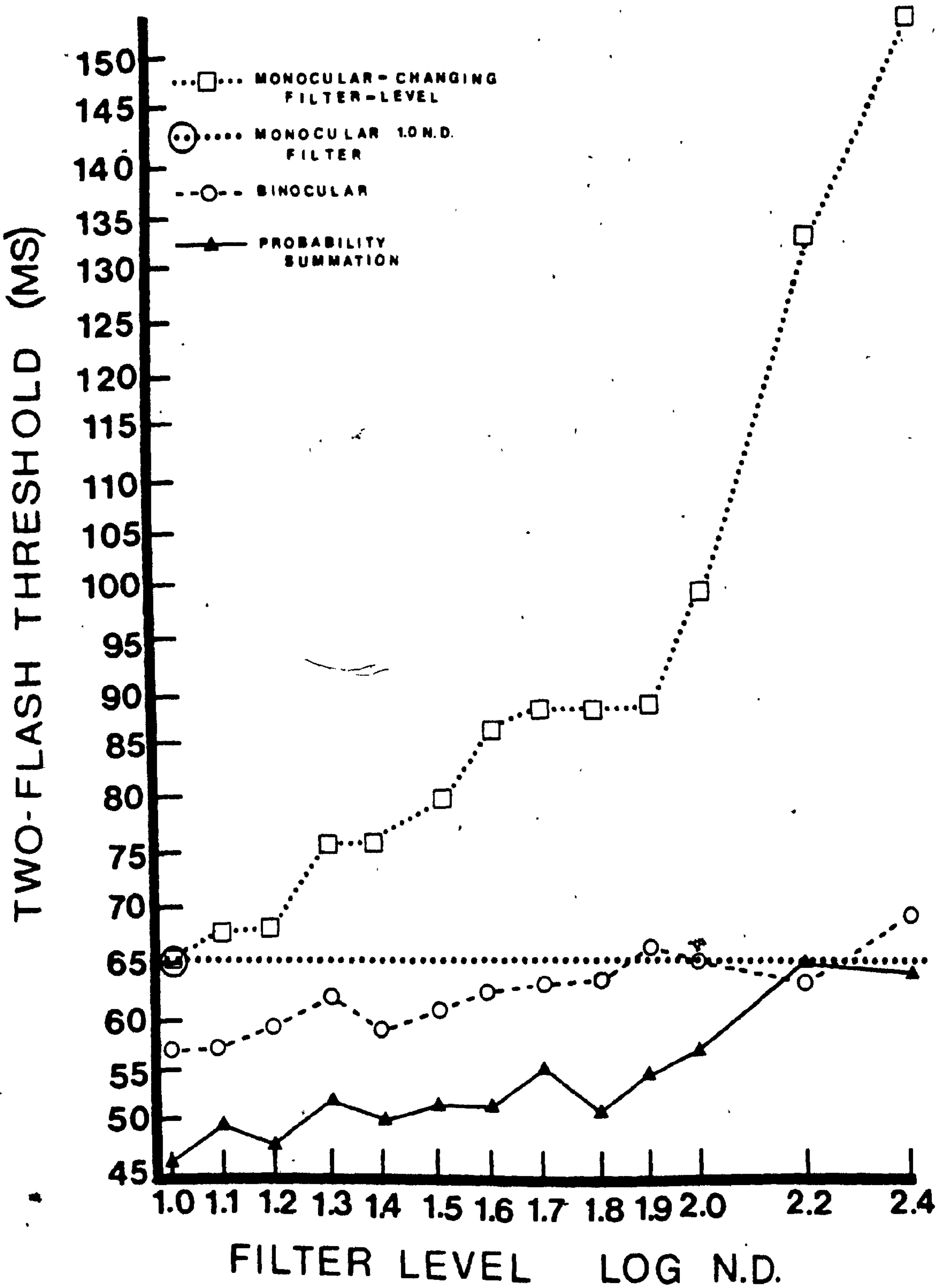

Figure 4. The mean thresholds for the monocular, binocular and predicted data.

Table 4

Binocular Versus Monocular Thresholds

Filter Level	Highest Monocular Threshold Minus Binocular Threshold (ms)
1.0	7.77
1.1	7.94
1.2	6.34
1.3	3.25
1.4	6.78
1.5	4.32
1.6	2.37
1.7	2.28
1.8	1.14
1.9	-1.63
2.0	-0.02
2.2	1.64
2.4	-4.10

Table 5

Predicted Versus Actual Binocular Data

Filter Level	Actual Threshold Minus Predicted Threshold (ms)
1.0	10.49
1.1	8.39
1.2	11.80
1.3	8.55
1.4	8.33
1.5	8.94
1.6	10.87
1.7	7.81
1.8	12.56
1.9	12.16
2.0	8.16
2.2	-1.38
2.4	5.04

It should be remembered that the threshold is the point of 50% detection probability; that there are many other points of potential interest. A detection probability by ISI plot of the binocular data and that predicted by probability summation is found in Figure 5. This is data for the 1.0, that is equal, filter level. As well as the correction procedures discussed above, the data was corrected such that intersubject variance was eliminated. For each subject the mean deviation from the overall average was obtained, and this amount was subtracted from each data point. After this was done each subject's mean was the same as the grand mean over all the subjects. Had this not been done the true shape of the functions would have been obscured by the intersubject variance. The bulk of the graph shows binocular performance inferior to that predicted by probability summation, only at the high end of the graph is this pattern reversed.

There have been three main aspects to the results presented above. The first is that the monocular two-flash threshold is a function of the luminance of the flashes. The second is that the binocular thresholds are superior to the monocular thresholds at the lower luminance disparity levels, and inferior at the higher levels. Finally, the binocular superiority at the lower disparity levels is not as great as would be predicted by the probability summation model.

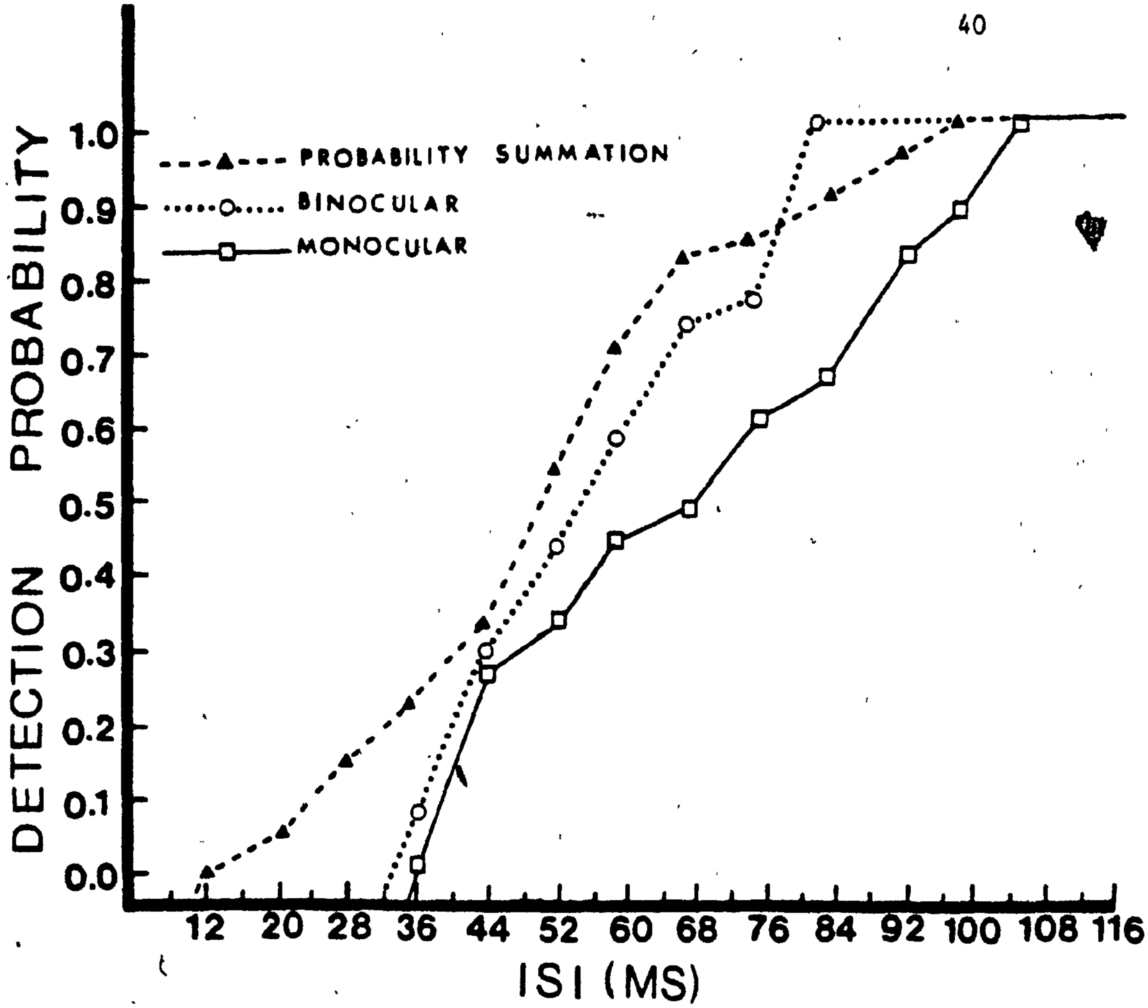

Figure 5. The detection probability by I.S.I. plot for equal luminance data.

Discussion

There is an obvious similarity between the data presented above and that of Thomas (1954) who studied, using dark adapted subjects and relatively large stimuli, flicker resolution under conditions of binocular luminance disparity. Recall that Thomas found a binocular advantage in flicker resolution when the luminance disparity was less than 0.25 log units, and a binocular disadvantage thereafter. In the data presented here the binocular advantage remained up to a 0.8 luminance disparity, and started to become a disadvantage thereafter. Thomas was able to trace the disadvantage up to a luminance disparity of four log units, whereas here the standard error became prohibitively high after the 1.4 log unit disparity level, thus lowering the ceiling.

This difference is probably not due to the fact that Thomas dark adapted his subjects; pilot work for the current research indicated that dark adaptation increases the standard error. Nor is it suspected that the difference is exclusively due to the difference between flicker and two-flash thresholds. It is true that flicker is easier than a two-flash stimulus to detect (Roufs, 1972), so flicker can be expected to be detectable under more adverse conditions (e.g., greater binocular luminance disparity). However, it is suggested that the difference is also due to the larger size of Thomas's stimuli; 6 and 2.2 degrees of visual angle as opposed to the 0.25 degree stimilus used here. It is known that the detectability of flicker increases with the size of the flickering target (Brown, 1965). Thomas was able to measure temporal resolution at higher luminance disparities, that is, using more dimly illuminated stimuli, because his stimuli were larger and, being flicker stimuli, easier to detect under these conditions.

Overall, there is general agreement between the two studies, that at low luminance disparities a binocular advantage is found, and at high luminance disparities binocular temporal resolution is poorer than the best of the two monocular resolutions. The binocular advantage at the lower luminance levels will be discussed first. Consider the results of this study compared specifically to those of Peckham and Hart (1960). These researchers conducted an equal luminance binocular flicker detection experiment, and reported their findings in terms of a detection probability at each flicker frequency. They also tested the predictive validity of the probability summation model. The only important similarity between Peckham and Hart's findings and those presented here is the size of the binocular advantage over the monocular threshold; Peckham and Hart found an 8% advantage while a 12% advantage was found here. While Peckham and Hart's advantage is slightly smaller, both are near the values found by other researchers, as discussed in the Introduction. However, whereas Peckham and Hart found a binocular advantage in excess of probability summation in flicker perception, here the reverse was found for two-flash thresholds.

The cause of this difference is unknown. It could be a difference inherent between two-flash and flicker paradigms, or it could be due to Peckham and Hart's very low contrast stimulus (5%). For this reason it would be especially interesting to investigate more closely the nature of the current results concerning probability summation. It is clear that the model does not fit the data but the extent of the non-fit is difficult to express in terms applicable to other areas where probability summation is also used.

An equation, taken from the standard probability summation equation but adjusted to allow the expression of binocular performance diverging from probability summation, is derived in Appendix D. The equation is:

$$B = 1 - (1 - pR)^F * (1 - pL)^F$$

where B is the predicted binocular detection probability, pL and pR are the obtained right and left detection probabilities, and F is the summation factor. When F equals one the equation is equivalent to the standard probability summation equation:

$$B = 1 - (1 - pR) * (1 - pL)$$

When F is greater than one this represents summation in excess of probability summation, and when F is less than one this represents summation less than probability. Thus F is an indication of how well the probability summation model fits the data and, more importantly, the equation can also be used to decribe the data mathematically. The right and left eye detection probabilities were entered into the equation, and F was changed until the resulting B was reasonably close to the actual binocular data. When F was set to 0.67, indicating summation well below that predicted by probability summation, the data predicted using the F fitted the actual data, except for the higher filter levels, fairly well (see Table 6 and Appendix F).

When the F in the above equation is changed to 0.67, the equation becomes a combinatorial rule for the binocular integration of two-flash information. That the combinatorial rule is a good predictor of the data up to the high filter levels is seen in Table 6. This equation is not meant to describe the neural integration of the right and left eye signals, but to describe this relationship mathematically. This equation should also be able to predict the binocular two-flash thresholds in future experiments, given knowledge of the monocular performances.

Now that the lower luminance binocular advantage has been described mathematically, an attempt will be made to explain the findings. That the binocular advantage is less than that predicted by probability summation might be explained by visual persistence and delay being induced in the more densely filtered eye. Delay refers to the filter induced increase in latency between the onset, or offset, of the stimulus and its effect on the visual system. Persistence refers to the perception of the stimulus outlasting the duration of the stimulus.

The argument is that due to filter-induced differential delay or persistence the binocular image is comprised of two temporally incongruous monocular luminance distributions. The delay effect is to shift the densely filtered eye's luminance distribution some amount out of phase from the other eye's distribution. Persistence, in effect, lengthens the duration of the first flash (see Figure 1), and correspondingly shortens the ISI needed to

Table 6

Predicted Binocular Data - Summation Factor of 0.67

Collapsed over all Six Data Sets

Filter Level	Obtained Binocular Thresholds	Predicted Thresholds	Obtained Minus Predicted
1.0	57.18	55.76	1.42
1.1	57.41	58.54	-1.13
1.2	59.01	57.21	1.80
1.3	62.10	64.05	-1.95
1.4	58.57	61.68	-3.11
1.5	61.03	64.96	-3.93
1.6	62.98	66.21	-3.23
1.7	63.07	67.22	-4.15
1.8	64.21	65.45	-1.24
1.9	66.98	65.42	1.56
2.0	65.37	66.40	-1.03
2.2	63.71	71.16	-7.45
2.4	69.45	81.33	-11.88

resolve the two flashes. If this occurs in the densely filtered eye the binocular threshold would be effected. In both the persistence and the delay cases it could be argued that the decrease in brightness per se is not the cause of the binocular loss of sensitivity with increasing filter level, but that the stimulus incongruity is.

The differential delay or persistence that a 1.4 log unit difference in luminance would produce can be ascertained from many studies. Bowen, Pola, and Matin (1974) tested luminance induced delay in the onset and offset of flashes, and found that, with a 1.4 N.D. filter, an approximately 11 ms onset delay and an approximately 43 ms offset delay would be expected. Bowen et al. used dark adapted subjects; this fact may limit the applicability of these findings to the current study. Using light adapted subjects Dodwell (1968) studied the filter-induced delay indirectly in the Pulfrich effect, and an examination of his data revealed that a 1.4 log unit disparity in luminance would cause the more densely filtered eye to finish processing approximately 9.3 ms later than the other eye. The cause of the difference in findings between Bowen et al. and Dodwell could be due to the different adaptation levels or to the tasks used. There seem to be no studies in the literature that estimate persistence or delay in a way directly applicable to the present study. Instead, the ability of the persistence and the delay hypotheses to account for these findings and those of other researchers must be investigated.

The effect of delay under conditions of luminance disparity would be to shift backward in time one of the two luminance distributions (see Figure 1). Thus the first flash would affect the densely filtered eye while the off period of the ISI is affecting the other eye. There would still be an interval during which both eyes would be exposed to the off period, but this interval would become shorter as the delay becomes greater. Thus delay could be used to explain the binocular loss of sensitivity as the binocular disparity, and with it the differential delay, becomes greater. For the monocular threshold, however, the delay hypothesis per se predicts no effect as luminance is decreased. The entire luminance distribution would be delayed, so one would expect the same two-flash threshold, merely somewhat later. For this hypothesis to work it must call upon a luminance effect to explain the rise in the monocular threshold as the luminance decreases.

Visual persistence, however, cannot explain the binocular departure from probibility summation at all. Persistence would affect the monocular threshold by effectively decreasing the size of the off period, and as the luminance decreases the persistence increases (Bowen et al. 1974), so this effect would be greatest at the highest filter levels. However, the effect on the binocular threshold of monocular persistence, and therefore a poorer monocular threshold, would be a poorer binocular threshold. There is no reason for the loss in binocular sensitivity to be other than would be predicted by probability summation, and thus persistence cannot explain the departure of the binocular data from probability summation.

Delay cannot explain the monocular data at all, and persistence cannot account for the binocular departure from probability summation. This does not imply, however, that delay or both delay and persistence is not at play in the binocular case. Indeed, since delay works to decrease sensitivity it may partly explain the fact that the binocular advantage at the lower luminance levels is less than would be expected from probability summation. Differential delay, however, is induced by differential luminances, so an explanation based on delay would predict that the extent of the departure from probability summation would decrease along with decreasing luminance disparity, such that at equal luminance probability summation would accurately describe the data. That this is not the case indicates that some factor other than delay is in effect. We lack, at the moment, the information necessary to determine what this factor is, but we can still gain some general knowledge of binocular two-flash thresholds by examining the posible explanations for the binocular disadvantage at the high filter levels.

Delay can also explain the binocular disadvantage. The disadvantage could be seen as the continuation of the loss in sensitivity as the filter level is increased, caused by delay. This would not explain, however, why the combinatorial rule breaks down at the higher filter levels. While delay may well be a factor in the binocular disadvantage, there is another factor also involved.

Consider Thomas's explanation for the binocular disadvantage at the high filter levels. It assumes that the lower luminance eye was, in effect, viewing a steady light, and it has been shown that viewing a steady light with one eye lowers the temporal resolution of the other eye (Vernon, 1934). This explanation is equally valid for the current research involving two-flash thresholds. An unresolved two-flash stimulus appears to be a steady light, in the case of the present study, from the end of the warning signal onward (see Figure 1). Therefore, at the higher filter levels, while one eye was viewing a two-flash stimulus, the other eye was effectively viewing a steady light. It can be concluded, then, that a binocular disadvantage occurs when the eyes receive grossly unequal luminances and it can be further concluded that the cause of this disadvantage is the effectively steady light seen by the densely filtered eye.

It is at these high filter levels that the equation presented above breaks down. It is also at the high filter levels that the binocular advantage disappears and a binocular disadvantage is found. This is most easily explained by the partial suppression of the densely filtered eye. The equation does not work at this level because it is assigning, in effect, equal weights to the two eyes; when the densely filtered eye is being partially suppressed its actual weight is reduced. In order for the equation to work it would have to assign less weight to the densely filtered eye. Notice too that the direction of the inaccuracy of the predicted thresholds at the higher filter levels is to predict too high a threshold, that is, too close to the threshold of the densely filtered eye alone. This is what one would expect given that the densely filtered eye was being somewhat suppressed. It can be concluded that at the higher filter levels the weight of the densely filtered eye is being reduced, that is, that eye is being, to some extent, suppressed. Why this is the case is also of interest.

That this loss of weight is not total is demonstrated by the binocular disadvantage at the highest filter level. The densely filtered eye has enough weight to contribute to the binocular percept, but the contribution has the effect of decreasing sensitivity. This is a temporal version of Fechner's Paradox, that two eyes can be less sensitive than one. This explanation is compatible with Thomas's (1954) explanation of the binocular disadvantage, and is supported by Vernon's (1934) finding that the brighter is the steady light in one eye's visual field, the worse will be the temporal resolution of the other eye. Levelt (1965), who investigated Fechner's Paradox in a steady-state binocular brightness paradigm, has shown that the weight is determined only by the contour and contrast in each eye's visual field. Thomas (1956) showed that contours play a part in temporal resolution too. From the data reported here, however, we have evidence that at least one factor besides contour and contrast is invloved in determining each eye's weight in a two-flash paradigm: luminance per se. It is argued that this is not a disguised contrast effect. Although different filter levels were used, the effect of a dense filter was to darken both the flashing dot and its surround by about the same factor; the contrast remained more or less constant. Since it was not the effect of a difference in contrast, it was the large disparity in luminance that caused the weights to change. Thus in binocular two-flash resolution luminance seems to be an important factor in determining the weight of each eye's contribition to the binocular temporal resolution, and thus luminance performs a function analogous to that performed by contour and contrast in binocular brightness perception.

There are some potential objections to the methodology used in this research which, if not answered, could call into question the validity of the data and therefore the conclusions arrived at. The first concerns the use of the probability summation equation to predict the binocular data given the assumption of independence between two monocular detectors. Variants of this objection have been raised by Guth (1971) and by Thorn and Boynton (1974). In essence, there are two conditions which must be met for the equation to be applicable.

First, the responses to all stimulus intensities in the testing session must be mutually independent, i.e., the response to one intensity must not systematically influence the response to another intensity, and therefore studies using the staircase technique should not also use the probability summation model. In the single staircase method, for example, it often happens that the probability of detecting a stimulus at intensity "x" is partly determined by the response to the previously presented intensity.

Subjects are more likely to report seeing stimulus number "s + 1" if they reported seeing stimulus number "s". In a single staircase paradigm a stimulus that elicited a "saw it" response is always followed by a stimulus of a one step lower intensity. So the obtained detectability at intensity "i" influences the obtained detectability at intensity "i - 1", and therefore there is no mutual independence.

This argument does not apply to the current study, however, due to the use of the multiple staircase procedure. With 16 randomized staircases operating simultaneously the intensity, or ISI, of a given stimulus is not determined by the response to its immediate predecessor, but by the response to a stimulus, on average, 16 trials earlier. Thus stimuli are presented in virtually random order and the response to a given stimulus was not systematically affected by any factor other than the intensity of that stimulus. The obtained detectability of each ISI is not influenced by the obtained detectability at any other ISI. All ISIs are mutually independent.

The second condition that must be met is that there be no, or very little, variance in sensitivity while the various thresholds are being measured. As discussed in the Results section the effects of most unwanted variance was removed by the correction factors, leaving only variance within individual sessions. Such variance is shown in the standard errors of the individual subject data tables in Appendix E. These standard errors are generally fairly small, and this fact is more impressive when it is realized that the standard errors are artificially inflated. The explanation of this inflation is as follows: with absolutely no variance in sensitivity a single five reversal staircase procedure with a 4 ms unit of resolution would yield a standard error of 0.98. Reversals could have occurred at 56, 60, 56, 60 and 56 ms, and the standard error of these numbers is 0.98. If in both of the 16 five reversal staircase procedures that went into each entry in Appendix E there were reversals only at 56 and 60 ms, the standard error would be 0.16. Thus it can be concluded that there was little variance within sessions, all other variance was removed, so the condition of no or little variance was met. The probability summation model is applicable in the present study.

Another potential problem, this one of a different nature, deals with binocular fixation; that the way the data were collected may have allowed a loss of fixation to be a confounding variable. At the lower luminance levels the fixation point was easily detectable in both eyes, and can be assumed to have fallen on the fovea of each eye. We can therefore be sure that corresponding retinal locations were being stimulated by the flash points. At the higher filter levels, however, the more densely filtered eye may have had trouble maintaining fixation. With this wandering fixation in one eye the flash points, at times, might have been effectively presented to non-corresponding retinal locations in the two eyes. Wandering fixation at the high filter levels may be responsible for the rise in the binocular threshold. With wandering fixation the two flashes would have been presented to two non-corresponding retinal locations, and Thorn and Boynton

(1974) have asserted that this lowers the binocular threshold. This was tested in two ways. First, the third subject, MZ, was run with holes in the centre of the filters. The holes allowed a totally unfiltered view of the fixation point while not affecting any of the flashed points. With this method fixation should not have been affected at all by different filter levels. As can be seen in the data tables in appendicies E and F, MZ's results do not differ from the other subject's results in any way that could indicate that the other subjects were having fixation trouble.

As a more direct test, all three subjects went through both the hole and the no hole procedure for a low (1.0) and a high (1.9) filter level, all in the binocular condition. In the absence of a wandering fixation effect one would expect higher thresholds in the 1.9 filter condition and no difference between the hole and no hole conditions. Wandering fixation would be expected to raise the threshold in the 1.9 filter level no hole condition. The results (see Table 7) show virtually no difference between the hole and no-hole conditions, but a large difference between the 1.0 and 1.9 filter level conditions. This was confirmed by an analysis of variance, which showed a filter level effect significant to the .001 level, and no hole effect or interaction effect. The conclusion is that there was no wandering fixation for any of the subjects, and the flash points always fell on corresponding retinal locations.

For these reasons we can be confident in the validity of the data presented above. First, there is a decrease in monocular temporal resolution as the stimulus becomes less intense. Second, the data show a binocular superiority over monocular two-flash thresholds for all but the highest luminance disparities, but this superiority is not as large as is predicted by the probability summation model. This may be due to a loss of sensitivity caused by filter-induced delay and persistence. The third is that a model that does predict the data well, except under conditions of high luminance disparity, is:

$$B = 1 - (1 - pR)^{0.67} * (1 - pL)^{0.67}$$

where B represents the predicted binocular detection probability, and pR and pL represent the right and left eye detection probabilities. The reason that this model does not fit the data under conditions of high luminance disparity is best explained by luminance-dependent changes in the weightings of each eye that the model does not take into account. The fourth conclusion, then, is that in two-flash resolution, luminance is a determinant of weighting. Finally, at the high luminance disparities a binocular disadvantage is found. The densely filtered eye has been partly suppressed, but not enough to prevent the effectively steady light it is perceiving from lowering the two-flash threshold of the other eye.

In summary, a two-flash version of Thomas's binocular disadvantage was found and is interpreted to be due to a luminance-disparity induced weighting effect. A mathematical model describing the binocular integration of two-flash information, accounting for this disadvantage, was produced.

Table 7

Hole Versus No-Hole Two-Flash Thresholds
and Analysis of Variance

Thresholds (ms)

Filter Level	Hole	No-Hole	
1.0	61.00	59.96	60.48
1.9	69.00	67.78	68.39
	65.00	63.87	

Analysis of Variance

Source	SS	df	MS	F
Hole	7.593	1	7.593	.330
Level	375.250	1	375.250	16.313*
Hole x Level	.050	1	.050	.002
Error	460.041	20	23.002	

* $p < .001$

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APPENDIX A

Weighted Polynomial Regression

Recall that each ISI's detection probability is derived by dividing the number of "Yes" responses collected at that ISI by the total number of responses. Since each ISI's detection probability is based on a different total number of responses, confidence in the accuracy of a detection probability varies with the number of responses it is based on. Weighted regression was developed to handle such analyses (see Allen and Cady, 1982). The sums of squares are calculated using the detection probabilities multiplied by their respective weights, and the weights are determined by the number of responses that the detection probability is based on. The relevant terms are as follows:

WEIGHTED SUM OF SQUARES: $\Sigma W_i P_i$

UNWEIGHTED SUM OF SQUARES: ΣP

Where W is the weight, P is the detection probability, and i is the ISI index.

The more common unweighted, or more accurately evenly weighted, regression merely dispenses with the multiplication by the weights. Apart from this, the two procedures are identical.

The weights used have to reflect the number of responses that each detection probability was based upon, and the method chosen was as follows: the number of responses for each detection probability was divided by the average number of responses to yield that detection probability's weight. The result was a set of weights proportional to the number of responses in each detection probability, yet which add up to the number of detection probabilities in the analysis. For a more detailed discussion of the choosing of weights, see Appendix B.

The order of the regression, linear, quadratic or higher, was determined using trend analysis as discussed in Appendix B. The highest order component found to be statistically significant at the .05 level determined the order. If none of the components were significant, the component with the highest F ratio determined the order of the regression. This method resulted in 58 linear regressions, 162 quadratic regressions and 14 cubic regressions.

Since the above procedure should provide a most accurate description of the data, the regression predicted 50% detection probability point should be an accurate estimate of the subject's two-flash threshold, as confirmed by a comparison of the thresholds calculated in this and the conventional manner.

The binocular data and data from the monocular unchanging filter condition from subject AM, in the condition where the left eye was variably filtered, is shown using both the mean and regression analysis methods in Table A1. It is clear that, given a unit of resolution of four ms, the two methods yield similar results.

Table A1

Thresholds Obtained by the Conventional and Regression Methods.

Binocular Condition

Filter Level	METHOD Conventional	Regression
1.0	57.2	58.6
1.1	61.5	60.8
1.2	60.8	59.0
1.3	58.1	57.8
1.4	60.2	57.5
1.5	63.4	61.4
1.6	62.4	63.3
1.7	59.9	61.2
1.8	65.0	63.7
1.9	59.2	61.2
2.0	67.8	66.2
2.2	64.5	67.9
2.4	67.4	71.3

Monocular Steady Filter Condition

Filter Level	Method Conventional	Regression
1.0	64.8	67.4

APPENDIX B

Weighted Trend Analysis

The data on which the regression was performed consisted of one data point (i.e., a detection probability) for each ISI. Were a trend analysis of ISI against detection probability to be performed it would have zero degrees of freedom in the within groups sum of squares, where one degree of freedom is a minimun requirement. To deal with this problem a new set of probabilities was extracted from the raw data. For each binocular and variably filtered monocular session a second set of detection probabilities was derived. Recall that every filter level condition was run two times for each ocular condition, once in the first and once in the second position of a pair of sessions. For the regression a single set of probabilities was derived from these two sessions; the data was collapsed across the two sessions. For trend analysis both the first and second session in each pair of sessions has its own set of detection probabilities. For the unchanging filter condition two sets of detection probabilities were derived, each based on half of the sessions, rather than a single set for all sessions combined, as was done for the regression. Thus trend analysis could now be performed on probabilities stemming from the same raw data as the regression, but with at least two data points, or one degree of freedom, for every within groups sum of squares.

The trend analysis could then be performed in the usual manner, as soon as a weighting factor was added. Since the trend analysis determined the order of the regression analysis, and the regression analysis was performed on weighted data, the trend analysis had to be performed on data weighted in the same way. As discussed below, each probability's weight was proportional to the number of responses that produced that probability. The various sums of squares were calculated by multiplying each squared probability by its respective weight. This is equivalent to entering each data point into the analysis a number of times equivalent to that data point's weight. To double the weight of data point X, for example, enter it into the analysis twice. The N in the analysis, from which the between groups degrees of freedom was calculated, was determined by taking the sum of the weights. Since in most trend analyses all data points have equal weight, by adding up the weights one obtains the number of measures, or the N of the analysis. The N here was calculated the same way, by taking the sum of the weights.

The straightforward method for determining a particular detection probability's weight would be to use the number of responses that went into that detection probability. Since the overall N is determined by the sum of the weights, as it is in unweighted trend analysis where each data point has the same weight, the overall N would be determined by the total number of responses. An F statistic obtained using such an N would be much more liberal than one calculated using an unweighted trend analysis, where the N would be the number of detection probabilities. A more conservative approach to weighting was used here, and the same approach was used for the weighted regression discussed in appendix A.

The weight for each detection probability was determined by dividing the number of responses involved in that detection probability by the average number of responses. This way the average weight is unity and the N is the number of detection probabilities in the equation. For example, if the number of responses for ISIs 56, 60 and 64 were three, four and six, respectively, the average number of responses would be 4.33. The respective weights would be 0.69, 0.92 and 1.38, for an average weight of one and an N of three.

In this manner the different amounts of confidence placed in each detection probability can be expressed by assigning each a different weight, while at the same time preventing the analysis from becoming overly liberal.

The orthogonal polynomials found in tables for trend analysis assume equal N's and therefore, in our terms, equal weights. The method for generating orthogonal polynomials for unequal N's (See Kirk, 1968, Appendix C), was used for weighted trend analysis by simply substituting weight for N. No other changes were necessary.

The relative strengths of the linear, quadratic, cubic and departure-from-cubic components were thus determined for each pair of sets of detection probabilities, corresponding to the single set used for regression. This information was used to determine the order of the regression analysis, as discussed in Appendix A.

APPENDIX C

Probability Summation

When two percentages are summated probabilistically the result is higher than either original value. The amount by which the result exceeds the original values varies depending on the original values. Consider a set of ordered pairs representing stimulus intensity and detection probability, and assume, for simplicity, that the two are related linearly (see Figure C1a). When this set of percentages is summated probabilistically with an identical set (Figure C1b), the result is curvilinear (see Figure C1c). Thus the shape of the original curves is not preserved in probability summation. The effect of ogive and linear functions, and of different amounts of overlapping of distributions, on the shape of the summated curve is shown in figures C2 to C6.

It is clear that the summated curves can assume a great variety of shapes depending on the shapes and degree of overlap of the original curves. Thus one can not expect an ogive function to describe probabilistically summated data even though the original data were ogive shaped. Furthermore, since the degree of overlap of right and left eye probability distributions decreases with increasing disparity of filter levels, one should expect to find different shaped distributions for different filter levels of probabilistically summated data.

Any method of obtaining the 50% threshold from the probabilistically summated data that assumes the same distribution for all filter levels will yield inaccurate results. The accurate method will have to be either distribution free or test for and accomodate the shape of each distribution of probabilities. The latter method was chosen and is discussed in appendicies A and B.

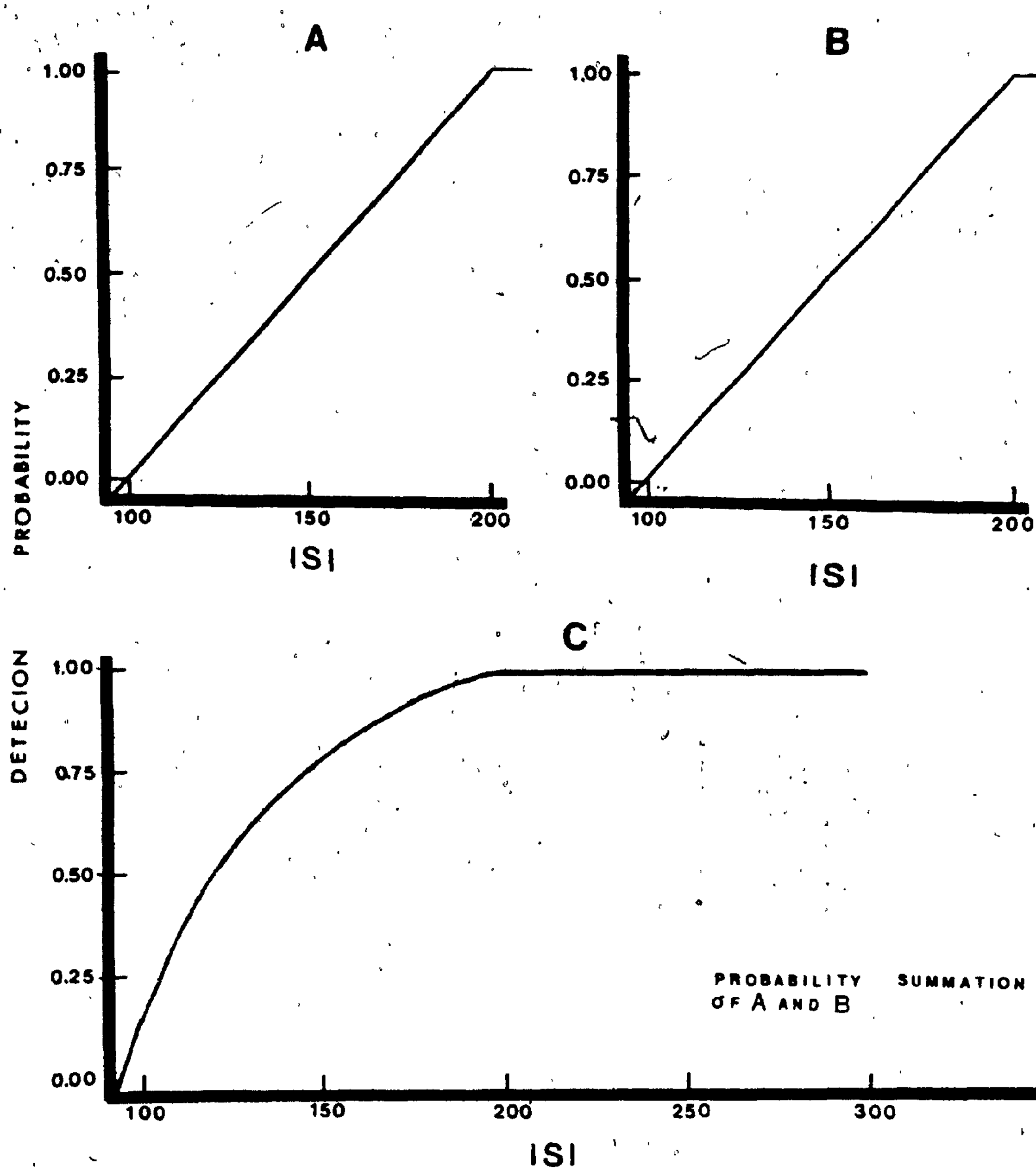

Figure C1. The probability summation of two straight lines: 100% overlap.

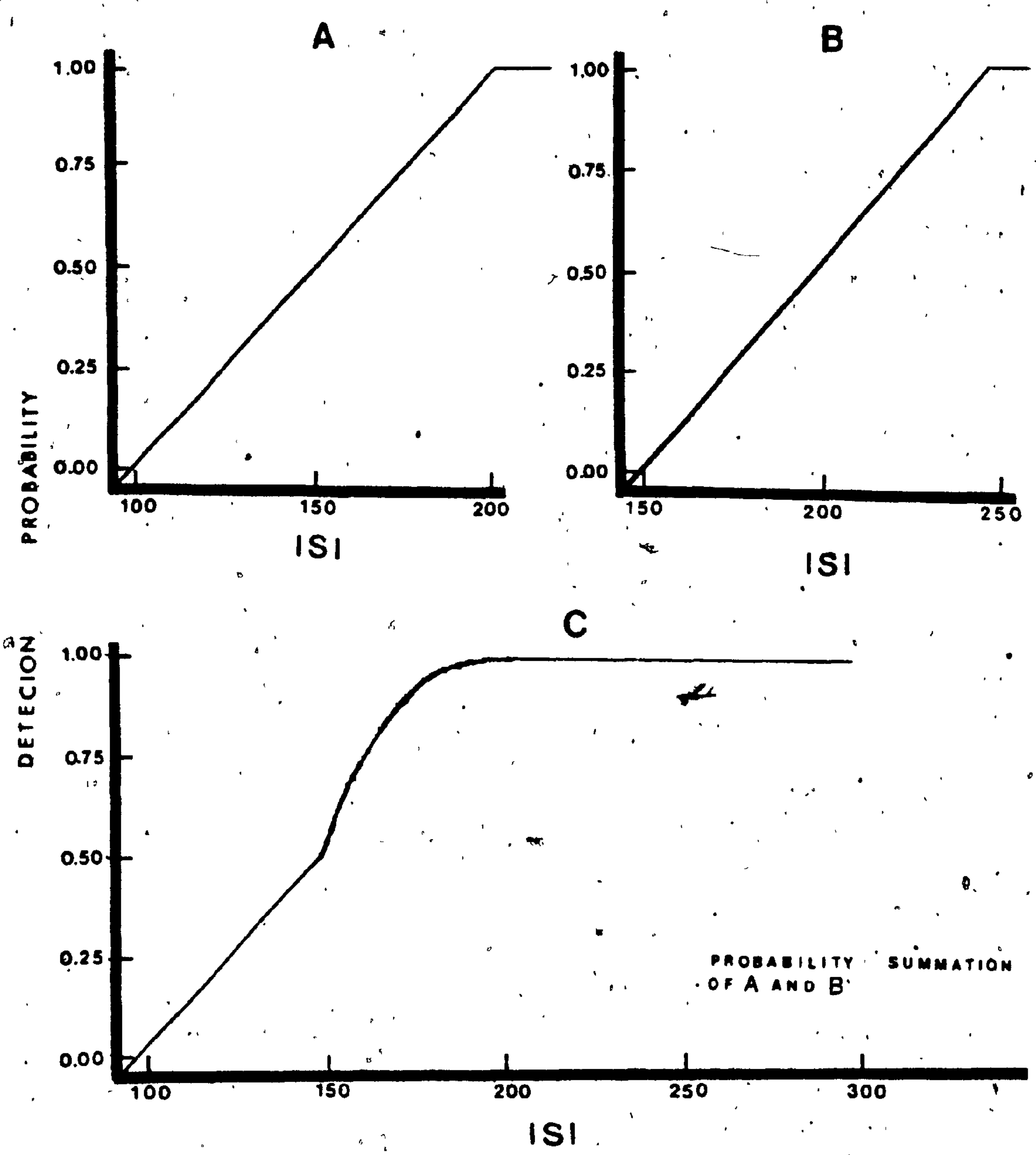

Figure C2. The probability summation of two straight lines: 50% overlap.

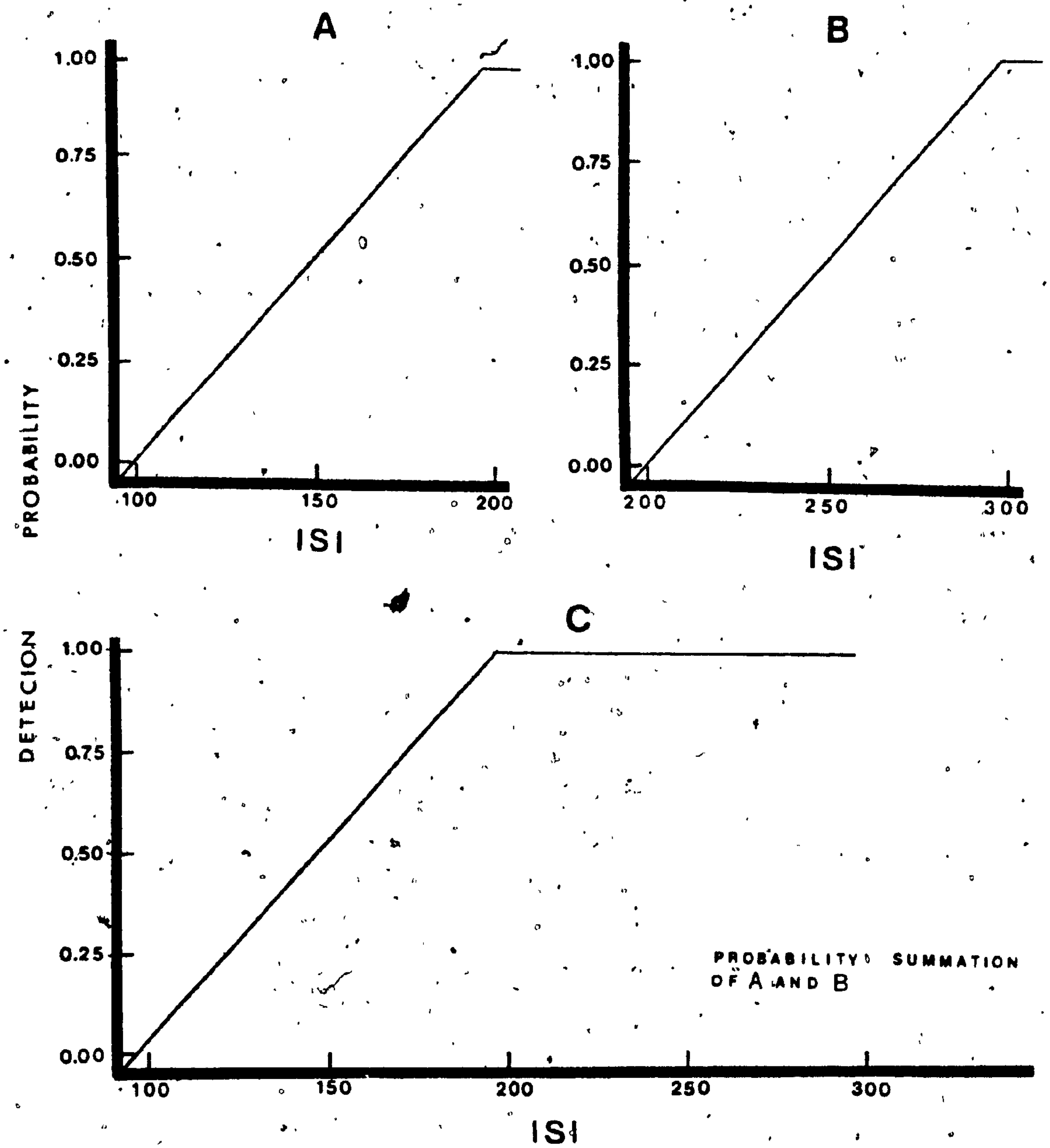

Figure C3. The probability summation of two straight lines: No overlap.

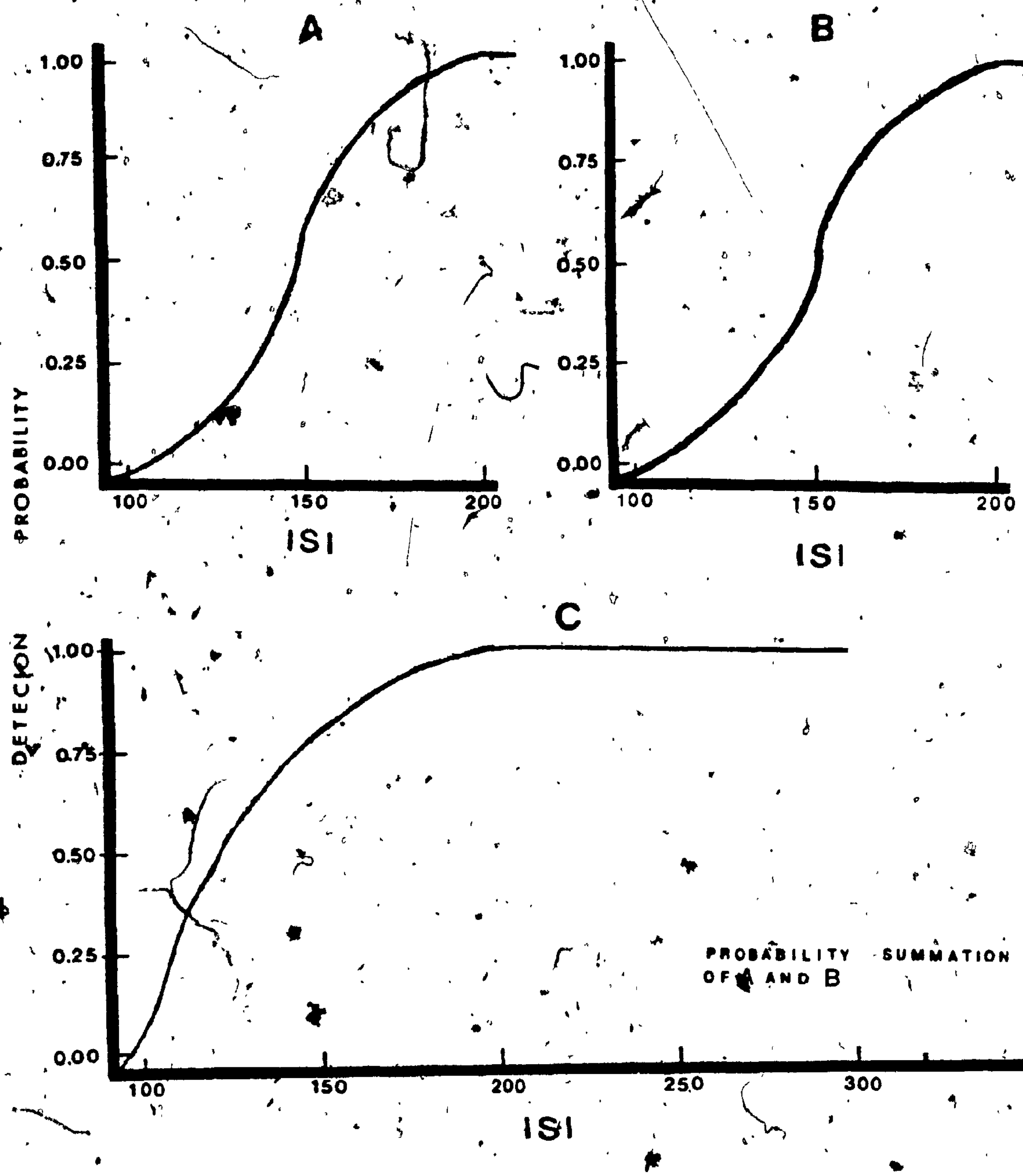

Figure C4. The probability summation of two ogives, 100% overlap.

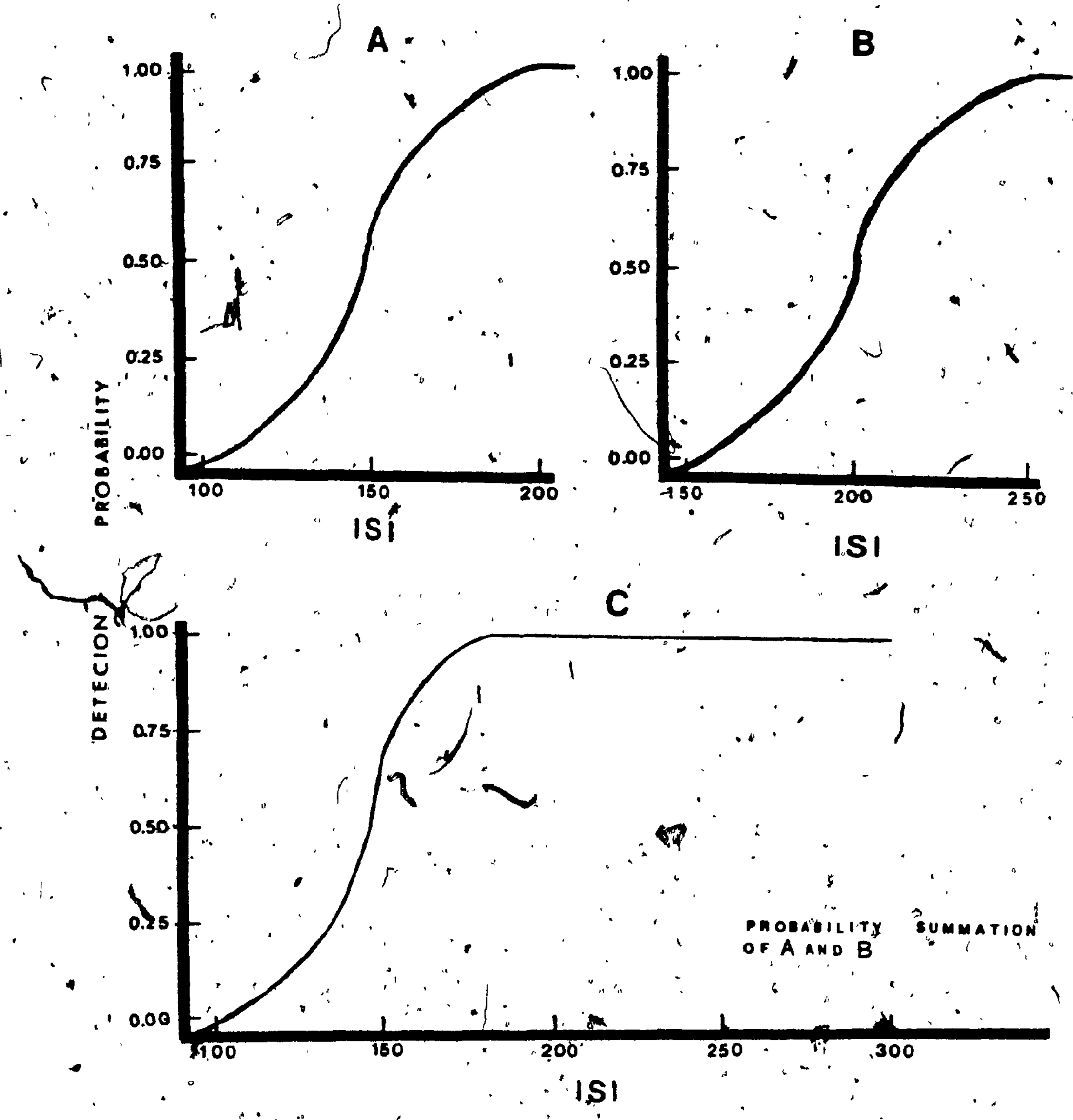

Figure C5. The probability summation of two ogives: 50% overlap.

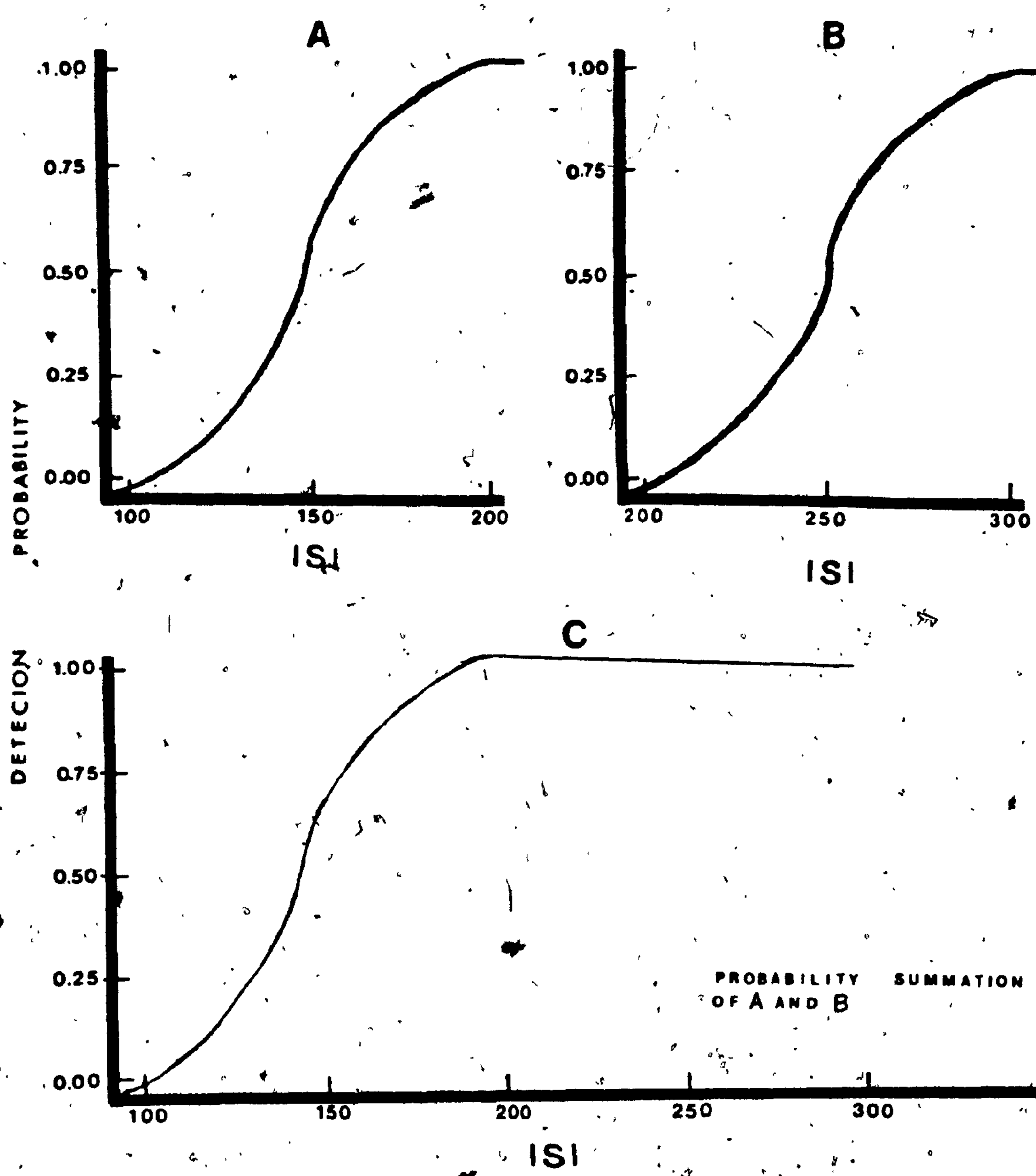

Figure C6. The probability summation of two ogives: No overlap.

APPENDIX D

Derivation of Adjustable Probability Summation

B = Predicted binocular detection probability.
pL = Optained left monocular detection probability
pR = Optained right monocular detection probability
F = Summation factor. See below

$$B = pR \cup pL - pR \cap pL \qquad \text{(Logical Equation)}$$

$$B = pR + pL - (pR * pL) \qquad \text{(Arithmetic Equation)}$$

$$B = 1 - 1 + pR + pL - (pR * pL)$$

$$B = 1 - (1 - pR - pL + (pR * pL))$$

$$B = 1 - ((1 - pR) * (1 - pL))$$

$$B = 1 - (1 - pR) * (1 - pL) \qquad \text{(Standard Equation)}$$

$$B = 1 - (1 - pR)^1 * (1 - pL)^1$$

$$B = 1 - (1 - pR)^F * (1 - pL)^F \qquad \text{Where } F = 1 \text{ (Adjustable Equation)}$$

An F greater than 1 indicates summation greater than probability summation, an F less than 1 indicates summation less than probability.

APPENDIX E

Individual Subject Thresholds for each Filter Level

In the six tables that follow the "S.E." refers to the standard errors of mean of the reversals from which the thresholds were derived, in most cases this involves 160 means. Any binocular threshold marked with an asterisk is significantly lower than the steadily filtered eye's threshold, and thus represents a binocular advantage, and any variably filtered monocular threshold marked by an asterisk is significantly higher than the steadily filtered eye's threshold. The binocular data marked by daggers are significantly higher than the steadily filtered monocular data, that is, the dagger marks a binocular disadvantage. No comparisons were made with the predicted data, as this data does not involve comparible variances. The overall error rate for any set of 12 or 13 comparisons was .05.

Table E1

Thresholds for Subject AM Right Eye Filter Unchanging

Unchanging Right Eye			Left Eye		
Filter Level	Threshold	S.E.	Filter Level	Threshold	S.E.
1.0	64.85	0.214	1.0	66.68	0.679
			1.1	67.39*	0.719
			1.2	70.30*	0.783
			1.3	71.90*	0.665
			1.4	71.50*	0.739
			1.5	75.59*	0.761
			1.6	79.35*	0.883
			1.7	76.54*	0.662
			1.8	79.57*	0.859
			1.9	86.72*	0.730
			2.0	83.22*	0.811
			2.2	111.05*	0.721
			2.4	111.42*	1.098

Binocular			Probability Summation	
Filter Level	Threshold	S.E.	Filter Level	Threshold
1.0	57.17*	0.558	1.0	51.68
1.1	61.55*	0.626	1.1	51.53
1.2	60.78*	0.574	1.2	50.64
1.3	58.10*	0.881	1.3	51.73
1.4	60.20*	0.586	1.4	47.18
1.5	63.77	0.656	1.5	50.10
1.6	62.40*	0.559	1.6	48.81
1.7	59.92*	0.568	1.7	53.94
1.8	64.95	0.612	1.8	52.42
1.9	59.17*	0.558	1.9	57.92
2.0	67.81†	0.595	2.0	52.87
2.2	64.55	0.538	2.2	64.85
2.4	67.42†	0.524	2.4	64.85

* For the left eye, this indicates significance above the unchanging right eye.
For the binocular condition this represents significance below the unchanging right eye.

† This represents significance above the unchanging right eye.

Table E2

Thresholds for Subject AM Left eye filter unchanging

Unchanging Left Eye

Filter Level	Threshold	S.E.
1.0	70.74	0.282

Right Eye

Filter Level	Threshold	S.E.
1.0	76.32*	0.602
1.1	72.79	0.814
1.2	66.60	0.762
1.3	78.46*	0.759
1.4	76.38*	0.947
1.5	78.05*	1.363
1.6	93.46*	0.820
1.7	88.80*	0.990
1.8	91.61*	1.059
1.9	93.43*	0.849
2.0	115.03*	1.663
2.2	106.02*	1.264
2.4	118.29*	1.280

Binocular

Filter Level	Threshold	S.E.
1.0	52.79*	0.578
1.1	58.75*	0.591
1.2	60.09*	0.682
1.3	65.92*	0.553
1.4	59.42*	0.775
1.5	60.64*	0.821
1.6	75.04†	0.547
1.7	66.10*	0.659
1.8	67.81*	0.518
1.9	76.79†	0.635
2.0	70.07	0.718
2.2	68.42	0.943
2.4	67.32*	0.727

Probability Summation

Filter Level	Threshold
1.0	36.21
1.1	48.73
1.2	44.45
1.3	54.61
1.4	43.19
1.5	47.23
1.6	36.02
1.7	53.77
1.8	43.82
1.9	43.40
2.0	53.00
2.2	68.36
2.4	68.43

* For the right eye, this indicates significance above the unchanging left eye.
For the binocular condition this represents significance below the unchanging left eye.

† This represents significance above the unchanging left eye.

Table E3

Thresholds for Subject MZ Right eye filter unchanging

Unchanging Right Eye

Filter Level	Threshold	S.E.
1.0	75.24	0.266

Left Eye

Filter Level	Threshold	S.E.
1.0	71.92	0.603
1.1	74.57	0.774
1.2	61.53	0.761
1.3	94.28*	0.793
1.4	87.97*	0.737
1.5	86.34*	0.923
1.6	101.67*	0.952
1.7	108.59*	1.405
1.8	107.18*	1.550
1.9	98.24*	1.516
2.0	106.44*	1.708
2.2	157.22*	2.674
2.4	175.17*	1.139

Binocular

Filter Level	Threshold	S.E.
1.0	66.14*	0.530
1.1	57.47*	0.583
1.2	60.76*	0.589
1.3	72.12	0.488
1.4	61.11*	0.988
1.5	66.07*	0.605
1.6	68.03*	0.673
1.7	69.84*	0.477
1.8	70.89*	0.770
1.9	78.22	0.921
2.0	64.48*	0.604
2.2	72.39	0.612
2.4	70.71*	0.642

Probability Summation

Filter Level	Threshold
1.0	61.83
1.1	50.43
1.2	46.55
1.3	65.13
1.4	60.06
1.5	58.48
1.6	69.42
1.7	65.69
1.8	65.55
1.9	60.98
2.0	62.84
2.2	75.24
2.4	75.24

* For the left eye, this indicates significance above the unchanging right eye.
For the binocular condition this represents significance below the unchanging right eye.

† This represents significance above the unchanging right eye.

Table E4

Thresholds for Subject MZ Left eye filter unchanging

Unchanging Left Eye

Filter Level	Threshold	S.E.
1.0	80.35	0.277

Right Eye

Filter Level	Threshold	S.E.
1.0	83.91	1.290
1.1	82.74	0.717
1.2	93.46*	1.567
1.3	96.86*	1.162
1.4	101.05*	1.884
1.5	105.59*	0.858
1.6	105.61*	1.047
1.7	135.26*	1.959
1.8	118.71*	1.242
1.9	108.52*	0.831
2.0	119.92*	0.935
2.2	158.19*	2.608
2.4	200.13*	1.242

Binocular

Filter Level	Threshold	S.E.
1.0	73.71*	0.564
1.1	74.47*	0.726
1.2	73.71*	0.949
1.3	79.31	0.778
1.4	77.15*	0.680
1.5	77.00*	0.822
1.6	72.81*	0.784
1.7	74.91*	0.733
1.8	78.93	0.685
1.9	83.69	0.749
2.0	88.02†	0.810
2.2	72.92*	0.672
2.4	72.34*	1.001

Probability Summation

Filter Level	Threshold
1.0	47.84
1.1	62.37
1.2	55.31
1.3	66.07
1.4	63.49
1.5	69.70
1.6	71.77
1.7	84.35
1.8	77.29
1.9	72.39
2.0	80.35
2.2	80.35
2.4	80.35

* For the right eye, this indicates significance above the unchanging left eye.
For the binocular condition this represents significance below the unchanging left eye.

† This represents significance above the unchanging left eye.

Table E5

Thresholds for Subject DL Right eye filter unchanging

Unchanging Right Eye

Filter Level	Threshold	S.E.
1.0	46.78	0.185

Left Eye

Filter Level	Threshold	S.E.
1.0	42.66	0.497
1.1	46.59	0.776
1.2	53.64*	0.451
1.3	52.92*	0.658
1.4	55.53*	0.788
1.5	58.88*	0.643
1.6	57.51*	0.790
1.7	65.16*	0.870
1.8	65.78*	0.964
1.9	74.59*	1.134
2.0	79.33*	0.926
2.2	98.11*	1.420

Binocular

Filter Level	Threshold	S.E.
1.0	43.13*	0.594
1.1	45.29	0.422
1.2	45.56	0.528
1.3	44.43*	0.446
1.4	45.07	0.673
1.5	45.48	0.561
1.6	45.17	0.527
1.7	46.45	0.531
1.8	47.31	0.538
1.9	44.26	0.624
2.0	49.11†	0.478
2.2	50.38†	[illegible].072

Probability Summation

Filter Level	Threshold
1.0	40.13
1.1	36.86
1.2	42.76
1.3	40.45
1.4	39.00
1.5	40.29
1.6	43.05
1.7	30.69
1.8	37.44
1.9	39.55
2.0	45.78
2.2	46.77

* For the left eye, this indicates significance above the unchanging right eye.
For the binocular condition this represents significance below the unchanging right eye.
† This represents significance above the unchanging right eye.

Table E6

Thresholds for Subject DL Left eye filter unchanging

Unchanging Left Eye

Filter Level	Threshold	S.E.
1.0	50.84	0.186

Right Eye

Filter Level	Threshold	S.E.
1.0	48.20	0.461
1.1	50.90	0.461
1.2	53.92*	0.627
1.3	57.79*	0.470
1.4	61.48*	0.574
1.5	65.18*	0.781
1.6	72.96*	0.731
1.7	59.79*	1.380
1.8	72.41*	0.869
1.9	77.02*	0.744
2.0	95.23*	1.167
2.2	169.94*	5.547

Binocular

Filter Level	Threshold	S.E.
1.0	50.14	0.562
1.1	47.86*	0.495
1.2	53.31	0.444
1.3	52.70	0.498
1.4	48.49*	0.467
1.5	53.24†	0.465
1.6	54.39†	0.538
1.7	61.19†	0.831
1.8	55.38†	0.573
1.9	59.77†	0.550
2.0	52.74	0.499
2.2	53.58†	0.640

Probability Summation

Filter Level	Threshold
1.0	42.46
1.1	44.21
1.2	43.56
1.3	43.33
1.4	48.49
1.5	46.71
1.6	43.59
1.7	43.10
1.8	33.37
1.9	54.67
2.0	55.95
2.2	50.84

* For the right eye, this indicates significance above the unchanging left eye.
For the binocular condition this represents significance below the unchanging left eye.
† This represents significance above the unchanging left eye.

APPENDIX F

Predicted Binocular Data - Summation Factor of 0.67

Table F1

Predicted and Obtained Thresholds:
Subject AM Right Eye Filter Unchanging

Filter Level	Obtained Binocular Thresholds	Predicted Thresholds	Obtained Minus Predicted
1.0	57.17	57.75	-0.58
1.1	61.55	58.38	3.17
1.2	60.78	60.36	0.42
1.3	58.10	62.60	-4.50
1.4	60.20	60.41	-0.21
1.5	63.77	61.94	1.83
1.6	62.40	63.66	-1.26
1.7	59.92	64.20	-4.28
1.8	64.95	63.41	1.15
1.9	59.17	66.48	-7.31
2.0	67.81	64.20	3.61
2.2	64.55	71.73	-7.18
2.4	67.42	78.15	-10.73

Table F2

Predicted and Obtained Thresholds:
Subject AM Left Eye Filter Unchanging

Filter Level	Obtained Binocular Thresholds	Predicted Thresholds	Obtained Minus Predicted
1.0	52.79	55.04	-2.25
1.1	58.75	57.87	0.88
1.2	60.09	61.59	-1.50
1.3	65.95	66.61	-0.66
1.4	59.42	60.71	-1.29
1.5	60.64	62.74	-2.10
1.6	75.04	58.97	16.07
1.7	66.10	65.43	0.67
1.8	67.81	61.51	6.30
1.9	76.79	64.39	12.40
2.0	70.07	67.13	2.90
2.2	68.42	82.00	-13.58
2.4	67.32	82.56	-15.24

Table F3

Predicted and Obtained Thresholds:
Subject MZ Right Eye Filter Unchanging

Filter Level	Obtained Binocular Thresholds	Predicted Thresholds	Obtained Minus Predicted
1.0	66.14	69.15	-3.01
1.1	57.47	59.89	-2.42
1.2	60.76	58.76	2.00
1.3	72.12	81.72	-9.60
1.4	61.11	73.74	-12.63
1.5	66.07	72.30	-6.23
1.6	68.03	82.21	-14.18
1.7	69.84	81.93	-12.09
1.8	70.89	81.76	-10.87
1.9	78.22	69.91	8.31
2.0	64.48	63.05	1.43
2.2	72.39	80.91	-8.52
2.4	70.71	80.57	-9.86

Table F4

Predicted and Obtained Thresholds:
Subject MZ Left Eye Filter Unchanging

Filter Level	Obtained Binocular Thresholds	Predicted Thresholds	Obtained Minus Predicted
1.0	73.71	60.99	12.72
1.1	74.47	75.96	-1.49
1.2	73.71	69.83	3.88
1.3	79.31	78.58	0.73
1.4	77.15	75.61	1.54
1.5	77.00	83.75	-6.75
1.6	72.81	85.10	-12.29
1.7	74.91	94.19	-19.28
1.8	78.93	91.93	-13.00
1.9	83.69	81.52	2.17
2.0	88.02	91.29	-3.27
2.2	72.92	79.05	-6.13
2.4	72.34	84.05	-11.71

Table F5

Predicted and Obtained Thresholds:
Subject DL Right Eye Filter Unchanging

Filter Level	Obtained Binocular Thresholds	Predicted Thresholds	Obtained Minus Predicted
1.0	43.13	45.97	-2.84
1.1	45.29	52.02	-6.73
1.2	45.56	44.91	0.65
1.3	44.43	45.58	-1.15
1.4	45.07	46.75	-1.68
1.5	45.48	47.70	-2.22
1.6	45.17	47.61	-2.44
1.7	46.45	50.27	-3.82
1.8	47.31	44.55	2.76
1.9	44.26	47.48	-3.22
2.0	49.11	49.91	-0.80
2.2	50.38	52.40	-2.02

Table F6

Predicted and Obtained Thresholds:
Subject DL Left Eye Filter Unchanging

Filter Level	Obtained Binocular Thresholds	Predicted Thresholds	Obtained Minus Predicted
1.0	50.14	45.66	4.48
1.1	47.86	47.11	0.75
1.2	53.31	47.80	5.51
1.3	52.70	49.20	3.50
1.4	48.49	52.83	-4.34
1.5	53.24	50.35	2.89
1.6	54.39	59.70	-5.31
1.7	61.19	47.28	13.91
1.8	55.38	49.51	5.87
1.9	59.77	62.71	-2.94
2.0	52.74	62.79	-10.05
2.2	53.58	60.85	-7.27