Detection uncertainty and the facilitation of chromatic detection by luminance contours

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Received November 21, 1989; accepted August 22, 1990

A suprathreshold luminance flash (1°, 200 msec) on a large uniform yellow field facilitates detection of a coincident (1°, 200 msec) red or green equiluminant flash and approximately linearizes the psychometric function for detecting the chromatic flash. The facilitation is produced by the suprathreshold contour created by the luminance flash. We tested whether the contour facilitates detection by reducing spatiotemporal uncertainty in detecting the chromatic flash. Uncertainty increases false alarms, and this effect can be factored out by correcting yes–no psychometric functions for guessing. Uncertainty also alters the shape of the receiver operating characteristic. Measurements of yes–no psychometric functions and receiver operating characteristics do not support the uncertainty reduction hypothesis.

INTRODUCTION

Discrimination of the color difference between two regions may be improved by a clear contour that separates the regions.[1,2] We have studied this facilitation with a uniform 6° yellow field whose central 1° disk area can be modulated in color, luminance, or both (Fig. 1). Using a two-temporal alternative forced-choice (2AFC) method, we observed[3] that a suprathreshold luminance pedestal (a luminance modulation of the 1° disk presented in both intervals) facilitates the detection of a coincident chromatic test presented in one of the intervals. The pedestal approximately halves the chromatic threshold and reduces the slope of the chromatic psychometric function (the Weibull exponent) from approximately 2 to nearly 1. Switkes *et al.*[4] measured similar threshold facilitation by using sinusoidal grating stimuli but did not measure psychometric slopes.

Near threshold, the chromatic test spot presented without the luminance pedestal appears as a diffuse colored blob extended in time [Fig. 1(b)], as if observers were uncertain about its time and place. When the flashed luminance pedestal produces a sharp edge around the chromatic test, the test appears temporally crisp and the color fills in the region demarcated by the pedestal [Fig. 1(c)], as if the observer were less uncertain when the luminance pedestal accompanied the test. Plausible models[5] indicate that uncertainty increases both the threshold and the slope of the psychometric function, as measured with forced-choice methods. The present study examines whether the luminance pedestal facilitates chromatic detection by reducing detection uncertainty.

Uncertainty Reduction Hypothesis

Uncertainty may be precisely defined by using the theory of signal detection.[6] The observer is assumed to have two classes of information: (1) relevant information owing to the test stimulus and (2) irrelevant information that is independent of the test stimulus. For example, uncertainty might cause the observer to monitor the unstimulated spatial regions adjacent to the test in addition to the test region. If the observer combines the relevant and the irrelevant information, both of which are noisy, the irrelevant information may cause additional false alarms and thereby degrade performance. The various sources of information are customarily referred to as channels and the uncertainty as channel uncertainty.[7]

The amount of uncertainty is defined as the number of irrelevant channels that influence the observer. M denotes the total number of channels and provides an index of uncertainty. For reasons given below, we assume here that there is only one relevant channel, so that $M = 1$ when there is no uncertainty. The model of uncertainty used here is that of Pelli.[5]

There are three ways in which a pedestal might facilitate detection, two of which involve uncertainty. First, the observer might monitor only a single relevant channel ($M = 1$), which has an accelerating input–output function, with the limiting noise added after the nonlinearity; facilitation results from the pedestal's shifting the operating point to a steeper part of the accelerated function,[8] and uncertainty plays no role. Second, there could be multiple channels, some of which are irrelevant. Even with linear input–output functions in the relevant channels, the net effectiveness of the stimulus grows more slowly at low intensities than at intermediate intensities[5]: activity in the irrelevant channels does not increase with test intensity, by definition, so the irrelevant channels degrade performance most at low test intensities. If the pedestal can move the operating point higher on the intensity axis, it can reduce the effect of uncertainty without changing M.[9] Third, the pedestal could reduce M, for instance, by permitting the observer to ignore the irrelevant channels.[10]

The first two models make equivalent predictions regarding pedestal effects on thresholds,[6] and both require the pedestal and the test to be on the same effective intensity axis. In many studies this is the case, since the pedestal and the test are both luminance spots or gratings.[7,8,11,13] Our experiments are different in several important respects[3]: (1) our luminance and chromatic stimuli are detected by independent mechanisms, as shown by the rectangular

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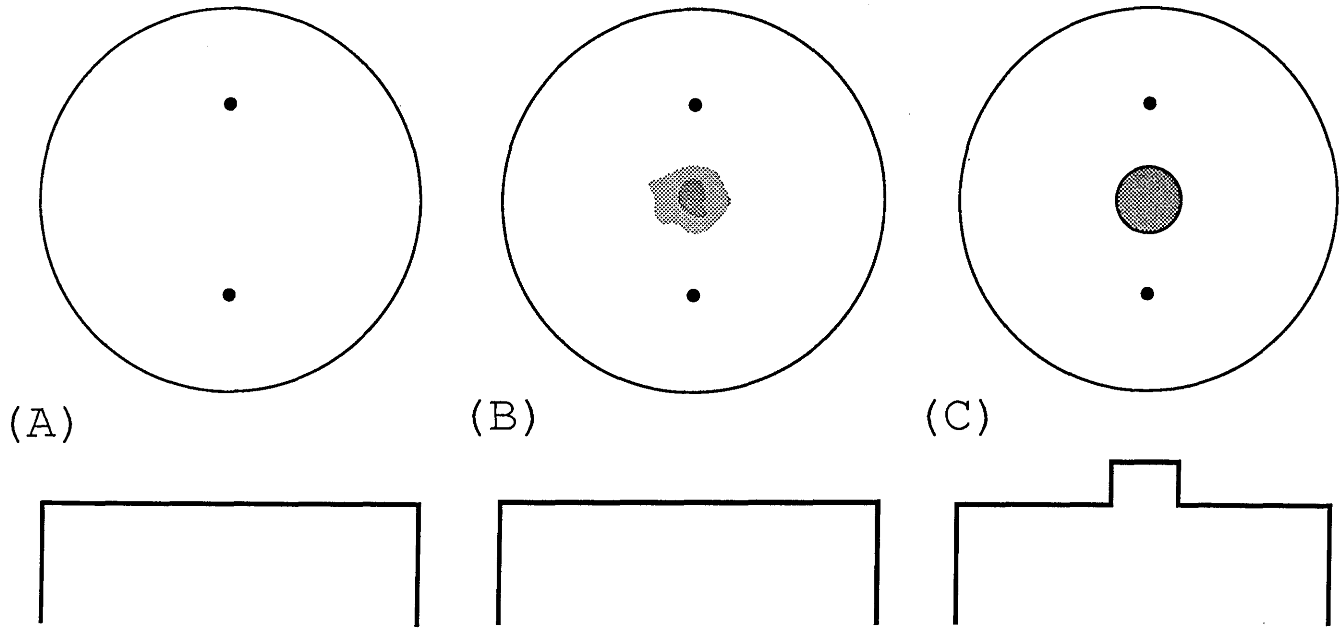

Fig. 1. Appearance of the stimulus (top) and its luminance profile (bottom): (A) between trials when the field is uniform, (B) with an equiluminant colored test, (C) with both an equiluminant test and a suprathreshold luminance pedestal. The dots are fixation marks.

shapes of detection contours[3,14] (and by results of Krauskopf *et al.*[15] using selective adaptation with large-field luminance or chromatic flicker); (2) although a subthreshold luminance pedestal strongly affects a luminance test (and similarly for a chromatic pedestal and a chromatic test), a subthreshold luminance pedestal has little effect on a chromatic test; instead most of the pedestal's effect occurs when the pedestal is suprathreshold; (3) although an intense luminance pedestal strongly masks a luminance test, the same pedestal facilitates the chromatic test independently of suprathreshold pedestal intensity; (4) the luminance–chromatic facilitation disappears if the 5° steady annular region surrounding the pedestal and the test is removed (replacing the yellow comparison region with a dark surround), but the luminance–luminance facilitation is largely unaffected; (5) the luminance–chromatic facilitation results from the edges of the pedestal, since substituting a thin ring for the luminance disk produces equivalent facilitation.

These results suggest that the chromatic and the luminance stimuli do not act together in a single detection channel. This would appear to rule out an explanation of the chromatic facilitation by the luminance pedestal based on a single detection channel with an accelerated transducer function. It would also appear to rule out an explanation based on a fixed uncertainty, in which the effect of the pedestal is to raise the operating point of the relevant channel above the noise level of the irrelevant channels. However, the pedestal might facilitate detection by reducing M. We refer to the view that the sole effect of the pedestal is to reduce M as the uncertainty reduction hypothesis. Previous experimental manipulations of factors related to uncertainty (such as providing a fixation cross hair to reduce spatial uncertainty) have not supported the uncertainty reduction hypothesis (Ref. 3 and the Discussion section below). In this paper we present a more general test of the hypothesis, as described below.

Pelli's Uncertainty Model

In the model of uncertainty by Pelli[5] the channels are assumed to be stochastically independent with additive Gaussian noise. The relevant channels respond linearly with test intensity, while the irrelevant channels are unaffected by the test. The responses of the relevant and the irrelevant channels are combined by a maximum rule: a detection response occurs when the response of any channel (more accurately, the likelihood based on the channel's response) exceeds a single, fixed criterion value. The equations of the model may be derived as follows, if one assumes for simplicity that there is only one relevant channel. The probability of detection by the relevant channel is

$$P_{\mathrm{rel}}(c) = 1 - \Phi(\lambda - c),$$

where $\Phi(\lambda)$ is the cumulative normal distribution function, λ is the detection criterion, and c is proportional to test intensity. The corresponding probability of detection for a single irrelevant channel is

$$P_{\mathrm{irrel}}(c) = 1 - \Phi(\lambda),$$

which is independent of test intensity. We will refer to $P_{\mathrm{irrel}}(c)$ as the probability of a single irrelevant channel's causing a spurious hit. The observer makes a spurious hit only by chance, since activity in the irrelevant channel is independent of test intensity. Assuming probability summation among all the channels, we find that the total probability of detection in a yes–no (Y/N) experiment is

$$P(c) = 1 - \Phi(\lambda - c)\Phi^{M-1}(\lambda), \tag{1}$$

since there are $M - 1$ irrelevant channels. The overall false-alarm probability is

$$P(0) = 1 - \Phi^{M}(\lambda) \tag{2}$$

[see also Ref. 16, Eqs. (12) and (13)]. $P(0)$ has two components: false alarms due to the $M - 1$ irrelevant channels and false alarms due to the one relevant channel. In a 2AFC procedure the probability correct is the area under the receiver operating characteristic[17] (ROC):

$$P_{2AFC}(c) = \int_{\lambda=-\infty}^{\lambda=+\infty} P(c)dP(0). \tag{3}$$

Experimental Rationale

One test of the uncertainty reduction hypothesis follows from the assumption in the model that irrelevant channels affect performance by increasing both false alarms and spurious hits and that these two rates vary together. If the facilitation is caused by a reduction of uncertainty, and if we could eliminate the effects of the spurious hits and the effects of those false alarms that are due to the irrelevant channels, then there would be no effect of uncertainty and the pedestal would have no effect. This can be achieved as follows. When M is large, almost all the overall false-alarm rate is due to the irrelevant channels, and $M \approx M - 1$. Using the Y/N psychometric method, we can distinguish false alarms from misses, and the false-alarm rate may be used to correct for guessing:

$$P_{corr}(c) = 1 - \{[1 - P(c)]/[1 - P(0)]\}. \tag{4}$$

Using the approximation $M \approx M - 1$ and substituting $P(0)$ from Eq. (2) and $P(c)$ from Eq. (1) into Eq. (4) make

$$P_{corr}(c) = 1 - \Phi(\lambda - c) = P_{rel}(c). \tag{5}$$

Equation (5) shows that uncertainty has no effect on the Y/N probability of detection after correction for guessing.

In Pelli's model, the slope and the threshold of the Y/N psychometric function depend on the criterion λ but are independent of M. On the other hand, the slope and the threshold of the 2AFC psychometric function depend on M but are independent of λ. The pedestal-induced change in our 2AFC data[3] is consistent with a reduction in M from 9 (for observer CFS) or 4 (for RTE) down to 1 or 2 [see Table 1 below and Ref. 5, Eq. (5.4)]. When there are only 4–9 channels, M is not a good approximation to $M - 1$; the consequences of small M are dealt with in the Discussion section.

We tested the uncertainty reduction hypothesis by measuring psychometric functions for the chromatic test, with and without the luminance pedestal, using both the Y/N and the 2AFC methods. The hypothesis predicts that the Y/N psychometric functions should have identical thresholds and slopes (after correction for guessing) when measured with and without the pedestal, provided that the criterion λ is constant. The test intensity was altered between the pedestal and no-pedestal conditions to obtain similar numbers of correct responses in the two conditions, and thus there is no reason to expect a substantial criterion shift due to the pedestal.

Uncertainty not only alters the psychometric function but also affects the shape of the ROC, the plot of $P(c)$ versus $P(0)$ as λ varies with the test intensity held fixed [Eqs. (1) and (2)]. To test for criterion effects, we measured ROC's. If the ROC's differ in shape, then the degree of facilitation will depend on λ, since the pedestal and the no-pedestal ROC's will be closer together for some criterion levels than for others.

METHODS

A brief description of methods is given here. A more complete description is provided by Cole *et al.*[3]

Apparatus

Stimuli were produced with an eight-channel Maxwellian view. The stimulus consisted of coincident, 1° central test disks or red, green, and yellow and matched contiguous annuli (6.2° outer diameter), each composed of light from light-emitting diodes (LED's) passed through interference filters. These components were superposed on an intense yellow adapting field of 6.2°. The entire stimulus appeared as a uniform yellow disk, since the unmodulated central test region matched its surround and the edge between the test and the surround was not visible [Fig. 1(A)]. The test area was fixated with the aid of two dark dots separated by 3°. The total illuminance was 3000 Td, with the LED's contributing less than 400 Td. All components were narrow band (8–10 nm half-bandwidth). The spectral centroids of the filtered red, green, and yellow LED's were 671, 551, and 579 nm, respectively. The yellow main field matched the yellow LED (nearly isomerically) and metamerically matched the sum of the red and the green LED's. Absolute radiance was calibrated each session.

Stimulus Representation

The coincident chromatic test and the luminance pedestal were flashed simultaneously for 200 msec. The luminance pedestal was produced with the yellow test LED, which matched the field chromaticity, so that the pedestal was simply an increment of intensity of the test region, with no color change. The equiluminant chromatic tests were either *green*, produced by simultaneous incremental green and decremental red flashes, or *red*, produced by inverting the polarities of the red and the green flashes.

The L- and M-cone fundamentals of Smith and Pokorny,[18] converted to a corneal quantal catch basis, were used to represent data in the Weberian coordinates ($\Delta L/L$, $\Delta M/M$). The change in cone quantal catch produced by modulating the central test region (e.g., ΔL) was normalized by the mean quantal catch (e.g., L) owing to all the steady components. The luminance pedestal is represented as a 45° vector in the ($\Delta L/L$, $\Delta M/M$) coordinates, whereas the green and the red chromatic flashes are represented as vectors of 135° and 315°, respectively. Green chromatic flashes were used for observers RTE and EJB, and red for CFS and CJP; detection thresholds are equal for the two chromatic polarities.[3,19] Cole *et al.*[3] showed by a number of tests that the chromatic flashes are approximately equiluminant hue shifts. For instance, they showed that the flashes on the pedestal are likely detected by a chromatic mechanism because the chromatic sign is discriminated with the same accuracy as the flashes are detected.

The intensities of the pedestal and the test are specified by the vector length of the stimulus $[(\Delta L/L)^2 + (\Delta M/M)^2]^{1/2}$ (the luminance contrast of the pedestal, ΔLum/Lum, can be obtained by dividing the vector length by $\sqrt{2}$). The vector length of the luminance pedestal was typically +0.053, which is 2–3 times threshold, an intensity at which the pedestal had clear edges. Cole *et al.*[3] showed that facilitation was approximately independent of suprathreshold pedestal intensity.

Procedure

Three procedures were used: (1) Psychometric functions were measured with the 2AFC method of constant stimuli, using 5–7 randomly intermixed intensities. On each trial there were two temporal intervals separated by 400 msec. The test was presented in either interval with equal probability; the pedestal, when used, was presented in both intervals. (2) Psychometric functions were also measured with the Y/N method of constant stimuli. Two intervals were presented, as in 2AFC, but the test occurred only in the second interval, with either 50% or 80% probability of occurrence (in separate experiments). Two pedestal conditions were used. In the single-pedestal case the luminance pedestal was presented only in the second interval on every trial. In the double-pedestal case the pedestal was presented in both intervals on every trial, so the observer could compare the appearance of the two luminance pedestals close together in time as in the 2AFC method (a procedure suggested to us by Pelli[20]). (3) ROC curves were measured with the Y/N method and a single test intensity. The test probability was set to 20%, 40%, 60%, and 80% on separate days. ROC's were measured both with and without the pedestal, using the double pedestal in the pedestal condition. As in the psychometric function measurements, two temporal intervals were always presented on each trial when the ROC curves were measured; the test stimulus could occur only in the second interval.

The observer adapted to the yellow field for 2 min before each run of 150–200 trials. Tones indicated each interval and provided response feedback. Each psychometric function was based on at least 1000 signal trials, and each point on the ROC was based on at least 200 trials for both the hit and the false-alarm probability estimates (e.g., 1000 trials in both the 20% and 80% conditions). Pedestal and no-pedestal conditions were alternated. Viewing was foveal unless stated otherwise.

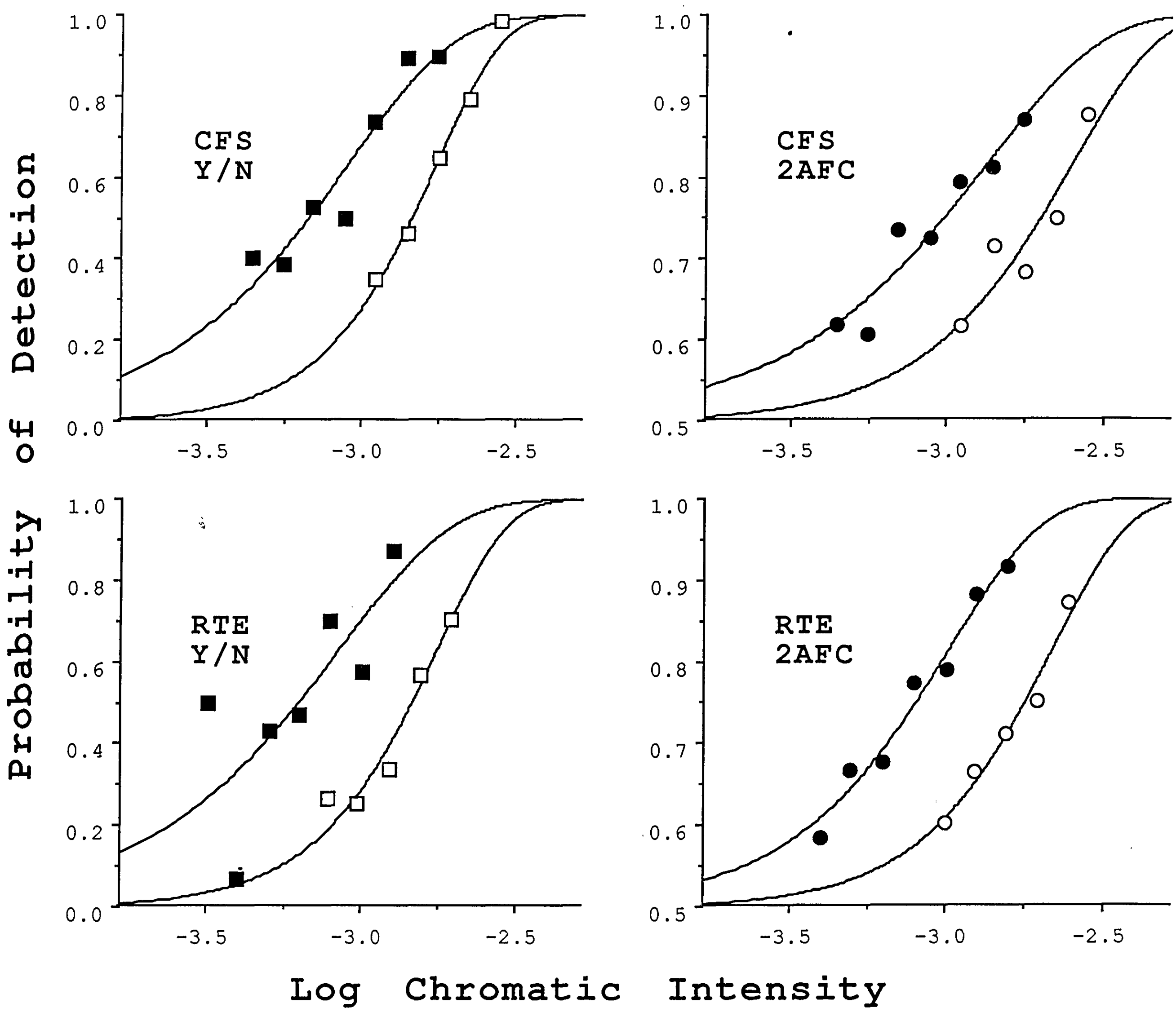

Fig. 2. Foveal psychometric functions measured by the 2AFC (right-hand side) and the Y/N (left-hand side) methods, with a signal probability of 80% for the latter. The Y/N data have been corrected for guessing. The filled data points were measured with the luminance pedestal, and the open data points were measured without the pedestal. Weibull functions are fitted to the data (parameters specified in Table 1). The luminance pedestal facilitates chromatic detection measured with both psychometric methods. The data are from observers CFS (top) and RTE (bottom).

Table 1. Parameters of Psychometric Functions for Foveal Chromatic Detection Measured With and Without Luminance Pedestals for Y/N and 2AFC Procedures[a]

Observer	Procedure	Pedestal Condition	$\alpha \times 10^3$	β	e	False-Alarm Rate
CFS	Y/N 50%	None	2.48 (0.15)	1.64 (0.32)	1.13 (0.19)	0.29
		Double	1.10 (0.11)	1.23 (0.33)	0.88 (0.25)	0.44
		None	2.19 (0.17)	1.63 (0.40)	1.19 (0.27)	0.32
		Double	1.08 (0.07)	1.53 (0.20)	1.18 (0.15)	0.40
	Y/N 80%	None	1.86 (0.04)	2.02 (0.05)	1.39 (0.09)	0.29
		Double	0.96 (0.07)	1.26 (0.34)	0.93 (0.22)	0.44
	2AFC	None	2.69 (0.43)	1.58 (0.69)	1.41 (0.08)	
		Double	1.43 (0.17)	1.16 (0.29)	1.02 (0.28)	
	Average 2AFC	None	2.65 (0.30)	2.13 (0.51)		
		Double	1.01 (0.21)	1.53 (0.16)		
RTE	Y/N 50%	None	1.73 (0.09)	1.64 (0.21)	1.37 (0.22)	0.41
		Double	0.92 (0.09)	1.27 (0.25)	1.07 (0.25)	0.47
		Single	0.92 (0.09)	1.44 (0.28)	2.42 (1.22)	0.43
	Y/N 80%	None	1.89 (0.17)	1.91 (0.51)	1.45 (0.46)	0.68
		Double	0.91 (0.28)	1.19 (0.82)	1.29 (1.10)	0.76
	2AFC	None	2.35 (0.13)	1.78 (0.33)	1.48 (0.27)	
		Double	1.10 (0.06)	1.47 (0.13)	1.23 (0.20)	
	Average 2AFC	None	2.17 (0.22)	1.76 (0.18)		
		Double	1.37 (0.22)	1.40 (0.26)		

[a] α, threshold; β, Weibull slope; e, d' power-law exponent. Values in parentheses indicate one half the 90% confidence intervals.

RESULTS

The Y/N data were first corrected for guessing [Eq. (4)]. Both the Y/N and the 2AFC data were then fitted by the Weibull psychometric function

$$P_{\text{corr}}(x) = 1.0 - (1 - \gamma)\exp[-(x/\alpha)^{\beta}], \tag{6}$$

using a quasi-Newton method and least-squares criterion, where x is chromatic intensity [proportional to c; Eq. (1)], α is the threshold, and β is the slope. For the 2AFC data $\gamma = 0.5$, while for the Y/N data $\gamma = 0.0$, since the data were corrected for guessing before the function was fitted.

Figure 2 shows psychometric functions measured with the pedestal (filled symbols) and without the pedestal (open symbols). The results on the left-hand side were obtained with the Y/N procedure with the probability of test occurrence set to 80%. The results on the right-hand side were obtained with the 2AFC procedure. For both procedures the pedestal approximately halves the chromatic threshold. Thus the correction for guessing does not eliminate the effect of the pedestal measured with the Y/N method, which is inconsistent with the uncertainty reduction hypothesis, when one assumes that (1) $M \cong M - 1$ (see the Discussion), and (2) the criterion is unchanged by the pedestal (see the subsection below, Analysis of Receiver Operating Characteristics).

Table 1 specifies the Weibull parameters α and β and the false-alarm rate for the psychometric functions including the 50% Y/N functions that are not plotted in Fig. 2. The values in parentheses indicate one half the 90% confidence intervals. The results labeled Average 2AFC represent extensive measurements made in a related study with similar conditions (these confidence intervals are based on the variability between experiments).

Although it is clear that the pedestal approximately halves the chromatic threshold, the behavior of the Weibull slope parameter β is more variable. For the Y/N procedure the pedestal slightly reduces β for observer CFS in all cases. For observer RTE the pedestal reduces β by approximately 0.8×—approximately the same as the average reduction in slope measured with the 2AFC method. The psychometric function without the pedestal is not extremely steep, and therefore the pedestal cannot produce a large reduction in slope. However, the confidence intervals for β are large, indicating that only large changes can be assessed reliably.

Table 1 also specifies the exponent of the d' power law fitted to the psychometric data:

$$\log d' = f + e \log x, \tag{7}$$

in which x is again stimulus intensity, e is the exponent, and f is a threshold parameter. Pelli[21] showed that the Weibull exponent is related to the d' exponent [Eq. (7)] by $\beta \cong 1.25e$. Thus the low Weibull exponents obtained for chromatic detection on the luminance pedestal ($\beta \cong 1.2$ to $\beta \cong 1.4$) correspond to an approximately linear relationship ($e \cong 1.0$) between d' and intensity and imply a single detection channel (one relevant mechanism).[22] Figure 8 of Cole *et al.*[3] shows similar d' power-law psychometric functions obtained for the same observers with the 2AFC method.

Table 1 shows that the single-pedestal condition produces facilitation similar to that produced by the double-pedestal condition, indicating that the observer need not compare two pedestals close together in time to obtain facilitation. This result is surprising, since Cole *et al.*[3] showed that observers can make such temporal comparisons and can do so linearly. However, in the present single-pedestal condition, the observer could be comparing pedestals across trials, since observers were self-paced and the pedestal occurred approximately every 2.5 sec.

Limited measurements were also made with observer CFS using parafoveal stimuli: a fixation dot was placed to the side so that the stimulus was centered 2.3° eccentric on the nasal retina. The intensity of the luminance pedestal was set to 3× threshold (0.23). For the Y/N procedure the probability of the test was 80%, and the double-pedestal condition was used. Figure 3 and Table 2 show that the slope parameter β for detection of the chromatic flash without the pedestal has increased considerably compared with the foveally viewed test and that the pedestal facilitation has increased to approximately 4×. The uncertainty reduction hypothesis would account for the increased facilitation (measured by the 2AFC method) by postulating high parafoveal uncertainty without the pedestal: the slope of $\beta = 3.45$ in Table 2 corresponds to $M \cong 400$ [Ref. 5, Eq. (5.4)]. The chromatic threshold measured without the pedestal has increased approximately 3.5× at 2.3° eccentricity compared with the foveal threshold.[23] The results again show that correcting the psychometric functions for guessing fails to eliminate the facilitation measured with the Y/N method. Here the approximation $M \cong M - 1$ is quite good. Thus, if the criterion can be assumed to be constant, then the uncertainty reduction hypothesis also fails in the parafovea even though the facilitation is larger.

Analysis of Receiver Operating Characteristics

The Y/N psychometric functions by themselves do not provide a complete test of the uncertainty reduction hypothesis because threshold and slope depend on the observer's criterion λ in the Y/N procedure.[5] The effects of a change in M can be offset by a change in λ. This can be illustrated by considering the false-alarm rates. The uncertainty reduction hypothesis requires that, if the observer maintains a constant criterion λ, the false-alarm rates must be lower with the pedestal [Eq. (2)]. Tables 1 and 2 specify the false-alarm rates for Y/N psychometric functions. The false-alarm rates for observer RTE were comparable for the pedestal and no-pedestal conditions. The rate did increase for the condition with the higher test probability, as predicted for an observer who attempts to maximize the number of correct decisions.[17] However, for CFS the false-alarm rates were lower than for RTE, did not increase with test probability, and, in fact, were higher in the pedestal conditions. For the parafoveal condition (Table 2), CFS's false-alarm rates were higher than in the fovea and hardly changed with the

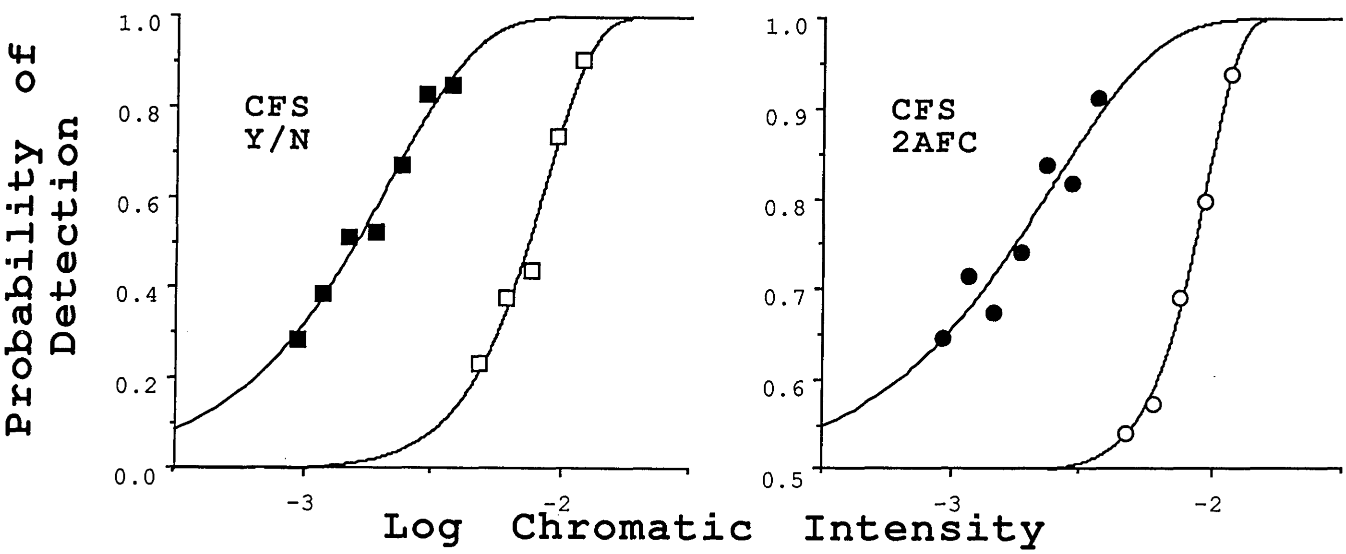

Fig. 3. Parafoveal (2.3° nasal retina) psychometric functions measured by the 2AFC (right-hand side) and Y/N (left-hand side) methods, with a signal probability of 80% for the latter. The Y/N data have been corrected for guessing. Parameters for the Weibull function are given in Table 2. Data are from observer CFS.

Table 2. Parameters of Parafoveal (2.3° Eccentric) Chromatic Detection Measured With and Without Luminance Pedestals for Y/N and 2AFC Procedures[a]

Procedure	Pedestal Condition	$\alpha \times 10^3$	β	e	False-Alarm Rate
Y/N 80%	None	8.62 (0.48)	2.38 (0.49)	1.83 (0.14)	0.47
	Double	2.10 (0.17)	1.26 (0.41)	0.99 (0.13)	0.50
2AFC	None	9.65 (0.22)	3.45 (0.24)	3.07 (0.19)	
	Double	2.47 (0.28)	1.09 (0.26)	0.86 (0.21)	

[a] α, threshold; β, Weibull slope; e, d' power-law exponent; observer CFS. Values in parentheses indicate one half the 90% confidence interval.

pedestal. These rates could be interpreted as showing that the pedestal reduced M, causing fewer false alarms, but λ was also reduced, increasing false alarms and compensating for the change in M.

In summary, the correction for guessing might have eliminated the effect of change in M on the Y/N data, bringing the pedestal and no-pedestal psychometric functions into agreement, and the observed difference in the two psychometric functions could be the result of a shift in λ. To eliminate this possibility and to show that the facilitation is not caused by uncertainty reduction, we must also show that facilitation is at least approximately independent of λ.

These considerations led us to measure ROC's. The same test intensity was used for the pedestal and no-pedestal conditions, and the observer was induced to alter his criterion by varying the probability of test occurrence from 20% to 80% on separate days. The observer had considerable initial practice with each probability, ensuring that the criterion did shift. Only foveal viewing was used. If the facilitation measured with the Y/N method results from a shift of criterion between conditions, then the ROC's for the pedestal and no-pedestal conditions will have different slopes.

Figure 4 shows ROC's for three observers plotted on normal-probability axes. The left-hand side also includes the data from the psychometric functions that were obtained at the same intensity used for the ROC's (smaller symbols).[24] For the data on the right-hand side, the pedestal intensity was increased to +0.106. The data on the right-hand side for RTE were collected six months later than those on the left-hand side, with a 20% higher test intensity (Table 3). The ROC is expressed as[25]

$$Z(\text{hit rate}) = b[Z(\text{false-alarm rate}) - d], \tag{8}$$

where $Z(\ )$ is the inverse cumulative normal transform $\Phi^{-1}(\ )$, b is the slope parameter (the ratio of standard deviations of the noise and the signal-plus-noise distributions), and d is the horizontal intercept corresponding to d' when $b = 1.0$.

Uncertainty alters the slope of ROC's. As Eq. (2) implies, the standard deviation of the noise distribution decreases as M increases [because the integral of the noise distribution, $P(0)$, rises more steeply for larger M]. With no uncertainty, the slope $b = 1.0$, and as M increases the ROC becomes flatter ($b < 1.0$).[7,16,25] Therefore the uncertainty-reduction hypothesis predicts that ROC's measured without the pedestal will be flatter than ROC's measured with it.

Table 3 lists the slope b and intercept d of the ROC's. An analysis of covariance was performed on each of the five data sets in Table 3, and the p values for the pedestal × slope interaction term are given in the last column of the table. In two cases (observer CFS, first line, and RTE, third line) the

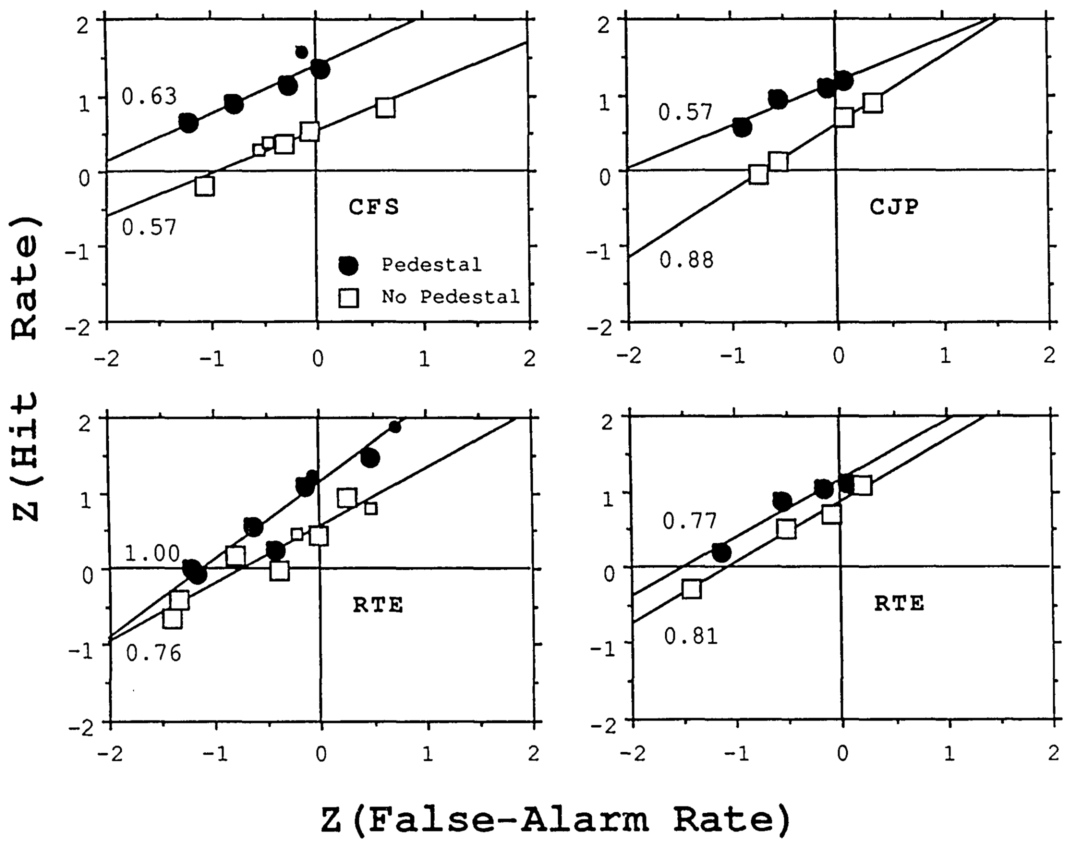

Fig. 4. ROC's plotted on inverse cumulative Gaussian axes. The stimulus intensity and the ROC parameters are given in Table 3; the slope of each ROC is also specified here. Filled and open symbols indicate the pedestal and no-pedestal conditions, respectively. Pedestal intensity was +0.053 on the left-hand side and +0.106 on the right-hand side. Facilitation, indicated by the higher position of the pedestal ROC, is maintained over a large range of criterion levels. Observers are CFS, RTE (two sets of measurements), and CJP. (Smaller symbols on the left-hand side are replotted from the 50% and 80% Y/N psychometric functions of Table 1 and were measured with the same stimulus intensity used for the larger symbols.)

Table 3. ROC Slope b and Intercept d Parameters for Chromatic Detection Measured With and Without the Luminance Pedestal[a]

Observer	Test Intensity $\times 10^3$	No Pedestal b	No Pedestal d	Pedestal b	Pedestal d	p
CFS	1.45	0.57	0.96	0.63	2.21	0.75
RTE	1.32	0.76	0.73	1.00	1.13	0.13
	1.58	0.81	1.09	0.77	1.51	0.81
CJP	1.06	0.88	0.70	0.57	2.03	0.05
EJB	2.38	0.76	1.09	1.24	1.82	0.09
Mean		0.76 (0.10)		0.84 (0.23)		
Mean excluding EJB		0.76 (0.13)		0.74 (0.16)		

[a] p is the probability that pedestal and no-pedestal slopes are the same; values in parentheses are one half the 90% confidence intervals.

pedestal and the no-pedestal ROC's are clearly parallel. RTE's first pair of ROC's is noisy (second line of Table 3 and left-hand side of Fig. 4), and the b values do not differ reliably ($p > 0.10$).[26] CJP has slopes that differ but in the direction opposite that predicted by the uncertainty-reduction hypothesis: the ROC in the pedestal condition is flatter than in the no-pedestal condition. Finally, note that although EJB's slopes differ significantly ($p < 0.10$), changes in uncertainty cannot account for a value of $b > 1.0$ as found for his pedestal ROC. EJB was the least-practiced observer, and he was considerably less sensitive than the other observers, suggesting that perhaps these data should be discounted. The ROC's in general do not support the uncertainty-reduction hypothesis, since the facilitation is approximately independent of the criterion.

DISCUSSION

The luminance pedestal reduces the foveal chromatic threshold approximately twofold and the parafoveal threshold approximately fourfold, even after the Y/N data are corrected for guessing. This result is at odds with the uncertainty reduction hypothesis, provided that two assumptions hold: (1) the correction for guessing is appropriate and (2) the criterion λ is constant.

The correction for guessing [Eq. (4)] exactly recovers $P_{\mathrm{rel}}(c)$, the psychometric function of the relevant channel, only when all the false alarms are caused by irrelevant channels (which is equivalent to high-threshold theory). Pelli (Ref. 5, App. A) demonstrated that, when uncertainty is large, the correction for guessing approximately recovers $P_{\mathrm{rel}}(c)$. However, when M is small, a substantial portion of the false alarms may be caused by noise in the single relevant channel. Therefore, when M is small, only a portion of the false alarms should be used to correct the data. If we assume that $M = 7$ for our foveal, no-pedestal condition, then Pelli's analysis can be used to show[27] that we would not be overcorrecting the data by using 86% of the false alarms to correct for guessing.

However, using 86% (rather than 100%) of the false alarms would cause the corrected pedestal and no-pedestal psychometric functions to differ more, not less, than as shown in Fig. 2 and Table 1 because there were somewhat more false alarms in the pedestal conditions than in the no-pedestal conditions (Table 1). This conclusion, taken with the parafoveal results (Fig. 3 and Table 2) for which the steep psychometric functions imply large M, indicates that the critical assumption in our analysis is not that M is large enough to justify the correction for guessing but that λ did not change enough to produce the observed difference between the pedestal and no-pedestal Y/N psychometric functions. However, recall that the test intensities were lowered in the pedestal condition to keep the proportion of correct responses approximately the same as in the no-pedestal condition, and so there was no inducement for these highly practiced observers to shift criterion. Also note that the corrected Y/N psychometric functions and the 2AFC psychometric functions show the same degree of facilitation, i.e., 2× in the fovea (Fig. 2) and 4× in the parafovea (Fig. 3). It seems implausible that a criterion shift would cause almost exactly the same facilitation for Y/N data as the putative reduction in M caused for 2AFC data.

The ROC's for the pedestal and no-pedestal conditions (Fig. 4 and Table 3) both have a slope $b = 0.75$, on average. This slope implies that the standard deviation of the noise distribution is approximately three quarters as large as the standard deviation of the signal-plus-noise distribution, independent of the pedestal, which is inconsistent with the uncertainty reduction hypothesis. If the ROC's are truly parallel, the facilitation cannot depend on λ, and thus the observed difference between the pedestal and no-pedestal psychometric functions cannot result from a criterion shift compensating for a reduction in M.

Unfortunately the ROC analysis is noisy, and it is difficult in principle to confirm that no difference exists between noisy sets of data (i.e., to confirm the null hypothesis). However, neither the ROC's nor the Y/N psychometric functions provide any support for the uncertainty-reduction hypothesis. It therefore seems most parsimonious to conclude that the mechanism that produces facilitation with the Y/N task is the same mechanism that produces facilitation with the 2AFC task. According to Pelli's uncertainty model, that mechanism cannot be a reduction in M, and therefore we tentatively reject the uncertainty reduction hypothesis.

Although our test of the uncertainty reduction hypothesis was based on the model of Pelli,[5] with a single relevant channel, our rejection of the hypothesis can be generalized. First, our main conclusions would not be altered if there were more than one relevant channel. Second, the model of Pelli[5] is based on Gaussian distributions. However, Poisson[25] and double-exponential[12] probability distributions generate similar predictions (although the magnitude of the effect of uncertainty depends on the assumed distribution). Third, although in Pelli's model the decision is based on the channel with the largest likelihood, Nolte and Jaarsma[16] show similar predictions for cases in which the decision is based on a sum of likelihoods (the optimum decision rule). Thus our rejection of the uncertainty reduction hypothesis does not depend on the details of the uncertainty model. We should emphasize that this rejection does not mean that the uncertainty models are wrong in general; it means only that they do not seem capable of accounting for the facilitation of chromatic detection by luminance contours.

Some forms of uncertainty can be manipulated directly.

For instance, better fixation stimuli might be expected to reduce spatial uncertainty. Cole *et al.*,[3] however, showed that the use of a fine fixation cross hair centered on the test did not reduce facilitation by the pedestal, suggesting that fixational uncertainty has little effect. The same study also found that facilitation is monoptic: facilitation does not occur when the chromatic test and the luminance pedestal are presented to opposite eyes (with the adapting field viewed by both eyes). The stimuli appear much the same with monoptic and dichoptic viewing, and thus facilitation might be expected to be equal for the two conditions, if the appearance and the uncertainty vary together. Finally, Cole *et al.*[3] observed that, with monoptic viewing, briefly increasing the luminance of the entire 6.2° field as a pedestal did not facilitate chromatic detection of the 1° test spot, indicating that reducing extrinsic temporal uncertainty alone is not sufficient to lower threshold.

The present study tested for intrinsic uncertainty effects that cannot be directly manipulated. The visual system might normally monitor many spatiotemporal locations and would switch to monitoring a smaller number of locations only if the field is divided into regions by suprathreshold contours. The current results show that even this form of uncertainty reduction does not adequately account for the facilitation.

The essence of our result is that the luminance pedestal does not just select a subset of chromatic detectors from a larger set, with the properties of the detectors themselves being unaffected by the pedestal. Other explanations might involve adaptive mechanisms, such as spatial integration within contours as suggested by Boynton *et al.*[1] or diffusive filling in around and between contours as proposed by Grossberg and Mingolla,[28] in which suprathreshold edges could alter the gain, integration area, or other properties of chromatic-detection mechanisms.

ACKNOWLEDGMENTS

This research was supported by grants AFOSR 89-0304 from the U.S. Air Force Office of Scientific Research and EY01808 from the National Institutes of Health. We are grateful for comments on the manuscript provided by Patrick Cavanagh, Denis Pelli, and Stanley A. Klein.

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10. Foley and Legge[11] also considered these two ways in which uncertainty can lead to pedestal facilitation: (1) they referred to a reduction of M as altering signal-only uncertainty and (2) they referred to a reduction of the effect of uncertainty (fixed M, shifted operating point) as altering signal-and-pedestal uncertainty because the test and the pedestal stimulate the same channel and uncertainty affects both. Discussions of intrinsic uncertainty usually focus on the latter model, whereas studies of extrinsic uncertainty (e.g., in which two or more test stimuli are intermixed[12]) attempt to manipulate M directly and are thus similar to signal-only uncertainty. The uncertainty examined here is similar to signal-only uncertainty, although the uncertainty is intrinsic in that we do not deliberately introduce it. These two uncertainty models make equivalent predictions for the facilitation effects discussed in the present paper, although their predictions for subthreshold summation are different, as discussed in the Introduction. The facilitation effects discussed by Pelli[5] are produced with M fixed and a shifted operating point, but equivalent predictions would be made for suprathreshold pedestals that reduce M.
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22. The e value for the 50% single-pedestal condition for observer RTE was inflated by a few slightly negative d' values at low intensities.
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966–1009 (1987). However, it is not obvious how to interpret the 44× *increase* in M, the number of channels, which is called for by the uncertainty model.

24. Two data points on the lower-intensity ROC's for observer RTE were replicated, as shown by the extra number of large symbols on the left-hand side, bottom of Fig. 3.
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26. We can also test whether RTE's first pair of ROC's are quantitatively consistent with the uncertainty reduction hypothesis. We assume that $M = 1$ for the pedestal condition, consistent with the slope of the psychometric function ($\beta \cong 1.25$). Calculations based on Eqs. (1) and (2) show that the no-pedestal ROC slope of 0.76 is too shallow to be produced by an increase in uncertainty, given that we start with $b = 1.0$ and $d = d' = c = 1.13$ for $M = 1$ (see the Introduction for the definition of c). An intuitive understanding of this result can be obtained by noting that uncertainty reduces b more at high d values.[7,16] The no-pedestal ROC for observer RTE is too shallow for its low d value. Therefore both pairs of ROC's for this observer are inconsistent with the pedestal's solely acting to reduce M, even if the first pair of slopes is treated as significantly different.
27. Pelli (Ref. 5, App. A) showed that when the ratio of irrelevant to relevant channels is greater than 99, the measured false-alarm rate is no more than 1% higher than the spurious hit rate, and therefore the corrected psychometric function closely approximates $P_{\text{rel}}(c)$. Let us assume that $M = 7$ and that one channel is relevant. Then $M/(M - 1) = 1.17$, and Pelli's Eq. (A.4) shows that the spurious hit rate (he calls this the irrelevant hit rate G) is no more than 1.17× the false-alarm rate. This provides a lower bound on the fraction of $P(0)$ due to irrelevant channels. Therefore using $P(0)/1.17$ in the correction for guessing would guarantee that we were not overcorrecting the Y/N psychometric functions.
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