Decoupling Stimulus Duration From Brightness in Metacontrast Masking: Data and Models

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A brief target that is visible when displayed alone can be rendered invisible by a trailing stimulus (metacontrast masking). It has been difficult to determine the temporal dynamics of masking to date because increments in stimulus duration have been invariably confounded with apparent brightness (Bloch's law). In the research reported here, stimulus luminance was adjusted to maintain constant brightness across all durations. Increasing target duration yielded classical U-shaped masking functions, whereas increasing mask duration yielded monotonic decreasing functions. These results are compared with predictions from 6 theoretical models, with the lateral inhibition model providing the best overall fit. It is tentatively suggested that different underlying mechanisms may mediate the U-shaped and monotonic functions obtained with increasing durations of target and mask, respectively.

A briefly presented target shape that is clearly visible when shown alone becomes nearly invisible when it is followed by a second (masking) shape consisting of closely adjacent but nonoverlapping contours. If perception were true to the temporal sequence of events, the display would be seen as consisting of a leading target and a trailing mask. Instead, at optimal target–mask intervals, the target is seen dimly or not at all, and only the mask is seen clearly. This indicates that the neural code of the target remains vulnerable to interference from the activity elicited by the trailing mask over delays of up to 100 ms. This form of masking, called *metacontrast masking*, has provided important insights into the temporal and spatial dynamics of visual processing for almost 100 years (Stigler, 1910; see reviews by Breitmeyer 1984; Breitmeyer & Ogmen, 2000).

Given the rich legacy of research on metacontrast masking, it is surprising that there is still uncertainty regarding its critical temporal factors. Three hypotheses have been proposed. A commonly advanced hypothesis specifies that the critical factor is the time that elapses between the onset of the target and the onset of the mask (*stimulus onset asynchrony* [SOA]). This hypothesis has received considerable support in the literature, with some research-

ers even referring to the *onset–onset law* (Kahneman, 1967) or *SOA law* (Breitmeyer, 1984). A second hypothesis identifies the critical factor as the time that elapses between the offset of the target and the onset of the mask (*interstimulus interval* [ISI]; Francis, 1997). A third hypothesis singles out the interval that elapses between the offset of the target and the offset of the mask (*stimulus termination asynchrony* [STA]; Macknik & Livingstone, 1998). The temporal relationships among SOA, ISI, and STA, as well as those between target and mask durations, are illustrated in Figure 1A.

On the face of it, deciding among these hypotheses should be a simple matter of matching their predictions against the relevant evidence, but things are not that simple. Consider the study cited most frequently as providing evidence for the importance of an SOA law. Kahneman (1967) systematically varied the exposure duration of the target and the ISI over a wide range of SOAs and reported the characteristic U-shaped function of target visibility. When SOA was very short or very long, the target was clearly visible; at intermediate SOAs, however, perception of the target was substantially impaired. An equally important aspect of these results was that, for any given SOA, the visibility curves for targets of different durations overlapped almost perfectly, thus ruling out ISI and implicating SOA as the critical temporal factor.

What is not often noted about Kahneman's (1967) study, however, is that the duration of the mask was covaried with the duration of the target: Brief masks followed brief targets, and long masks followed long targets. This covariation makes it impossible to be sure whether the SOA law will still hold if the duration of the target is varied and the mask is fixed at a single duration. It can be noted only that it should hold, because what happens after the onset of the mask is of no relevance to the SOA law, which refers to target and mask onsets.

The covaried duration of target and mask in Kahneman's study (1967) has also opened up the results to alternative interpretations. For example, the object-substitution theory proposed by Di Lollo, Enns, and Rensink (2000) predicts that masking will increase as a function of mask duration. From this perspective, the progressively
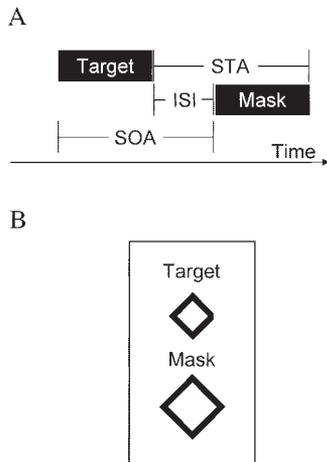
A

B

Figure 1. A: Schematic representation of the temporal relationship among interstimulus interval (ISI), stimulus onset asynchrony (SOA), and stimulus termination asynchrony (STA). B: Schematic representation of the stimuli used in Experiments 1–3.

stronger masking observed by Kahneman as target duration was increased to an intermediate level can be attributed to corresponding increments in the duration of the mask. At durations beyond an intermediate level, more processing of the target could be accomplished before the arrival of the mask, and target visibility improved accordingly. On this account, the U-shaped masking function obtained by Kahneman is attributable not to increments in the duration of the target, which increase the SOA, but to increments in the duration of the mask, which are independent of SOA.

Evidence that ISI can play a critical role has also served to undermine the general importance of SOA in metacontrast. A formal model espousing ISI as the critical temporal factor in metacontrast masking has been proposed by Francis (1997). This proposal was based in part on Schiller's (1965) finding that the accuracy of target identification improved monotonically as the duration of the target was increased. If SOA were critical in these data, the function relating identification accuracy to target duration should have been U-shaped, not monotonic.

However, Schiller's (1965) finding cannot be regarded as unambiguous evidence against the SOA law. This is because increments in stimulus duration were always accompanied by corresponding increments in overall stimulus energy. This is of relevance because of the time–intensity reciprocity in vision known as *Bloch's law* at threshold. This reciprocity means that the perceived brightness of a brief stimulus will covary with its duration. If target brightness has an influence on target visibility, then increments in target duration, such as those implemented by Schiller, would be expected to reduce masking simply because of concomitant increments in perceived target brightness. Target duration might in itself not be critical.

This possibility was raised by some of the earliest researchers of metacontrast masking. For example, Alpern (1953) reported masking under conditions of varying target and mask duration, with results similar to Schiller's (1965), but he warned, "For short flashes, prolonging the duration of the [target] should be comparable to increasing its luminance" and "prolongation of [the mask's] duration would tend to increase the magnitude of [mask-

ing] due to the increase in energy of the [mask]" (Alpern, 1953, pp. 651–652). Yet, for reasons unknown to us, this issue was not considered important in the ensuing literature on metacontrast masking.

A third challenge to the importance of SOA comes from experiments showing the importance of STA in metacontrast masking (Macknik & Livingstone, 1998). In this study, target and mask durations were varied systematically from 20 to 90 ms, with ISIs and SOAs varying over a wide range (0–200 ms). The main finding was that optimal masking across these various conditions did not occur at any particular ISI or SOA. Instead, many of the accuracy functions reached the lowest level when the interval between target offset and mask offset (STA) was approximately 100 ms. But given what we have already noted for Kahneman's (1967) and Schiller's (1965) data, alternative interpretations are possible. For example, object-substitution theory also predicts that masking will be especially strong when the mask has been on view for as long as 100 ms following the offset of the target, regardless of SOA or ISI (Di Lollo et al., 2000). Also, given that stimulus duration and brightness were covaried in the Macknik and Livingstone study, it is possible that the strength of masking obtained at longer mask durations was due, at least in part, to concomitant increments in mask brightness.

The present experiments were designed to help pinpoint the critical temporal factors involved in metacontrast masking. A crucial first step was to decouple the close link in past studies between stimulus duration and brightness. This step was important because both of these factors are varied when comparisons are made between different values of SOA (holding ISI constant) and between different values of ISI (holding SOA constant), as is illustrated in Figure 1A. The goal of decoupling duration and brightness was accomplished in the present study by comparing display sequences in which brightness was matched for stimuli of varying duration with display sequences in which brightness covaried with duration, as in previous studies.

In the present work, we focused on two temporal factors in metacontrast masking: SOA and mask duration. In Experiments 1 and 2, we examined the role of SOA by manipulating target duration while holding ISI constant at zero, except in a control condition in which the ISI was varied systematically, as in conventional metacontrast studies. The effect of varying mask duration was examined in Experiment 3. However, it should be clear that this is only a beginning. It is our understanding that once stimulus duration and brightness have been decoupled for the temporal effects regarding SOA, it will be important in future studies to test whether (a) any of the other temporal factors proposed for metacontrast masking (e.g., STA) are also critical with regard to time per se or (b) these temporal factors merely contribute to visibility through their influence on stimulus brightness.

Experiment 1: Masking as a Function of Target Duration

In Experiment 1, we studied the magnitude and time course of metacontrast masking as a function of the exposure duration of the target stimulus. The experiment comprised three conditions designed to decouple increments in target duration from concomitant increments in target brightness: the *gap* condition, the *fixed-luminance* condition, and the *brightness-matched* condition. In the gap condition, the display began with a brief presentation of the

target, continued with a variable temporal gap (ISI) during which the screen remained blank, and ended with a brief presentation of the mask. This display sequence is similar to that used in conventional masking studies. The fixed-luminance condition was the same as the gap condition, except that the target was displayed throughout the period occupied by the ISI in the gap condition. The target was displayed at a fixed luminance, and its duration was varied systematically, with the ISI always equal to zero. This condition was designed to study the effect of target duration when brightness is allowed to covary with duration, as was done by Schiller (1965). Finally, the brightness-matched condition was the same as the fixed-luminance condition, except that the target was displayed at progressively lower levels of luminance as exposure duration was increased so as to maintain a constant level of brightness at all durations. The range of SOAs was the same in all three conditions.

The critical comparison in this experiment is between the gap and the brightness-matched conditions. According to the SOA law, U-shaped metacontrast functions should be obtained in both these conditions because they share the same range of SOAs. In contrast, if masking is governed by ISI rather than SOA, a U-shaped function should be found in the gap condition but not in the brightness-matched condition because, in the latter, the ISI is equal to zero at all target durations. For this reason, the ISI hypothesis would predict that the brightness-matched condition should yield a flat function of accuracy throughout the domain. Finally, according to the STA hypothesis, the magnitude of masking should be a function of STA, with a maximum at an STA of about 100 ms. This prediction would apply to the gap condition, in which STA varies over a range set by the sum of ISI and mask durations. In the brightness-matched condition, however, the STA hypothesis would predict that masking, if any, should remain constant throughout the domain because the STA has a constant value, set by the duration of the mask, at all target durations.

Method

Observers. Two of the authors (Adrian von Mühlenen [AVM] and Vincent Di Lollo [VDL]) and 2 assistants unaware of the purpose of the study (MIR and SMG) participated in all of the experiments. All had normal or corrected-to-normal vision and received approximately 500 practice trials before beginning the experiments.

Apparatus. The experiments were conducted in a darkened room. Stimuli were presented on a Tektronix 608 point-plotting oscilloscope equipped with fast P15 phosphor. Observers viewed the display with natural pupils from a distance of 57 cm, set by a headrest. Screen illumination of 10 cd/m² was provided by a pair of shielded 15-cm Sylvania F4T5CW fluorescent tubes located to the front and sides of the display surface. All stimuli were constructed with closely spaced dots that were seen as green–blue on a uniform white background. The oscilloscope was driven by an Interactive Electronic Systems point plotter (Finley, 1985) that displayed dots at a rate of $1/\mu s$. Photometric measurements were made with a Minolta LS-100 luminance meter. Responses were recorded using the arrow keys of a computer keyboard.

Stimuli. The stimuli are illustrated in Figure 1B. The target stimulus consisted of a diamond-shaped outline with outer-side length of 1.10° (1° 6 min of arc) and thickness of 0.18° (10.8 min of arc). One corner of the target diamond, chosen randomly on each trial, was truncated. Observers were required to indicate the location (top, bottom, left, or right) of the truncated corner. The masking stimulus consisted of a larger diamond outline, with outer-side length of 1.50° (1° 30 min of arc) and thickness of 0.18° (10.8 min of arc). The spatial separation between target and mask

was 0.044° (2.64 min of arc). When displayed simultaneously, the target and the mask formed a uniform diamond shape without any visible border or interruption between them.

Design and procedure. A dim fixation point was displayed at all times in the center of the screen. Observers initiated a trial by pressing the spacebar, and the display sequence began after an interval of 250 ms. In the gap condition, the target was presented for 10 ms at a luminance of 100 cd/m². This was followed by an ISI of either 0, 10, 20, 30, 50, 70, or 150 ms during which the screen remained blank. The mask was then displayed for 10 ms at a luminance of 100 cd/m². In the remaining two conditions, the target was presented for 10, 20, 30, 40, 60, 80, or 160 ms at a luminance that depended on the condition, as described below. The mask was then presented for 10 ms at a luminance of 100 cd/m² directly after target offset. One experimental session comprised 50 trials at each of the seven SOAs. In each of the three conditions, each observer completed two sessions: one in ascending order of SOA, the other in descending order. The order of sessions was determined randomly for each observer. Thus, each observer completed a total of 2,100 trials (3 conditions × 7 SOAs × 2 blocks × 50 trials per block).

Brightness matching. The principal objective of the present study was to decouple the effects of target duration and target brightness on the magnitude of metacontrast masking. For that purpose, we used two main conditions: fixed luminance and brightness matched. In the fixed-luminance condition, all stimuli were displayed at a luminance of 100 cd/m². This made the brief 10-ms target stimulus comfortably visible, but the brightness of the target increased markedly as its exposure duration was increased so that stimulus brightness covaried with stimulus duration, as in earlier studies (e.g., Alpern, 1953; Schiller, 1965). That covariation was avoided in the brightness-matched condition by progressively reducing the luminance of the target as its duration was increased so as to maintain a fixed level of brightness across all exposure durations.[1]

We adopted a version of the brightness-matching procedures used by earlier investigators for the same purpose (e.g., Di Lollo & Finley, 1986; Servière et al., 1977). This procedure ensures that stimuli of different durations have equal levels of energy (integrated over the critical period of time–intensity reciprocity) rather than equal levels of luminance. This means that luminance levels are decreased correspondingly as stimulus

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[1] An important consideration regarding brightness-matched stimuli is the latency of the visual response. It is known that for stimuli of equal duration, the latency of the visual response varies inversely with stimulus luminance. This inverse relationship was discovered long ago using response measures ranging from single-unit recordings (Hartline, 1934, 1938) to psychophysical reaction time (Cattell, 1885). However, in those experiments, the higher luminance stimuli were also visibly brighter. A question now arises regarding the latency of the visual responses triggered by brightness-matched stimuli of different durations. Bearing in mind that, by definition, such stimuli must vary in absolute level of luminance, the question is this: Do visual responses triggered by brief high-luminance stimuli have shorter latencies than those triggered by longer low-luminance (brightness-matched) stimuli, thereby confounding response latency with stimulus duration? Servière, Miceli, and Galifret (1977) answered this question in the negative by recording the latency of cortical evoked-potential responses to brightness-matched stimuli that varied in duration from 0.5 to 320.0 ms. They found that the slope of the function relating latency of the visual response to the duration of the brightness-matched stimuli was equal to zero. This finding with cortical responses is in agreement with earlier findings using single-unit recordings (Hartline, 1934). It is also in agreement with Onley and Boynton's (1962) finding that the magnitude of visual responses to brightness-matched stimuli is related not to the physical luminance of the stimulus but to its brightness. Thus, the extant results clearly indicate that the latency of the visual response for brightness-matched stimuli is constant across all stimulus durations within the range of our experiment.

duration is increased. The luminance values used in the present brightness-matched condition were taken from those used in earlier studies performed with the same equipment (Bischof & Di Lollo, 1995; Di Lollo, Hogben, & Dixon, 1994; Dixon & Di Lollo, 1994). As a check on the validity of those luminance values for the present study, a separate calibration run was performed by one of the authors (VDL), a practiced psychophysical observer. The luminance values thus obtained matched those of the earlier studies.

In the calibration run, as in the earlier studies, a dynamic threshold-tracking procedure (PEST; Taylor & Creelman, 1967) was used to converge on a critical luminance value for each stimulus duration. Two square patches ($0.5° \times 0.5°$) were displayed side by side. The *standard patch* was displayed for 10 ms at a luminance of 100 cd/m²; the *comparison patch* was displayed for one of the remaining six durations (20, 30, 40, 60, 80, or 160 ms, in separate blocks) at an initial luminance of 100 cd/m². The location (left or right) of the longer patch was determined randomly on each trial. Observers indicated which patch was brighter, and PEST varied the luminance of the comparison patch until its brightness became indistinguishable from that of the standard patch. The levels of luminance at which longer stimuli were displayed in order to appear as bright as a 10-ms stimulus displayed at a luminance of 100 cd/m² were 100, 43, 29, 21, 16, 15, and 14 cd/m² for stimulus durations of 10, 20, 30, 40, 60, 80, and 160 ms, respectively.[2]

Results and Discussion

Figure 2 shows the individual and group results for the brightness-matched and the gap conditions. In every case, the results reveal classical U-shaped masking functions peaking at SOAs around 30–40 ms. For 2 observers (AVM and VDL), the magnitude and time course of masking were virtually the same in the two conditions, pointing to SOA as the main determining factor. For the remaining 2 observers (MIR and SMG), the magnitude of masking was somewhat reduced in the brightness-matched condition, confirming the importance of SOA, but suggesting a possible role for ISI. Even for the latter 2 observers, however, masking followed similar time courses in the two conditions, again pointing to SOA as the main determining factor.

The pattern of results in Figure 2 is broadly consistent with expectations based on the SOA law. In contrast, the results are at odds with predictions based on ISI or STA. If the magnitude and temporal course of metacontrast masking is governed mainly by ISI, then it is necessary to explain why the results in the gap condition, in which the ISI varied over an appreciable range, are so similar to those in the brightness-matched condition, in which the ISI was always equal to zero.

The results are equally unsupportive of the STA hypothesis, which postulates that the strength of metacontrast masking is governed by the temporal interval that elapses from the offset of the target to the offset of the mask, with optimal masking occurring at an STA of about 100 ms (Macknik & Livingstone, 1998). This prediction is disconfirmed by the data in Figure 2 in three ways. First, the magnitude of masking in the brightness-matched condition should have remained constant across all values of SOA because STA was set at a constant 10 ms throughout the domain. This does not describe the data in Figure 2. Second, on the basis of Macknik and Livingstone's results, little or no masking should have occurred at an STA as brief as 10 ms, yet substantial masking was in evidence in the brightness-matched condition for each observer. Finally, it should be noted that in the gap condition, STA increased apace with SOA. Therefore, masking should have increased progressively up to an SOA of 80 ms, corresponding to an
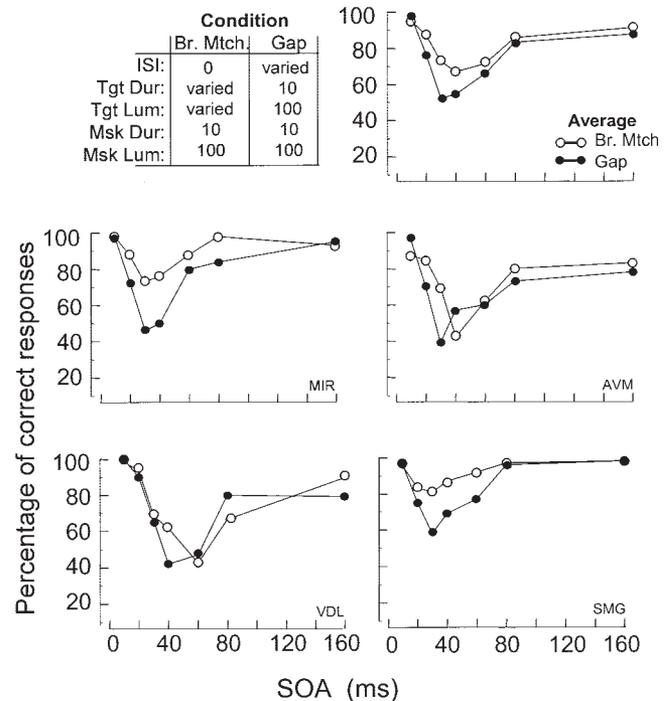

Figure 2. Percentages of correct responses in the brightness-matched (Br. Mtch.) and gap conditions as a function of the duration of the target stimulus for all observers (MIR, AVM, VDL, and SMG) in Experiment 1. ISI = interstimulus interval (ms); Tgt Dur = target duration (ms); Tgt Lum = target luminance (cd/m²); Msk Dur = mask duration (ms); Msk Lum = mask luminance (cd/m²); SOA = stimulus onset asynchrony.

STA of 70 ms, which is close to the optimal STA of 100 ms postulated in the STA hypothesis. Again, this expectation is not supported by the data in Figure 2, which show clear minima at an SOA of about 40 ms. These results are therefore clearly in need of explanatory factors other than STA.

Illustrated in Figure 3 are the results for the fixed-luminance condition. The effect of the covariation between duration and brightness is revealed by a comparison of the data in Figure 3 with the results of the brightness-matched condition in Figure 2. At the shortest target duration (10 ms), the display sequences in the two conditions were identical, and accuracy of target identification was nearly perfect in both cases. As target duration was increased, accuracy first declined and then improved in the brightness-matched condition (see Figure 2) but remained consistently high in the fixed-luminance condition (see Figure 3). We suggest that the absence of an initial decrement in the fixed-luminance condition (see Figure 3) should be ascribed to a covariation of duration and

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[2] The present brightness-matching procedure was designed to compensate not only for Bloch's law (which, strictly speaking, applies exactly only at threshold and over durations of less than about 60 ms in photopic viewing; Biersdorf, 1955) but also for other factors that covary with exposure duration and influence the brightness of the display. Included among these are the Broca–Sulzer effect and the temporal dynamics of the oscilloscope's phosphor in response to brief bursts of activation. The brightness-matched values obtained with this procedure, therefore, represent the combined influences of all these factors at each exposure duration.
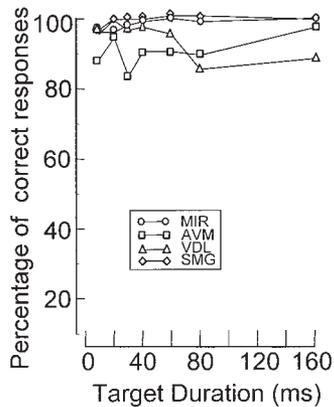
Figure 3. Percentages of correct responses in the fixed-luminance condition as a function of the duration of the target stimulus for all observers (MIR, AVM, VDL, and SMG) in Experiment 1.

brightness. As target duration was increased beyond 10 ms, the corresponding increment in target brightness due to time–intensity reciprocity compensated for the loss of target visibility due to masking. Thus, the U-shaped masking function predicted by the SOA law was in evidence in the brightness-matched condition but not in the fixed-luminance condition because duration and brightness were confounded in the latter.

Before reaching a definitive conclusion on this issue, it is prudent to consider whether the absence of an initial decrement in the fixed-luminance condition (see Figure 3) may have arisen spuriously through a ceiling effect. It is possible that the effect of target duration was actually the same in the brightness-matched and fixed-luminance conditions but that a U-shaped function is not in evidence in the fixed-luminance results because accuracy was compressed against the 100% limit imposed by the response scale. To examine this possibility, we performed a subsidiary experiment (Experiment 1a) in which the fixed-luminance condition was replicated using a lower level of target luminance so as to bring performance within a measurable range.

Experiment 1a

Method

Observers, apparatus, and procedure in Experiment 1a were the same as in the fixed-luminance condition in Experiment 1, except that the target was displayed at each of three levels of luminance: 43, 21, and 16 cd/m², which were the luminance levels used in Experiment 1 to match the brightness for target durations of 20, 40, and 80 ms, respectively. Data for the three luminance levels were collected in separate blocks of trials.

Results and Discussion

The results, averaged over the 4 observers, are illustrated in Figure 4. Also illustrated in Figure 4 are the results of the fixed-luminance condition in Experiment 1, averaged over the 4 observers. A 4 (luminance levels) × 7 (target durations) within-subject analysis of variance was performed on the results. The analysis revealed significant effects of target luminance, $F(3, 9) = 6.24$, $p < .02$, $MSE = 159.45$, and target duration, $F(6, 18) = 32.46$, $p < .001$, $MSE = 160.50$; the Target Luminance × Target Duration interaction was also significant, $F(18, 54) = 12.53$, $p < .001$,

$MSE = 60.97$. The curves in Figure 4 are uniformly monotonic, with no evidence of the initial decrement characteristic of U-shaped functions. We can, therefore, be confident that the curves illustrated in Figure 3 failed to reveal an initial decrement not because of a ceiling effect but because the visibility of the target increased progressively as its brightness increased with increasing exposure duration.

The results in Figure 4 are very similar to the results obtained by Schiller (1965) in a masking study in which the energy (brightness) of the target covaried with its exposure duration. This is the kind of evidence that led Francis (1997) to question the SOA law of metacontrast masking in favor of an ISI law. We have argued, however, that Schiller's failure to obtain a U-shaped metacontrast function does not provide conclusive evidence against the SOA law because duration and brightness covaried in that study. In brief, we believe that the reason for the absence of a U-shaped masking function was the same for Schiller's study as for the present work.

But there are also some important differences between Schiller's (1965) study and the present work. Perhaps most notable is the difference in the range of target durations between Schiller's study (5–13 ms) and the present experiment (10–160 ms). This difference is important because, as we have noted, Francis's (1997) rejection of SOA in favor of ISI as the critical temporal factor in metacontrast masking was based in part on Schiller's work. It is important, therefore, to establish how the strength and time course of metacontrast masking are affected by the covariation of duration and brightness over the range of target durations used in Schiller's study. Mainly for this reason, the fixed-luminance and the brightness-matched conditions in Experiment 1 were explored further in Experiment 2, with three modifications. First, we used the same range of stimulus durations as were used by Schiller. Second, we reduced the intensity of the target in order to bring performance below the ceiling level imposed by the response scale. Third, we added a fixed-duration condition in which target duration was held constant at 5 ms, and target luminance was increased systematically to match the brightness increments in the fixed-luminance condition according to Bloch's law. Our intent in adding this condition was to emphasize the equivalence of lumi-
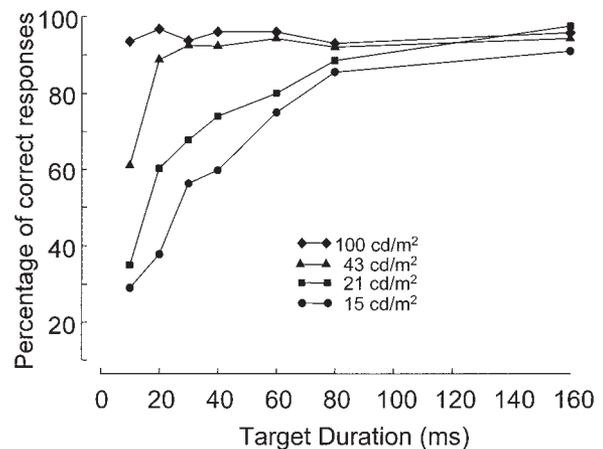

Figure 4. Mean percentages of correct responses as a function of target duration and target luminance in Experiment 1a. Data for the 100-cd/m² condition are from the fixed-luminance condition in Experiment 1.

nance and duration as determinants of metacontrast masking in the fixed-luminance and fixed-duration conditions.

Experiment 2: Further Decoupling of Duration and Brightness

Method

Observers, apparatus, and procedure in Experiment 2 were the same as in Experiment 1, except for the following. Experiment 2 comprised three conditions: fixed luminance, brightness matched, and fixed duration. In the fixed-luminance condition, the target was displayed for either 5, 7, 9, 11, or 13 ms, as in Schiller's (1965) study, at a luminance of 50 cd/m^2, followed directly by a 10-ms presentation of the mask at a luminance of 100 cd/m^2. We used a lower target luminance than in the corresponding condition in Experiment 1 in order to bring performance within a measurable range and, thus, avoid the ceiling problem evident in Figure 3. The brightness-matched condition was the same as the fixed-luminance condition, except that as the duration of the target was increased, its luminance was decreased correspondingly. The specific levels of luminance were 95, 66, 50, 37, and 32 cd/m^2 for target durations of 5, 7, 9, 11, and 13 ms, respectively. These luminance levels were determined by Observer VDL (who had verified the luminance levels for Experiment 1) with the PEST procedure described in Experiment 1. In the PEST run, the duration of the standard stimulus was set at 9 ms, and its luminance was set at 50 cd/m^2. We chose a value of 50 cd/m^2 because, in the fixed-luminance condition in Experiment 1, that value yielded a level of performance that was about halfway between chance and 100% correct responses. The luminance of the stimuli for all other durations was determined on this basis.

In the fixed-duration condition, the target's duration was fixed at 5 ms, which is the shortest duration used in the other two conditions and in Schiller's (1965) study. The main factor manipulated in this condition was the luminance of the target, which could be either 50, 70, 90, 110, or 130 cd/m^2. Our objective in selecting these luminance values was to match the energy level at each step in the fixed-duration condition to the corresponding step in the fixed-luminance condition on the basis of Bloch's law. That is, the product of luminance and duration was the same for corresponding combinations of the two variables in the two conditions. For example, in the fixed-luminance condition, the product of the shortest target duration (5 ms) and the level of luminance (50 cd/m^2) was equal to 250. This is the same as the product of the lowest luminance level (50 cd/m^2) and the

duration of the target (5 ms) in the fixed-duration condition. Similar equivalence held for each target duration in the fixed-luminance condition and for the corresponding target luminance in the fixed-duration condition. This procedure could be applied validly in the present experiment because the stimulus durations were well within the range for which the multiplicative time–intensity relationship expressed in Bloch's law is known to apply exactly (Biersdorf, 1955).

Results and Discussion

Figure 5A shows the individual results for the fixed-luminance condition. Also shown in Figure 5A are the results obtained by Schiller (1965) in a similar experiment in which target durations ranged between 5 and 13 ms, with ISI equal to zero. The uniformly monotonic slopes revealed in this type of study have been regarded as evidence that accuracy improves (i.e., strength of metacontrast masking decreases) as target duration is increased, thus disconfirming the SOA law (Francis, 1997). Such an interpretation, however, is vitiated by the fact that in these studies, target brightness was invariably confounded with target duration. This means that the improvements in performance shown in Figure 5A and in Schiller's study could have been mediated by increments in either target duration or target brightness or a combination of both.

A comparison between the fixed-luminance and brightness-matched conditions (see Figures 5A and 5B) indicates that the critical factor underlying the positive slopes in Figure 5A was target brightness and not target duration. When duration and brightness were decoupled (see Figure 5B), the slopes become uniformly negative: −1.3, −0.1, −1.9, and −0.7, for Observers MIR, AVM, VDL, and SMG, respectively. Negative slopes as a function of target duration is precisely what would be expected on the SOA hypothesis: They represent the incipient descending arm of the U-shaped functions illustrated in Figure 2. What is more, very similar negative slopes were found in the brightness-matched condition of Experiment 2 (see Figure 5B) and over comparable target durations (10–20 ms) in the brightness-matched condition of Experiment 1 (see Figure 2). The corresponding slopes were −0.73 in Experiment 1 and −0.99 in Experiment 2. We conclude

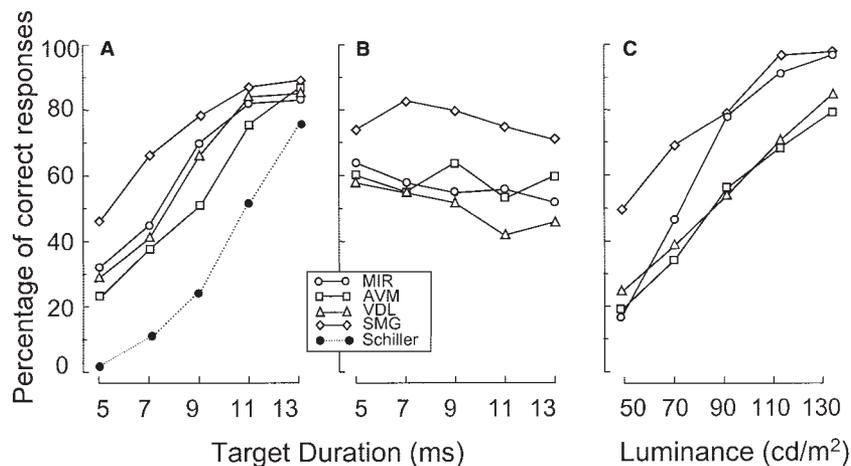*Figure 5.* Percentages of correct responses as a function of target duration in Experiment 2. A: The continuous lines represent the results of individual observers (MIR, AVM, VDL, and SMG) in the fixed-luminance condition; the dotted line represents results reported by Schiller (1965). B: Results of individual observers in the brightness-matched condition. C: Results of individual observers in the fixed-duration condition.

that the positive slopes seen in Figure 5A and in Schiller's (1965) study were due to increments in target brightness, not increments in target duration per se.

This conclusion is buttressed by a comparison between the fixed-luminance and the fixed-duration conditions (see Figures 5A and 5C). The correspondence between the two sets of results is remarkable. Not only is the overall pattern in Figure 5A very similar to that in Figure 5C, but there is a strong tendency for the results of individual observers to maintain their relative ranks in the two figures. For example, accuracy for Observer SMG was the highest, and that for Observer AVM the lowest, in both conditions. The common factor in the two sets of results was the progressive increment in target brightness (energy) arising from time–intensity reciprocity (Bloch's law) in the fixed-luminance condition (see Figure 5A) and from corresponding luminance increments in the fixed-duration condition (see Figure 5C). This means that the positive functions seen in Figures 5A and 5C were the result of increments in target brightness, regardless of whether they were produced by increments in target duration or in target luminance. Increments in target duration per se yield the negative slopes seen in Figure 5B.

There is one further, and even more cogent, reason why U-shaped metacontrast functions could not be in evidence in any of the conditions in Experiment 2 or in Schiller's (1965) experiment. The reason is that, in every case, the absolute values of SOA—set by the target's exposure duration—were too small, and their range too narrow, to yield a U-shaped function. The metacontrast literature indicates that SOAs as brief as 5–13 ms are insufficient to produce masking of any consequence, let alone U-shaped functions, which typically show minima over SOA ranges of 100 ms and beyond (Breitmeyer, 1984; Breitmeyer & Ogmen, 2000). In contrast, increasing the target's exposure duration over the 5–13 ms range is a perfectly adequate way of revealing the effects of stimulus energy (brightness), which, according to Bloch's law, increases by 260% over the range 5–13 ms when energy covaries with duration (see also Breitmeyer, 1978).

Collectively, the results of the experiments reported thus far are unambiguous: Increments in target duration, when decoupled from concomitant increments in brightness, yield the U-shaped functions predicted by the SOA law. No U-shaped functions are in evidence, however, when the brightness of the target is allowed to covary with its duration, as was done in Schiller's (1965) study and in the fixed-luminance condition of Experiment 2, because the initial decrement in target visibility due to masking is obscured by the rapid increments in target visibility due to increasing brightness. Francis's (1997) simulation of Schiller's data, therefore, must be regarded as modeling not the effect of target duration per se but the effect of target brightness.

This is shown clearly in Figure 6, which presents the averaged results of the fixed-luminance, brightness-matched, and fixed-duration conditions (see Figures 5A, 5B, and 5C, respectively) along with Francis's (1997, Figure 7) simulation of Schiller's (1965) results (illustrated in Figure 5A). The simulation is a good match to the data when the determining factor is target brightness (fixed-luminance and fixed-duration conditions) but not when it is target duration alone (brightness-matched condition). It must be concluded, therefore, that Francis's rejection of the SOA law and assertion of the ISI law applies only in the very special case in which the brightness of the target covaries with its duration within the range of Bloch's law.
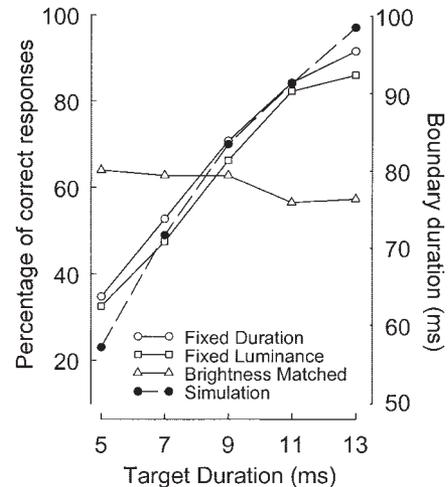

Figure 6. Mean percentages of correct responses as a function of target duration in Experiment 2. The continuous lines represent the results in each of the three conditions, averaged over all 4 observers. The segmented line represents Francis's (1997) simulation of the results obtained by Schiller (1965) in an experiment in which target brightness and duration covaried over the same range of durations as in the fixed-luminance condition. The results of the simulation are plotted against the ordinate labeled *Boundary duration.* From "Cortical Dynamics of Lateral Inhibition: Metacontrast Masking," by G. Francis, 1997, *Psychological Review, 104,* p. 580. Copyright 1997 by the American Psychological Association. Adapted with permission of the author.

Experiment 3: Masking as a Function of Mask Duration

Experiments 1 and 2 were designed to decouple the effects of target duration and target brightness on the strength and time course of metacontrast masking. Experiment 3 was designed to do the same with respect to the duration and the brightness of the mask.

In earlier studies, mask brightness was invariably allowed to covary with mask duration. We have noted that early researchers were aware of the confound arising from this practice (e.g., Alpern, 1953). Indeed, the covariation of duration and brightness has been used deliberately, and to advantage, in order to manipulate mask intensity over exposure duration within the range of time–intensity reciprocity (e.g., Breitmeyer, 1978). In other instances, however, that confound has not been fully acknowledged. For example Breitmeyer's (1978) results have been used to model the effect of mask duration independent of mask brightness (Francis, 1997). Clearly, to be used unambiguously for that purpose, the effects of mask duration and mask brightness must first be decoupled. The main objective of Experiment 3 was to achieve such a decoupling.

Method

Observers, apparatus, and procedure in Experiment 3 were the same as in Experiment 1, except for the following. The design of Experiment 3 comprised two conditions: fixed luminance and brightness matched. In both conditions, the target was displayed for 10 ms at a luminance of 100 cd/m², with the mask presented directly after the target (ISI = 0 ms). In the fixed-luminance condition, the mask was displayed for 10, 20, 30, 40, 60, 80, or 160 ms at a luminance of 100 cd/m². The brightness-matched

condition was the same as the fixed-luminance condition, except that as the duration of the mask was increased, its luminance was decreased correspondingly. The specific levels of luminance were the same as for the brightness-matched condition in Experiment 1: 100, 43, 29, 21, 16, 15, and 14 cd/m² for mask durations of 10, 20, 30, 40, 60, 80, and 160 ms, respectively.

Results and Discussion

Figure 7 shows the group and individual results, separately for the two conditions. In every case, the functions are monotonic, with performance declining more rapidly in the fixed-luminance than in the brightness-matched condition. The more rapid decline in the fixed-luminance condition represents the combined effects of duration and brightness. The relatively slower decline in the brightness-matched condition, however, represents only the effect of duration, because the brightness covariation was ruled out as a determining factor.

A comparison of Figures 2 and 7 shows that the time course of metacontrast masking is affected in different ways by increments in target duration and in mask duration. Increments in target duration yield the U-shaped curves in Figure 2. Corresponding increments in mask duration, however, yield the uniformly monotonic functions in Figure 7. A second important difference is that the covariation of duration and brightness has diametrically opposite effects for target stimuli and for masking stimuli. In the case of target stimuli, duration and brightness work in opposition to one another. That is, increasing target duration independent of bright-

ness leads to stronger masking (lower accuracy), as shown in the descending portions of the brightness-matched functions in Figure 2. In contrast, increasing target brightness by itself leads to weaker masking (greater accuracy), as reported by Alpern (1953) and illustrated in Figure 5A.

In the case of masking stimuli, however, duration and brightness work in conjunction to strengthen masking. Increasing mask brightness leads to correspondingly stronger masking (Alpern, 1953; Breitmeyer, 1978). Similarly, increasing mask duration by itself also leads to stronger masking, at least in the case of common-onset masking (Di Lollo, Bischof, & Dixon, 1993; Di Lollo et al., 2000). Thus, in the present work, the factors of duration and brightness worked in opposition to one another in Experiments 1 and 2, in which the independent variable was target duration, but they worked in conjunction in Experiment 3, in which the independent variable was duration of the mask.

In summary, the strength and time course of metacontrast masking seems to be affected in different ways by the same manipulations of target and masking stimuli, whether the manipulation involves exposure duration or covariation of duration and brightness. This raises the possibility that SOA effects and the effects of mask duration on the strength and time course of masking may be based on different mechanisms that would require correspondingly different models.

General Discussion

The principal objective of the present work was to examine the strength and time course of metacontrast masking as a function of exposure duration of target and masking stimuli. Such a study had been hindered in the past by a covariation of duration and brightness due to the time–intensity reciprocity known as Bloch's law. We decoupled duration and brightness by displaying longer stimuli at correspondingly lower levels of luminance so that all images were seen as equally bright regardless of exposure duration. This procedure permitted an unambiguous assessment of the effect of stimulus duration, independent of stimulus brightness. With brightness-matched stimuli, accuracy of target identification was found to be a U-shaped function of target duration and a monotonic decreasing function of the duration of the mask.

Because these results place important constraints on theories of metacontrast masking, we now examine how individual theories handle the present results. First, we evaluate the predictions made by an influential qualitative model, based on cross-channel inhibition, proposed by Breitmeyer and Ganz (1976). We then examine the fit between the empirical results and specific predictions made by five separate quantitative models of metacontrast masking. Predictions from a sixth quantitative model (Reeves, 1982) could not be tested because the model requires judgments of synchrony between target and masking stimuli, which were not collected in the present experiments. Predictions from a qualitative model based on STA (Macknik & Livingstone, 1998) have been described and evaluated in the *Results and Discussion* section of Experiment 1.

An implicit assumption, commonly made in models of metacontrast masking, is that the same mechanisms mediate the effects of duration of the target and the mask. For example, in Francis's (1997) boundary contour system, increasing the duration of a stimulus, whether the target or the mask, increases the duration of the boundary signal, which, in turn, improves the quality of the

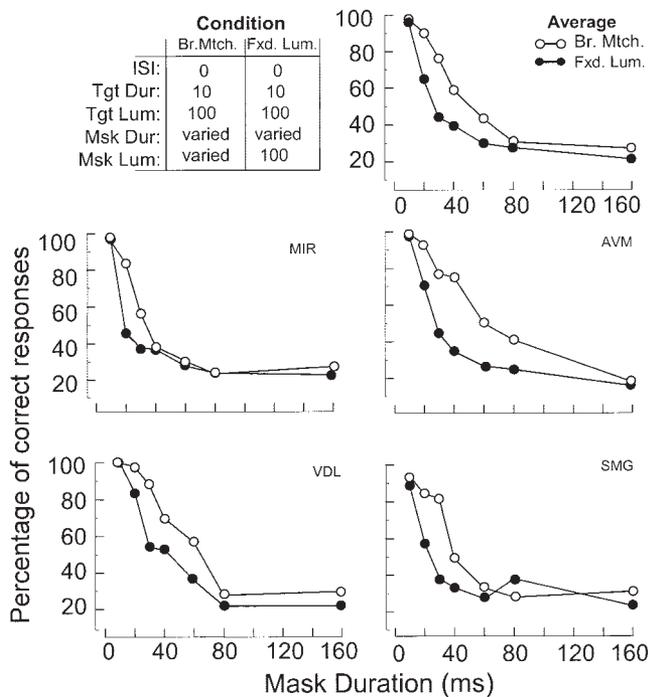*Figure 7.* Percentages of correct responses in the brightness-matched (Br. Mtch.) and fixed-luminance (Fxd. Lum.) conditions as a function of the duration of the masking stimulus for all observers (MIR, AVM, VDL, and SMG) in Experiment 3. ISI = interstimulus interval (ms); Tgt Dur = target duration (ms); Tgt Lum = target luminance (cd/m²); Msk Dur = mask duration (ms); Msk Lum = mask luminance (cd/m²).

visual percept. Thus, as is discussed below, increasing target duration should lead to progressively weaker masking, whereas increasing mask duration should lead to progressively stronger masking. The underlying mechanism (strength of the boundary signal), however, is assumed to be the same for the target as it is for the mask. Similarly, in Bridgeman's (1971, 1978) model, a common underlying mechanism—lateral inhibitory interactions amongst neurons activated by the incoming stimuli—is said to mediate the effects of exposure duration of both the target and the mask.

We have argued in the preceding section that there is reason to believe that the effects of target and mask duration may be mediated by different mechanisms that should, therefore, be modeled in correspondingly different ways. On this reasoning, the failure of any given model to provide an accurate account of the effects of target and mask duration cannot be regarded as disconfirmation of the entire model. Rather, such a failure should be regarded as evidence that the model is, to that extent, incomplete. By the same token, models like object-substitution masking (Di Lollo et al., 2000), which offer an account of the effect of mask duration but not of target duration, must be regarded as legitimate potential accounts of the effects of mask duration examined in Experiment 3.

Qualitative Model: Cross-Channel Inhibition

A basic assumption in this model, first proposed by Breitmeyer and Ganz (1976), is that any given visual stimulus activates two visual pathways or channels: a transient channel, which has short latency and responds optimally to low spatial frequencies of fast-changing stimuli, and a sustained channel, which has longer latency and is attuned to figural aspects of the stimulus, such as details carried by higher spatial frequencies. Activity in the transient channel is regarded as having an inhibitory effect on concurrent activity in the sustained channel.

Suppression of the target in metacontrast masking is explained in terms of the joint effects of the shorter latency of transient responses and transient-on-sustained inhibition. Given two spatially adjacent stimuli (target and mask) displayed in succession at the appropriate temporal interval (SOA), the fast transient activity triggered by the onset of the trailing mask inhibits the ongoing, more sluggish sustained activity triggered by the onset of the leading target, thus suppressing perception of its contours and of related figural details. A distinguishing characteristic of this model, therefore, is that all neural responses, whether transient or sustained, are time locked to stimulus onset. Stimulus duration, as such, is not regarded as an important factor.

Predictions from this model are consistent with the outcome of Experiments 1 and 2 (effect of target duration) but not with the outcome of Experiment 3 (effect of mask duration). A U-shaped function is predicted as the duration of the target is increased because the model is based on the SOA law. As the temporal interval between the onsets of the target and the mask is increased, the model predicts that accuracy of target identification should first decrease and then increase, in the manner illustrated in Figure 2. Whether the temporal interval between target offset and mask onset is filled with a blank screen or with a continued display of the target is immaterial to this model.

In contrast, increments in the duration of the mask are not expected to affect masking appreciably because the important factor is said to be the strength of the fast transient response triggered by the onset of the mask, not its duration. In this respect, the brightness-matching procedure used in Experiment 3 leads the model to predict that increments in mask duration will either have no effect on masking (if the magnitude of the onset transient is assumed to depend on stimulus brightness) or will yield progressively weaker masking (if the magnitude of the onset transient is assumed to depend on stimulus luminance). In either case, the model predictions are inconsistent with the experimental outcome shown in Figure 7.

Failure to account for the effect of mask duration, however, need not be regarded as grounds for disconfirming the entire model or, for that matter, rejecting the principle of lateral inhibitory interactions on which the model is based. As we noted above, the effects of target and mask duration may be mediated by separate mechanisms that should therefore be modeled separately. In this light, the cross-channel inhibitory model need not be regarded as failing but merely as being incomplete. Of course, this also makes the model less powerful. One way of expanding the model to account for the effects of mask duration may be to incorporate notions of reentrant signaling (Di Lollo et al., 2000), which are entirely compatible with the model's tenet of cross-channel inhibitory interactions. By the same token, models like object substitution (Di Lollo et al., 2000), which offer an account of mask duration but not of target duration, might be regarded as potential precursors of models capable of differentiating between the effects of target duration (Experiments 1 and 2) and the effects of mask duration (Experiment 3).

Quantitative Models

To gain a better understanding of the mechanisms that might underlie metacontrast masking, we simulated the present results using five published mathematical models. These models were developed to account for U-shaped masking functions and some other properties of metacontrast using mathematical formulations that simulate neural networks. Thus, the models are homeomorphic, with each property of a model matching a property of biological connectivity known to exist in the visual system. None were designed to simulate the present results, so our simulations are tests of the generalizability of the models.

Though the models have differing neural architectures, all have properties that are required to simulate an interaction in which two stimuli do not overlap either spatially or temporally. Assumed in all of the models is a trace of the target that moves laterally in the representation of the stimulus space, either by spreading as it moves through successive layers or by recurrent interactions. In addition, the trace of activity elicited by the target is maintained in the network for a long enough time for it to interact with the mask.

Francis (2000) pointed out that U-shaped masking is a common property of neural network models that create a lasting trace of a brief stimulus. The models can be differentiated, however, in terms of their ability to simulate other properties of masking, including the conditions simulated here.

Simulation Methods

All of the models were tested with the brightness-matched conditions described above. To maintain as consistent a modeling environment as possible, we used the default parameters for each

model given in the original publications for their basic metacontrast simulations whenever feasible, changing only those parameters necessary to establish the appropriate stimulation conditions. Target or mask durations of 10, 20, 30, 40, 60, 80, and 160 ms were simulated for each model at the corresponding psychophysically determined intensities from Experiments 1 and 3. In a first set of simulations, the duration of the simulated target was varied, and the simulated mask duration was held constant at 10 ms. In a second set of simulation runs, the target duration was held constant, and the mask duration was varied. ISI was always set to zero. A successful model would simulate the U-shaped function for varying target duration shown in Figure 2 as well as the monotonic decreasing functions for varying mask duration shown in Figure 7. We begin by presenting brief outlines of the basic tenets of five quantitative models. Justifications for these parameter settings can be found in the original sources for the respective models. All of the parameters were held constant for all of the simulations below, except those regulating target and mask intensity and duration.

Each model requires a *linking hypothesis* (Weisstein, 1968), a hypothesized relation between some output of the model and the resulting perception. Most of the models hypothesize that the activity of one or a few neurons corresponds to perceived stimulus strength. The efficient-masking model uses an even smaller fraction of the network's output as its measure of perception, the duration of the afterdischarge of the final-level neuron that corresponds to the topographic position of the target.

In the section below, we describe the architecture of each of the five simulated models. The parameters used in each simulation are given in the Appendix.

Outline Sketches of Five Quantitative Models

Lateral inhibition. This model was developed by Bridgeman (1971, 1978) from a recurrent-network architecture based on the Ratliff–Hartline equations for describing lateral inhibition in the limulus eye, adapted for mammalian cortex. In a single layer of identical neurons, the model receives excitation from outside and passes a fraction of that excitation from each neuron to its immediate neighbors as inhibition. A delay in the inhibition causes the resulting activity to reverberate through the network. The reverberations then cause dampened oscillations of activation and inhibition to spread spatially and temporally beyond the original target area. Secondary interactions cause both spatial and temporal activity to spread beyond the direct connectivity of the network. Metacontrast masking is predicted from this model because the activity from the target alone is stored in the neural network and is then compared with the activity produced by the target–mask combination. Target identification is predicted by the degree to which these two signals are correlated.

Decaying trace. Developed from models of brightness perception, this model superimposes receptive field effects of two neurons represented as a differential equation (Anbar & Anbar, 1982). A receptive field representing the mask inhibits the receptive field representing the target. Peaks of metacontrast masking at a delay between target and mask are achieved by making the activation from the mask occur with a shorter latency than activation from the target. Target visibility is measured as the activity of a single neuron on which target and mask channels converge. Masking is driven only by the onset of the mask, so simulations varying the mask duration in this model cannot be balanced to titrate intensity

against duration. Like the cross-channel inhibitory model (Breitmeyer & Ganz, 1976), the decaying trace model predicts that only the onset intensity of the mask, not its duration, should affect masking.

Efficient masking. This architecture, developed by Francis (2000, 2003), is related to a six-layered neuronal architecture of interacting receptive fields originally developed to simulate other psychophysical brightness effects. All of the layers consist of arrays of neurons modeled after known characteristics of afferent visual systems. Lateral interactions are indirect, mediated by excitation of large receptive fields in the top layer that, in turn, feed back inhibition to smaller receptive fields below them, including cells lateral to those stimulating the top-layer cells. Thus, unlike the other models considered, here there is both feedforward (to higher levels) and feedback (from higher to lower levels), introducing the possibility of repeated interactions of neural layers. Temporal storage of information occurs because of an exponential decay of activity following the termination of stimulation. Target visibility is measured by the duration of an afterdischarge in the top layer neurons.

Two channel. Weisstein (1972) developed this model to simulate slow excitation in a neuron stimulated by the target followed by fast inhibition in a neuron stimulated by the mask. At the appropriate SOA, the inhibition catches up to the excitation and masking is obtained. The fast neurons are conceived as transient neurons, and the slow neurons are conceived as sustained neurons. The five-neuron model, simulating a Rashevsky–Landahl neural net, had to be kept very simple because the original simulation was done on an analog computer. Target and mask channels each have two neurons, one picking up the physical signal and the other acting as an interneuron. The two interneurons converge on the final, fifth neuron. Input neurons are identical in each channel, but second-order neurons differ.

Reentrant processing. This model works at a higher level than the others, simulating representations of objects rather than individual neurons. It was designed to account for properties of object substitution as a function of the duration of the trailing mask (Di Lollo et al., 2000). For this reason, the model does not generate predictions with respect to masking as a function of target–mask SOA. Target and mask are considered single objects rather than geometric patterns. Time steps in increments of 13 ms.

Results of the Simulations

The results of Experiments 1 and 3, together with the results of the corresponding simulations, are shown in Figure 8, for the target-varying condition, and in Figure 9, for the mask-varying condition. Please note that, in order to compare the empirical results with the results of the simulations on an equal basis, we normalized all scores to the range 0%–100%. For this reason, the observed data in Experiments 1 and 3 appear to be stretched vertically along the *y*-axis.

The results are limited to the models run with the values of their parameters given above. Other parameter settings would have resulted in different masking functions. Tweaking the parameters might have given better fits in our conditions; the parameters, however, were optimized by the authors of the respective original models to best produce U-shaped metacontrast masking functions and to use values that were the most consonant with known neurophysiology. Changing them would have meant compromis-
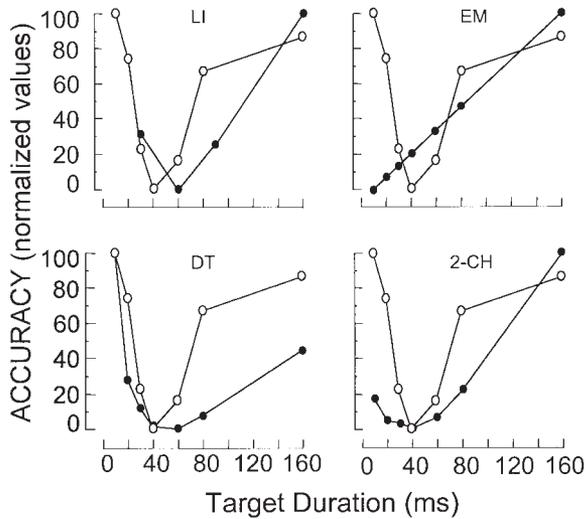
Figure 8. Comparisons of the theoretical predictions of the effect of target duration derived from four quantitative models of metacontrast masking (filled symbols) with the results of the brightness-matched condition (open symbols) in Experiment 1. Note that all data have been normalized to the range 0%–100%. This causes the plots to be stretched vertically as compared with the corresponding plots in Figure 2. LI = lateral inhibition; EM = efficient masking; DT = decaying trace; 2-CH = two channel.

ing either the ability of a model to simulate its original conditions or its fit with physiological knowledge.

It is immediately evident from Figures 8 and 9 that although the models are mathematically related, they produce very different predictions in the simulation runs. We now examine the predictive accuracy of individual models, separately for the target-varying and mask-varying conditions.

Target-varying condition. It is clear from Figure 8 that three of the four applicable models produce U-shaped functions. The exception is the efficient masking model, which produces a linear increase in simulated visibility with increased target duration. This is because, according to this model, a longer period of charge results in a longer period of afterdischarge. Being normalized for range, the plots in Figure 8 do not show that the actual difference in the duration of afterdischarge that defines stimulus strength in this model varies over a narrow range, from 157 ms at the shortest target duration to 307 ms at the longest. Physiologically, even the shortest of these afterdischarges is substantial, so, in fact, there was very little masking at any target duration in this model.

The decaying trace and two-channel models are mathematically related and give similar U-shaped curves whose minima are somewhat wider than the psychophysical minimum. The lateral inhibitory model is the only one that yields a sharp minimum of the function. Its minimum occurs slightly later than the psychophysical data, perhaps because of delays from the 30-ms minimum iteration time of the model.

Mask-varying condition. Here a different pattern emerges. All of the models except the decaying trace model show a decline in visibility as mask duration increases. As was the case for the cross-channel inhibitory model, the decaying trace model considers only the strength of the transient triggered by mask onset to be important for masking. Given the present brightness-matching

procedure, the luminance of the mask, but not its brightness, decreased progressively as its duration increased. A progressively weaker mask meant that target visibility in this model increased monotonically with mask duration, the opposite of the psychophysical result. Comparison of the decaying trace model's result with those of the other models shows that mask duration is indeed critical in determining the visibility of a target in the presence of a mask, even when brightness is compensated (see Footnote 1).

Of the other models, the efficient masking model was already disconfirmed in the target-varying condition, and its simulated afterdischarge declines only from 159 ms at the maximum to 139 ms at the minimum, a difference that does not mirror the massive decline obtained psychophysically (see Figure 7). The two-channel model shows a decreasing target visibility with increasing mask duration, like the psychophysical function, but visibility does not begin to decline significantly until a mask duration of about 80 ms, at which point the psychophysical function has already reached asymptote at its minimum value. The reentrant processing model provides an excellent fit; indeed, the model was designed to fit just such situations, and the fact that its fit remains good when apparent brightness is held constant shows the robustness of object substitution in this situation.

The lateral inhibitory model provides a good fit, again with a delay especially at short mask durations, possibly due to the
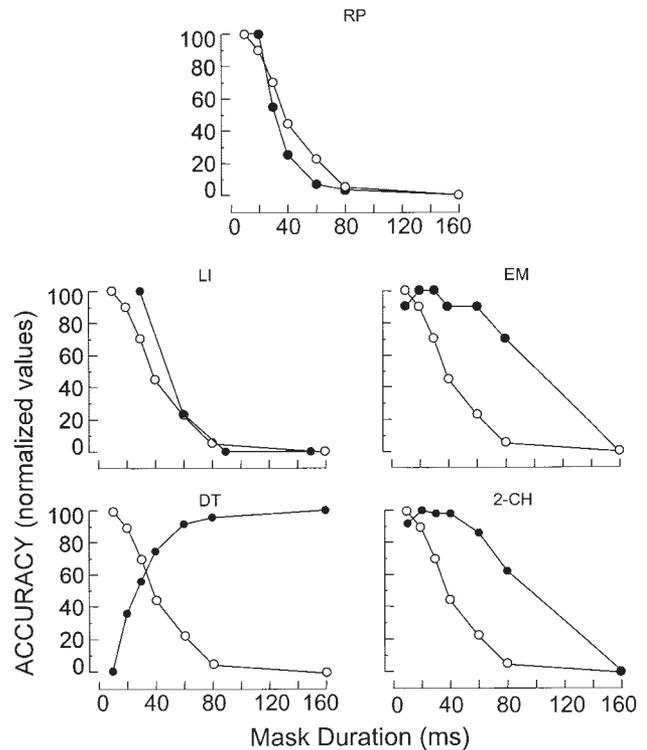

Figure 9. Comparisons of the theoretical predictions of the effect of mask duration derived from four quantitative models of metacontrast masking (filled symbols) with the results of the brightness-matched condition (open symbols) in Experiment 3. Note that all data have been normalized to the range 0%–100%. This causes the plots to be stretched vertically as compared with the corresponding plots in Figure 7. RP = reentrant processing; LI = lateral inhibition; EM = efficient masking; DT = decaying trace; 2-CH = two channel.

minimum iteration time. Thus, the lateral inhibitory model is the only one of the five to provide a reasonable fit to both the target-varying and the mask-varying results.

Concluding Comments

Because all of the models except the reentrant-processing model invoke lateral inhibition directly or indirectly at some stage, why was the performance of the lateral inhibitory model so different? One reason may lie in the linking hypothesis: Though all of the models use related mathematics to set up neural networks, the lateral inhibitory model and the reentrant processing model use a very different linking hypothesis. Their measure of perceived visibility is not the activity of one or a small number of neurons but, rather, the pattern of activity of the whole nerve network. The linking hypothesis is based on the observation that the cortex cannot see the world—it must use only the pattern of activity present in cortical neurons to make decisions about what is present in the world. There is no way to select particular neurons for scrutiny; the whole net must be involved.

In both the lateral inhibitory model and the reentrant processing model, the linking hypothesis measures the similarity of activity elicited by a target–mask combination over the whole network to activity elicited by the target or the mask alone. The pattern of activity, not a peak excitation or inhibition, is critical. This is a distributed coding of a stimulus over many neurons, not just a handful of detector neurons. The implication is that examination of the whole output of a simulated nerve net is critical for an accurate account of the psychophysical results.

A second way in which the lateral inhibitory and reentrant processing models differ from the other models is that they both contain an explicit comparison process between neural activity generated by recently stored visual information and neural activity generated by visual information currently being registered by the system. It is this feature of an ongoing comparison between the events of recent memory and the events of current perception that is likely the critical ingredient underlying the strong effects of mask duration in metacontrast masking. In previous reports, Bischof and Di Lollo (1995) and Di Lollo et al. (2000) have argued that it is this aspect of recurrent processing that is responsible for the strong masking that occurs even when the target and the mask have common onset (i.e., when the SOA is equal to zero), provided that the mask outlasts the target.

We therefore conclude with two points. First, we affirm that the SOA law for metacontrast masking obtains whether the SOA is manipulated by varying (a) the duration of the target or (b) the duration of the target–mask ISI. The important temporal factor governing the strength and time course of metacontrast masking is the time that elapses between the onset of the target and the onset of the trailing mask. Second, the present data and modeling point to the strong possibility that the effects of target–mask SOA (Experiments 1 and 2) and the effects of mask duration (Experiment 3) are mediated by separate mechanisms. We think that this is an important issue to be addressed directly in future research.

References

Alpern, M. (1953). Metacontrast. *Journal of the Optical Society of America, 43,* 648–657.

Anbar, S., & Anbar, D. (1982). Visual masking: A unified approach. *Perception, 11,* 427–439.

Biersdorf, W. R. (1955). Critical duration in visual brightness discrimination. *Journal of the Optical Society of America, 45,* 920–925.

Bischof, W. F., & Di Lollo, V. (1995). Motion and metacontrast with simultaneous onset of stimuli. *Journal of the Optical Society of America A, 12,* 1623–1636.

Breitmeyer, B. G. (1978). Metacontrast masking as a function of mask energy. *Bulletin of the Psychonomic Society, 12,* 50–52.

Breitmeyer, B. G. (1984). *Visual masking: An integrative approach.* New York: Oxford University Press.

Breitmeyer, B. G., & Ganz, L. (1976). Implications of sustained and transient channels for theories of visual pattern masking, saccadic suppression, and information processing. *Psychological Review, 83,* 1–36.

Breitmeyer, B. G., & Ogmen, H. (2000). Recent models and findings in visual backward masking: A comparison, review, and update. *Perception & Psychophysics, 62,* 1572–1595.

Bridgeman, B. (1971). Metacontrast and lateral inhibition. *Psychological Review, 78,* 528–539.

Bridgeman, B. (1978). Distributed sensory coding applied to simulation of iconic storage and metacontrast. *Bulletin of Mathematical Biology, 40,* 605–623.

Cattell, J. M. (1885). The influence of the intensity of the stimulus on the length of the reaction time. *Brain, 8,* 511–515.

Di Lollo, V., Bischof, W. F., & Dixon, P. (1993). Stimulus-onset asynchrony is not necessary for motion perception or metacontrast masking. *Psychological Science, 4,* 260–263.

Di Lollo, V., Enns, J. T., & Rensink, R. A. (2000). Competition for consciousness among visual events: The psychophysics of reentrant visual processes. *Journal of Experimental Psychology: General, 129,* 481–507.

Di Lollo, V., & Finley, G. (1986). Equating the brightness of brief visual stimuli of unequal durations. *Behavior Research Methods, Instruments, & Computers, 18,* 582–586.

Di Lollo, V., Hogben, J. H., & Dixon, P. (1994). Temporal integration and segregation of brief visual stimuli: Patterns of correlation in time. *Perception & Psychophysics, 55,* 373–386.

Dixon, P., & Di Lollo, V. (1994). Beyond visible persistence: An alternative account of temporal integration and segregation in visual processing. *Cognitive Psychology, 26,* 33–63.

Finley, G. (1985). A high-speed point plotter for vision research. *Vision Research, 25,* 1993–1997.

Francis, G. (1997). Cortical dynamics of lateral inhibition: Metacontrast masking. *Psychological Review, 104,* 572–594.

Francis, G. (2000). Quantitative theories of metacontrast masking. *Psychological Review, 107,* 768–785.

Francis, G. (2003). Online simulations of models for backward masking. *Behavior Research Methods, Instruments, & Computers, 35,* 512–519.

Hartline, H. K. (1934). Intensity and duration in the excitation of single photoreceptor units. *Journal of Cellular and Comparative Physiology, 5,* 229–247.

Hartline, H. K. (1938). The response of single optic nerve fibers of the vertebrate eye to illumination of the retina. *American Journal of Physiology, 121,* 400–415.

Kahneman, D. (1967). An onset–onset law for one case of apparent motion and metacontrast. *Perception & Psychophysics, 2,* 577–584.

Macknik, S. L., & Livingstone, M. S. (1998). Neuronal correlates of visibility and invisibility in the primate visual system. *Nature Neuroscience, 1,* 144–149.

Onley, J. W., & Boynton, R. M. (1962). Visual responses to equally bright stimuli of unequal luminance. *Journal of the Optical Society of America, 52,* 934–940.

Reeves, A. (1982). Metacontrast U-shaped functions derive from two monotonic processes. *Perception, 11,* 415–426.

Schiller, P. H. (1965). Metacontrast interference as determined by a method of comparison. *Perceptual and Motor Skills, 20,* 279–285.

Servière, J., Miceli, D., & Galifret, Y. (1977). Electrophysiological corre-

lates of the visual perception of "instantaneous" and "durable." *Vision Research, 17,* 57–63.

Stigler, R. (1910). Chronophotische Studien über den Umgebungskontrast [Effects of exposure duration and luminance on the contrast of the surround]. *Pflügers Archiv für die gesamte Physiologie, 134,* 365–435.

Taylor, M. M., & Creelman, C. D. (1967). PEST: Efficient estimates on

probability functions. *Journal of the Acoustical Society of America, 41,* 782–787.

Weisstein, N. (1968). A Rashevsky–Landahl neural net: Stimulation of metacontrast. *Psychological Review, 75,* 494–521.

Weisstein, N. (1972). Metacontrast. In D. Jameson & L. Hurvich (Eds.), *Handbook of sensory physiology* (Vol. VII/4, pp. 233–272). Berlin, Germany: Springer-Verlag.

Appendix

Parameter Settings Used in the Simulations for Each of the Five Models

Lateral Inhibition

Parameter settings for the simulation of this model were derived from physiological properties of neurons. Because the model calculates interactions in 30-ms increments—a value derived from physiological measures of the latency of lateral inhibition in the cortex—the 10-, 20-, and 40-ms durations were omitted, and the constant-duration stimulus was set to 30 ms, at the relative intensity found in Experiment 1. Instead of 80 and 160 ms, the model was run at 90- and 150-ms stimulus durations, with stimulus intensities interpolated from Experiment 1 at 14.9 and 14.1 units, respectively. Coefficients of lateral inhibition, the fraction of a neuron's activity that inhibits neighboring neurons, were set to 0.3, 0.3 and 0.1 for the first, second, and third neighbors, respectively, on each side of a neuron. These values were derived from coefficients in the limulus eye, the only system for which the coefficients are known with precision. Gaussian noise with root-mean-square amplitude of 0.1 was added to each of the 30 neurons on each iteration. The design of this model allows translational invariance; target and mask configurations can be presented at any location on the simulated array as long as their relative positions remain constant.

Decaying Trace

In the parameter settings of this model, *gamma* is an exponent that influences both the strength of the target signal and the rate of decay of the target receptive field. Anbar and Anbar (1982) set it equal to 0.3 on the basis of models of brightness perception. That value is used here. The exponent *p*, equal to 0.442857, influences the effect that the mask has on the target, larger values tending to make the mask stronger. Simulation runs continue until the target strength goes below a threshold value of $G = 10^{-8}$.

Efficient Masking

The specific setting of each parameter in the model is based on data from physiological measurements in neurons and on considerations of stability rather than being optimized for any particular masking result. Parameter *A*, equal to 0.01, sets the rate of decay of the target receptive field. Parameter *B*, equal to 1.0, scales the additive contribution of the target input, and it also provides an upper limit on the magnitude of the target receptive field. Parameter *C* also equals 1.0 and scales the contribution of the target input to the rate of change of the target receptive field. Parameter *D* equals .00031 and scales the additive contribution of the mask input. That is, larger values of *D* lead to a larger influence of the mask. Parameter *E*, equal

to .001, is related to the derivative of *D*, scaling the contribution of the mask input to the rate of change of the target receptive field. Finally, Parameter *G*, equal to 0.2, is a threshold; when receptive field activity goes below *G*, the simulation is terminated. Thus, its function is similar to *G* in the decaying trace model, though it scales differently.

Two Channel

This model has 21 parameters—12 for the target channel and 9 for the mask channel—and a choice of three linking hypotheses. *A1-T* and *A1-M*, each equal to 1.5, scale input to the target and mask channels, respectively. Rates of decay for the first cells of the target and mask pathways are also the same for the two channels, at 0.025, as are inputs feeding into the hyperpolarizing component of the first cells in the target and mask pathways (each equal to 1.5). Passive decay rates for these cells are also the same in both pathways (each equal to 0.1). The pathways diverge at the level of the second cell in each pathway, with the input setting the depolarizing component of the second cell equal to 1.2 in the target pathway and 1.6 in the mask pathway. The rates of passive decay for the depolarizing component of the second cells also differ: 0.03 in the target pathway but 0.3 in the mask pathway. Thus, the mask decays faster than the target. The third cell in the target pathway is not activated in these simulations. The linking hypothesis used is integration above a threshold *G*, set to 1,000 for these simulations.

Reentrant Processing

There are only six parameters. *Lambda*, equal to 0.025, scales the stimulus input to the model. A noise-intensity parameter of 0.4 sets a noise level for a signal-detection modeling. The set size ($n = 4$) indicates the number of elements that are presented with the target. The model operates by shifting simulated attention from one item to the other, regulated with a parameter *S* (equal to 12). *K* is a scaling factor that quantifies the linking hypothesis by setting an asymptotic value, 0.525, for which probability correct approaches the value 1.0. The only other parameter is a guess rate that links the value of the model to accuracy of target detection. The guess rate of 0.25 is what would correspond to the hit rate if subjects just guessed in the experiment.