Analysis and test of laws for backward (metacontrast) masking

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Abstract

In backward visual masking, it is common to find that the mask has its biggest effect when it follows the target by several tens of milliseconds. Research in the 1960s and 1970s suggested that masking effects were best characterized by the stimulus onset asynchrony (SOA) between the target and mask. In particular, one claim has been that the SOA for which masking is optimal remains fixed, even as target and mask durations varied. Experimental evidence supported this claim, and it was accepted as an SOA law. However, recent modeling (Francis, 1997) and experimental studies (Macknik & Livingstone, 1998) argued for new ISI (interstimulus interval) and STA (stimulus termination asynchrony) laws, respectively. This paper reports a mathematical analysis and experimental tests of the laws. The mathematical analysis demonstrates unsuspected relationships between the laws. The experiments test the predictions of the SOA, ISI, and STA laws. The data favor the ISI law over the SOA and the STA laws.

Key words: backward masking, dynamic vision, metacontrast

Introduction

In backward visual masking, the subsequent appearance of a mask stimulus tens of milliseconds after a briefly presented target stimulus can render the target nearly invisible. In many studies of masking, performance on some task that measures visibility of the target is plotted against the stimulus onset asynchrony (SOA) or the interstimulus interval (ISI) between the target and mask. The resulting curve is called a masking function.

One of the interesting properties of backward masking is that the masking function is often u-shaped (e.g., Alpern, 1953). U-shaped masking functions are particularly common for metacontrast masking, where the mask contours do not overlap the target contours. For short SOAs the target is clearly seen, and the required task fairly easy to perform. For middle duration SOAs (often around 80 milliseconds), the target is harder to see and the task difficult to perform. For long duration SOAs the task performance is again quite good, perhaps because the target is processed before the mask appears. The decrease in performance as the SOA increases is interesting because it implies that the effect of the mask is not just to halt the processing of the target. If the mask simply halted target processing, then increases in SOA would be expected to allow for more processing and so better performance on the task (or at least, not worse performance). Because of this characteristic, the u-shaped masking function and its properties have been heavily investigated (see Breitmeyer & Öğmen (2000) and Francis (2000) for recent reviews).

Several laws of backward masking have been formulated that describe the properties of these u-shaped curves. The earliest backward masking law was called the SOA law (Kahneman, 1967). This law stated that the strength of masking was primarily determined by the SOA, so that even as target and mask durations varied, the masking function would not change shape or magnitude. Recently two other laws have been proposed (Francis, 1997; Macknik & Livingstone, 1998) for masking functions that are based on ISI or STA (stimulus-termination asynchrony: the interval between the termination of the target and the termination of the mask).

The purpose of this paper is to test the validity of these laws and to identify which (if any) is most appropriate. The next section describes the laws in more detail. Mathematical instantiations of the laws are then analyzed to show relationships between the laws. The following section then describes experiments that test the validity of the laws.

Laws of backward masking

Each law makes claims about whether masking is best characterized as a function of SOA, ISI, or STA. The following sections describe the different laws and give a bit of background about how the laws came to be formulated.

Equal duration SOA law

Kahneman (1967) measured masking functions for a variety of target and mask stimuli. In his experiment observers viewed a square target that was followed by two flanking mask squares. Kahneman used five equal target and mask durations (25, 50, 75, 100 and 125 ms) and 11 SOA values for each of the durations. The observers were asked to rate the degree of masking on a scale of 0 (no masking) to 5 (strongest masking).

The resulting masking functions are shown in Figure 1. The most striking characteristic of this data was the overlap of the curves for different stimulus durations. Kahneman (1967) proposed that the experimental data could be summarized by an SOA law of backward masking.[1] Kahneman's (1967) SOA law claimed that masking occurs as a function of SOA and is not dependent upon target or mask durations.

- Figure 1 -

Shortly after the Kahneman (1967) study, experimental evidence against the SOA law was found. Weisstein and Growney (1969) used the same rating task as Kahneman (1967) with similar equal target and mask durations. Their first experiment found that masking was

[1] The term SOA law has also been used by some authors (e.g., Enns & Di Lollo, 2000) to refer to the finding that the strongest masking often occurs for a positive SOA rather than for common onset of the target and mask. This is an entirely different use of the term.

stronger for shorter stimulus durations. The masking curves were all similar in shape, but were shifted down (indicating weaker masking) as stimulus duration increased. However, in the same study, additional experiments found that the masking functions largely overlapped, with less influence of the stimulus duration. Because a rating task was used in both the Kahneman (1967) and the Weisstein and Growney (1969) studies, the differences across experiments may have been due to variations in how observers based their ratings.

Stronger experimental evidence against the original formulation of the SOA law is available. Schiller (1965) found that increases in target duration with a fixed mask led to weaker masking. Likewise, Breitmeyer (1978) found that increases in mask duration with a fixed target led to stronger masking. Perhaps the strongest evidence comes from Macknik and Livingstone (1998), who varied both target and mask durations and found that the resulting masking functions had different shapes when plotted against SOA. To summarize, the original version of the SOA law is rejected by existing experimental data.

However, it is possible that a variant of an SOA law is still supported by the experimental data. Kahneman's (1967) original data used only equal target and mask durations. All of the strong experimental results against the SOA law were found with unequal target and mask durations. Thus, it is possible that an SOA law remains valid for equal target and mask durations. In our discussion below, we consider a still weaker version of the SOA law that requires only that the SOA value that gives rise to the strongest masking is constant across all equal target and mask durations. Since the stronger versions are all special cases of the weaker version, if the weaker version is not valid, the stronger versions are also not valid. To distinguish the new law from earlier versions of the SOA law, we refer to it as the equal duration SOA law (ED-SOA law). The ED-SOA law is supported by the Kahneman (1967) data and by all of the experiments in Weisstein and Growney (1969). The studies of Schiller (1965), Breitmeyer (1978), and Macknik and Livingstone (1998) did not use equal duration target and mask stimuli, so their data do not test the ED-SOA law.

Fixed mask ISI law

Francis (1997) analyzed simulations of a neural network model of visual perception (Grossberg & Mingolla, 1985a,b) and found that the model predicted that backward masking functions should obey a certain type of ISI law. In the model, variations in target duration have virtually no effect on the ISI that produces maximal masking. Figure 2A shows simulated data generated by the model. In the figure, masking strength is shown as a function of ISI for different target and mask durations. Mask duration was either 25 or 100 ms, and target duration was varied from 25 to 125 ms.

- Figure 2 -

The curves are grouped together by mask duration. All of the conditions with the mask duration of 25 ms (filled symbols) are grouped together with an ISI for maximal masking at around 50 ms. All of the conditions with the mask duration of 100 ms (open symbols) are grouped together with an ISI for maximal masking at around 0 ms. There is an effect of target duration; masking is weaker as the target duration increases, but the ISI for maximal masking does not change with variations in target duration. Francis (1997) called this prediction an ISI law, but to avoid confusion with other uses of that term, we now refer to this prediction as a fixed mask ISI law (FM-ISI law).

At about the same time that Francis (1997) described the FM-ISI law, Macknik and Livingstone (1998) published experimental data that seemed to be consistent with the law. Macknik and Livingstone (1998) investigated masking functions with unequal target and mask durations. The target stimuli were two unequal length bars with two flanking bars as masks around each target. The observers were asked to judge which bar (left or right of a fixation point) was larger. The data are plotted against ISI in Figure 2B, with smaller percentage correct indicating stronger masking. The curves with filled symbols correspond to a mask duration of 50 ms, while the open symbols correspond to a mask duration of 90 ms. The masking curves separated into two sets according to which mask duration was used. The vertical lines drawn down from each curve indicate the ISI for maximal masking. The ISI for maximal masking was around -25 ms when the mask duration was 90 and around 35 ms when the mask duration was 50 ms. Changes in target duration seemed to make little difference to the ISI for maximal masking. This pattern of results is entirely consistent with the FM-ISI law.

While the study of Macknik and Livingstone (1998) provides evidence in support of the FM-ISI law, due to publication lag times Macknik and Livingstone (1998) were unaware of Francis' (1997) prediction, and they proposed an STA law, as described in the next section.

STA law

Figure 3 shows the data of Macknik and Livingstone (1998) plotted against STA. The vertical lines drawn down from each curve indicate the points of maximal masking. If an STA law held, then plotting the data against STA should cause the bottoms of the curves to cluster around a common STA.

- Figure 3 -

Macknik and Livingstone (1998) suggested that the data do cluster closely around a common STA for maximal masking. They compared the clustering tendencies for different laws by measuring the standard deviation of the points of maximal masking. They found that the standard deviation among the points of maximal masking was least when the masking functions were plotted against STA and highest when the masking functions were plotted against SOA. Therefore, they proposed that an STA law was the best description of backward masking.

Macknik and Livingstone (1998) also considered an ISI law, but it was a different law than the one proposed by Francis (1997). Macknik and Livingstone (1998) tested an ISI law that predicted no variation in the ISI for maximal masking, even as the target and mask duration varied. In contrast, the FM-ISI law proposed by Francis (1997) predicted that the ISI for maximal masking would not vary with target duration, but might vary with mask duration. The SOA law rejected by Macknik and Livingstone (1998) was also different from the ED-SOA law that is being tested in this paper.

Mathematical description of the laws

Another way to characterize the laws is to consider them as models of the effect of varying target and mask durations. Let the SOA that produces maximal masking, $S(T, M)$, be a function of target duration T and mask duration M. The function could include other factors (such as stimulus intensity, context, task, and attentional focus), but in the current analysis and in the experiment below, we assume that these factors are held constant, so they can be dropped from the notation.

The ED-SOA law predicts that if the target and mask durations are the same, there will be no change in the value of $S(T, M)$. Stated mathematically, it claims that when the target and mask durations are the same ($T = M = D$), the function must equal a constant:

$$S(D, D) = c_1. \tag{1}$$

The FM-ISI law predicts that as T varies and M is held fixed, the ISI for maximal masking will not change. Since SOA = ISI+T, if ISI is constant for a fixed mask then:

$$S(T, M) = f(M) + T, \tag{2}$$

where $f(M)$ is a function of the mask duration and task, stimulus, and context properties. The FM-ISI law makes no specific claims about the properties of $f(M)$, although the model of Francis (1997) predicts that $f(M)$ decreases as M increases.

The STA law predicts that changes in the target or mask duration will not cause changes in the STA for maximal masking. Since SOA = STA$-M + T$, if STA is constant, then:

$$S(T, M) = c_2 - M + T, \tag{3}$$

where c_2 is a constant STA value that reflects the effect of task, stimulus, and context properties.

Of the three laws, the STA law makes the most specific claims. Indeed, it is easy to verify that if the STA law is true, then both the ED-SOA law and the FM-ISI law are also true. The reverse statement is also true; the joint validity of the ED-SOA law and the FM-ISI law means that the STA law must be valid. This can be proven fairly easily. Suppose both the

ED-SOA and the FM-ISI laws are true. Then $S(T, M)$ must obey both equation (1) and equation (2) for $T = M$. So, plugging in M for both T and D, setting the right hand side of the equations equal to each other, and solving for $f(M)$ yields:

$$f(M) = c_1 - M. \tag{4}$$

Which must hold for all values of M. Plugging this solution for $f(M)$ back into equation (2) gives:

$$S(T, M) = c_1 - M + T, \tag{5}$$

which is equivalent (with a change in the name of the constant) to the STA law given in equation (3).

Based on the mathematical analysis of the laws, there are only four logical possibilities. First, it is possible that none of the laws are valid. Second, it is possible that the STA law is valid. If the STA law is valid, then the ED-SOA and the FM-ISI laws must also be valid, but then the STA law would be a more parsimonious description of the data. Third, it is possible that the ED-SOA law is valid, but none of the other laws are valid. Fourth, it is possible that the FM-ISI law is valid, but none of the other laws are valid.

The data from Macknik and Livingstone (1998) seemed to be consistent with the second possibility. Their data were consistent with an STA law, and were thus also consistent with the FM-ISI law. However, the range of target and mask durations used in their study did not allow for a test of the validity of the ED-SOA law, and perhaps did not properly challenge the STA law. In particular, if more varied mask durations were used, then the STA law might break down, even as the FM-ISI law continued to hold. We designed an experiment that measured the validity of each of the laws. Two versions of the experiment were carried out. The first version (Experiment 1) uses data from a large number of observers who saw each condition only a few times. The second version (Experiment 2) runs the same experiment on a single observer who saw each condition many times.

Experiment 1: Multiple observers

Figure 4 shows the target and mask durations used in the experiment and, for comparison, shows the durations used by Kahneman (1967) and Macknik and Livingstone (1998). The duration times used by Kahneman (1967) fall along the main diagonal, indicating equal target and mask durations. The Macknik and Livingstone (1998) study used a mixture of target and mask durations indicated by the two rows of squares at 50 ms and 90 ms mask durations. Our sample of the target and mask duration space is indicated in Figure 4 by the large open triangles. We took four samples of equal target and mask durations (main diagonal) as well as eight unequal target and mask durations.

- Figure 4 -

Methods

Participants

145 observers were recruited from the undergraduate student body at Purdue University as partial fulfillment of requirements for an introductory psychology course. Each observer reported normal or corrected to normal vision.

Apparatus and stimuli

All stimuli were displayed on a personal computer monitor with a refresh rate of 75 hertz. All durations given here were as close to the indicated values as the refresh rate of the monitor allowed. The observer's head was supported by a chin-rest 54 cm from the monitor. All stimuli were white (75 cd/m^2) on a black background (0.3 c/m^2). The experiment room was dimly lit by the computer monitor.

Each trial started with a fixation point directly in the middle of the screen for 500 ms before the presentation of the target. The target consisted of four shapes arranged in a square, as schematized in Figure 5. The center to center distance between the shapes was 10° 10' of visual arc. Three shapes were filled circles, while one shape was a half-circle. The half-circle could be in one four orientations, so that the flat side faced: up, down, left, or right. The observer's task was to report the orientation of the flat side of the half-circle. The location of the half-circle and the orientation of the half-circle were randomly chosen on each trial.

The mask consisted of circular annuli that appeared around each target shape. The mask's thickness subtended 25 minutes of arc with the total diameter subtending 2° 33' of visual arc. There was a small gap (subtending 13 minutes of arc) between the boundary of each target circle and its mask. Each target and mask duration combination was tested at 18 SOAs, between 0 and 255 ms in steps of 15 ms.

- Figure 5 -

Procedure

The observer initiated each trial by pressing the space bar on a keyboard. After all of the stimuli were presented, the observer made a choice about the orientation of the flat side of the half circle. The observer indicated the choice (guessing if necessary) by making a key press on a keyboard. With each key press, the corresponding oriented half-circle appeared on the screen to insure that the observer pressed the intended key. If desired, the observer could modify his selection. Once satisfied with the choice, the observer pressed the space bar to start the next trial. Before the start of the next trial, the correct orientation of the half-circle for the just completed trial appeared on the screen for 500 ms.

Each observer received 18 practice trials and then 432 experimental trials, with 2 trials for each target duration, mask duration, and SOA. During the practice trials, the experimenter explained the observer's task and showed the observer how to enter responses, watch for feedback, and start trials. The experimental trials were presented in a random order. The experiment was self-paced and took between 30 to 45 minutes to complete.

Results

Figure 6 plots the percent correct detection as a function of SOA. This figure can be compared to the backward masking data of Kahneman (1967) (Figure 1) and Macknik and Livingstone (1998) (Figure 3A). A u-shaped masking function was found for every target and mask combination.

- Figure 6 -

The target and mask durations did affect the strength of masking. Figure 7 plots the percentage of correct responses against target duration, with separate curves for different mask durations. Each percentage combined the responses across all 18 SOAs so that there are 5220 trials for each data point. Increasing the target duration improved identification of the target, as can be seen by the increasing slope of the lines. The effect of target duration did not seem to interact with mask duration, as the lines for different mask durations were nearly parallel. Increasing the mask duration decreased the percent correct identifications, as shown by the downward shift in the lines as mask duration goes from 30 ms to 120 ms. The overall effects of target and mask duration are consistent with previous studies of backward masking (e.g., Schiller, 1965; Breitmeyer, 1978; Macknik & Livingstone, 1998; Di Lollo, Bischof & Dixon, 1993).

- Figure 7 -

Testing the validity of the laws

To test the validity of the backward masking laws, it is necessary to identify the SOA that produces maximal masking (the ISI and STA for maximal masking can be directly computed from the SOA for maximal masking). This was done by reading off the SOA that has the lowest percentage correct for a given target and mask duration. In the case that two or more SOAs had the same lowest percentage correct, the average of these SOAs was taken as the SOA for maximal masking.

We wanted to know if the experimental data deviated from any of the theoretical laws.

However, we did not know of any parametric tests that applied to this situation. Most significantly, the sampling variability in the selection of the SOA for maximal masking was unknown. To deal with these problems, we used a bootstrapping analysis (Efron & Tibshirani, 1993). A bootstrapping analysis provides a means of estimating the sampling distribution of virtually any statistic by repeatedly drawing random samples from the gathered data. With each random sample, we computed the statistic of interest and combined these statistics across samples to produce a histogram of the frequency of different statistic values. This provides an estimate of the variability the statistic across different samples.

For each target duration, mask duration, and SOA, there were a total of 290 trials in the experiment. On each bootstrapping run, 290 trials were drawn, with replacement, from the trials gathered for each target duration, mask duration, and SOA. These sampled trials then produced a percentage of correct identifications for each condition. This resulted in a new data set that was equivalent in size to the original data set. From this new data set, the SOAs for maximal masking could be computed, as above. These SOA statistics were kept for each combination of target and mask duration and contributed to the creation of sampling distributions. A total of 25,000 bootstrapping runs were carried out to produce sampling distributions for the SOAs for maximal masking.

Figure 8A shows the masking functions for equal target and mask durations. If the ED-SOA law was true, the SOA for maximal masking would be constant. As can be seen, it is difficult to be confident about the location of the SOA for maximal masking. Figure 8B shows the sampling distributions of the SOA for maximal masking for different target and mask equal durations. While the sampling distribution for target and mask durations of 60 ms sharply peaks at 105 ms, the sampling distributions of the other conditions are more spread out and are sometimes skewed.

- Figure 8 -

To test the validity of the ED-SOA law, we computed the 95% confidence interval[2]

[2]The 95% confidence interval is defined as the range of values that cover the middle 95% of the sampling distribution. That is, the SOA for maximal masking will be outside the confidence interval only 5% (2.5% above and 2.5% below) of the time due to sampling variation. The modal SOA for maximal masking is

for each equal target and mask duration. If the 95% confidence intervals overlapped, this would indicate that the data did not reject the ED-SOA law. Figure 9A shows the 95% confidence intervals that test the ED-SOA law. For each duration, the filled circle marks the modal SOA for maximal masking from the sampling distribution. (The modal SOAs for maximal masking will generally be the same as the bottom of the masking curves in Figure 6; differences would occur only when the original or some bootstrap samples have two or more bottoms and their SOAs are averaged.) The modal SOA for maximal masking tends to increase with the target and mask duration, but since all of the confidence intervals overlap, the data could be consistent with the ED-SOA law.

- Figure 9 -

A similar analysis was used to test the validity of the FM-ISI and STA laws. Figure 9B plots the modal ISI for maximal masking and the 95% confidence interval for various mask and target durations. Within each mask duration, there is no systematic relationship between the modal ISI for maximal masking and target durations. Moreover all of the confidence intervals within a given mask duration overlap, so the data could be consistent with the FM-ISI law.

Figure 9C plots the modal STA for maximal masking and its 95% confidence intervals for various mask and target durations. The modal STA for maximal masking tends to increase with mask duration. Moreover, several of the confidence intervals do not overlap, which indicates that the STA for maximal masking varies significantly as target and mask duration vary. The non-overlapping pairs of confidence intervals are for T90/M30 vs. T60/M90, T90/M30 vs. T60/M120, T90/M30 vs. T90/M120, and T60/M60 vs. T90/M120. These differences suggest that the data are *not* consistent with the STA law.

provided only to describe a point estimate of the SOA for maximal masking; it does not contribute to the statistical analysis at all.

Contrasting laws

The experimental data reject the STA law. Based on the mathematical analysis of the laws, if the STA law is not valid then it is not possible for both the ED-SOA and the FM-ISI law to be valid. The data suggest that the ED-SOA law may not be valid because the modal SOA for maximal masking tends to increase with stimulus duration. However, the changes in the SOA for maximal masking do not reach statistical significance. On the other hand, the data do seem to be consistent with the FM-ISI law. There are no systematic effects of target duration within a fixed mask duration. To quantify whether the data best support the ED-SOA law or the FM-ISI law, we followed the approach used by Macknik and Livingstone (1998) and computed the standard deviation of the modal SOA for maximal masking and the modal ISI for maximal masking, across their relevant target and mask durations.

For the ED-SOA law, the standard deviation was across those conditions that have equal target and mask durations. This was for T30/M30, T60/M60, T90/M90, and T120/M120, and the standard deviation was 38.73 ms. For the FM-ISI law, the standard deviation was computed for each fixed mask duration, across the different target durations. These standard deviations were then pooled to produce a single number that indicated how much the ISI for maximal masking varied when the target duration changed but the mask duration was held fixed. The pooled standard deviation was 12.99 ms. For completeness, the standard deviation for the STA for maximal masking was also computed by using every combination of target and mask duration. This standard deviation was 35.30 ms. If a law was obeyed perfectly, and there was no noise in the experimental data, its standard deviation would be zero.

We used Bartlett's test (Snedecor & Cochran, 1989) to determine if the standard deviations were statistically different for the ED-SOA and the FM-ISI laws. Bartlett's test computes a test statistic, $T = 6.90$, which is compared to the upper critical value of a χ^2 distribution with one degree of freedom. The standard deviation among the SOAs for maximal masking and the standard deviation among the ISIs for maximal masking were different ($p = 0.0086$). Because the FM-ISI law has a smaller standard deviation, it provides a better description of the data than the ED-SOA law.

Discussion

The bootstrap analysis of the data from experiment 1 rejects the STA law directly. The STA for maximal masking seems to increase with mask duration. The bootstrap analysis was unable to reject either the ED-SOA law or the FM-ISI law. A comparison of the fit of the data to these laws suggest that the FM-ISI law provides a better fit. Thus, if any of the laws are valid the FM-ISI law seems to be the best choice.

One concern with experiment 1 is that it used a large number of observers who saw the different conditions only a few times. Masking functions vary across individuals, so the data in experiment 1 likely blurs a large number of different masking functions. Such blurring would likely flatten the bottom of the masking functions, and thereby increase the magnitude of the confidence intervals used to test the laws. The large size of the confidence intervals would tend to make it more difficult to reject any of the laws.

Experiment 2: Single observer

To generate data with less variability, the experiment was repeated with a single observer (the first author), who ran thirty-three sessions, so that each target/mask/SOA condition was seen 66 times.

Results

Figure 10 plots the percent correct detection as a function of SOA. A u-shaped masking function was found for every target and mask combination. As expected, the u-shapes are generally less broad and have more precisely defined bottoms than for experiment 1 (Figure 6). Performance was generally better for the single observer, which likely reflects that fact that the observer was well trained at the task even before beginning the experimental sessions.

- Figure 10 -

The validity of the various laws was again analyzed with a bootstrapping analysis. Figure 11 shows the modal value of the SOA, ISI, and STA for maximal masking and the 95% confidence intervals. The overall pattern of the modes is similar to that of experiment 1, but the confidence intervals tend to be smaller (note that the range on the vertical axis is smaller in Figure 11 than in Figure 9.)

- Figure 11 -

Figure 11A shows that the modal SOA for maximal masking increases as target and mask duration increase together. Moreover, the confidence interval for target and mask duration 30 ms does not overlap the confidence interval for target and mask duration 90 ms. This finding invalidates the ED-SOA law, which predicted that the SOA for maximal masking should be constant under these conditions.

The ISIs for maximal masking in Figure 11B are quite similar to the data from experiment 1. There is a slight tendency for the modal ISI for maximal masking to decrease as mask duration increases, but within a fixed mask duration there is no systematic change in the ISI as target duration varies. All of the confidence intervals within a fixed mask duration overlap, which is consistent with the FM-ISI law.

The STAs for maximal masking in Figure 11C are also quite similar to the data from experiment 1, and show a trend for larger STAs as mask duration increases. As in experiment 1, some of the confidence intervals do not overlap, which indicates that the STA law is not valid. The violations of the STA law are more numerous than in experiment 1. The STA for maximal masking for conditions T30/M30 and T60/M30 are different from all of the M90 conditions and from T60/M120. In addition, T60/M120 is different from all of the M60 conditions, and T120/M90. Finally, T60/M90 is different from T90/M60.

Conclusions

Our analysis and data suggest that if any of the laws of masking are true, it is the FM-ISI law (Francis, 1997). Neither experiment 1, which averaged data from many different observers, nor experiment 2, which used data from a single observer, found statistically significant evidence against the FM-ISI law. Nor was there any systematic trend in the data that hinted that the FM-ISI law might be invalid. In contrast, both experiment 1 and experiment 2 rejected the STA law. Contrary to the prediction of the STA law, the STA for maximal masking tended to increase with mask duration.

In both experiments 1 and 2 the SOA for maximal masking tended to increase with target and mask duration. The increase was statistically significant for experiment 2 but not for experiment 1. Further analysis of the data in experiment 1 took advantage of the mathematical analysis of the laws, which proved that if the STA law was not valid, then only one of the ED-SOA and the FM-ISI laws could possibly be true. A comparison of which law best matches the data favored the FM-ISI law over the ED-SOA law.

This preference of the FM-ISI law over the ED-SOA law is in conflict with the data of Kahneman (1967) and Weisstein and Growney (1969). All of their data are generally consistent with the ED-SOA law. However, a potential problem with their experiments is that observers made subjective ratings of the strength of masking. In our own experience with this type of subjective rating, the masking effect seems qualitatively different for short SOAs and long SOAs (see also Reeves, 1982, 1986). With shifting criterion, we suspect observers may also be changing the basis for their report as the target and mask durations change. As a result, we feel that the objective task used in our experiment and Macknik and Livingstone (1998) is a more reliable measure of masking effects across different target and mask durations.

The conclusion that the data support the FM-ISI law seems contrary to the study of Macknik and Livingstone (1988). They concluded that their masking data was best characterized by the STA law. If the laws are to have any practical significance, they should hold across a variety of experimental conditions. It should be emphasized that the FM-ISI law is a special case of the STA law, so the only discrepancy to explain is the conclusions around the validity of the STA law. We feel the source of the different conclusions involves the selection of target and mask durations used to test the laws. Macknik and Livingstone (1998) used only two mask durations, while our experiments used four (see Figure 4). These four mask durations allow for a better test of the STA law's prediction that increases in mask duration cause a corresponding shift in the SOA for maximal masking to smaller values. The data suggest that there is such a shift, but its magnitude is not as big as the STA law predicts. This is why the modal STA for maximal masking increases with mask duration in Figures 9C and 11C. Macknik and Livingstone (1998) might not have included mask durations that were different enough to measure this effect. Indeed, if we selected only the target and mask durations that were most similar to those used by Macknik and Livingstone (T30/M60, T90/M60, T90/M90), the present data would not reject the STA law.

Macknik and Livingstone (1998) used the properties of the STA to justify a neurophysiological exploration of after discharge responses among cells in cortex (see also Macknik, Martinez-Conde & Haglund, 2000). Although the STA law does not seem to be valid, the FM-ISI law also justifies such investigations. Indeed, the only difference between the FM-ISI law and the STA law is in characterizing how variations in mask duration affect the SOA for maximal masking. The STA law says that the effect should exactly equal the change in mask duration, while the FM-ISI law makes no claims about the exact magnitude of the effect. However, the FM-ISI law and the STA law both suggest that persisting responses generated by the target (after discharges in the terminology of Macknik and Livingstone (1998)) are important for backward masking (Francis, 1997). Therefore, our results clarify and elaborate on the conclusions of Macknik and Livingstone (1998) rather than contradict them.

Systems other than Francis' (1997) neural network model could also produce an FM-ISI law. Francis (2003) analyzed a different quantitative model of backward masking, which also predicts an FM-ISI law for large enough target durations (see Corollary A.1). As another example, Reeves (1982, 1986) argued that the u-shaped masking function was the result of two separate processes (integration and differentiation). The integration process occurs for short SOAs and masking gets stronger as SOA increases and integration is less likely to occur. Likewise, differentiation occurs for long SOAs, and masking gets weaker as SOA increases and differentiation is more likely to occur. In this scheme, the SOA at the bottom of the u-shaped masking function is the SOA that fails to produce strong integration or strong differentiation. Integration is related to persistence of the target signals (Francis, 1996), which suggests that it is the time after of the offset of the target (the ISI) that will be critical for determining whether the target and mask integrate.

A final comment should be made about the generality of any of these laws. Even in the forms tested here, the laws are quite restricted. Their validity depends on keeping everything about the stimuli except the target and mask durations fixed. These restrictions are severe because it is known that factors such as intensity (Weisstein, 1972), attentional focus (Weisstein, 1966), judgment (Stober, Brussell & Komoda, 1978), flicker adaptation (Petry, Grigonis & Reichert, 1979), and light adaptation (Purcell, Stewart, & Brunner, 1974) can influence the value of the SOA that produces maximal masking. In a sense the term "law" is a misnomer because it implies that these factors do not matter. Were it not for historical usage of the term, we would not use it.

The two experiments reported here are consistent with the FM-ISI law, but this could be either because the FM-ISI law is true or because the data contain too much noise to demonstrate the discrepancies in the law. Moreover, it remains a real possibility that the FM-ISI law will not hold for other stimuli and/or tasks. Nevertheless, it is encouraging that the FM-ISI law holds for both the present study and the study of Macknik and Livingstone (1998). The model of Francis (1997) suggests that the FM-ISI law should hold for any experiment where only the target and mask durations vary.

References

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

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

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

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.

Efron, B. & Tibshirani, R. J. (1993). *An Introduction to the Bootstrap.* New York: Chapman & Hall.

Enns, J. T. & Di Lollo, V. (2000). What's new in visual masking? *Trends in Cognitive Sciences*, **4**, 345–352.

Francis, G. (1996). Cortical dynamics of visual persistence and temporal integration. *Perception & Psychophysics*, **58**, 1203–1212.

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). Developing a new quantitative account of backward masking. *Cognitive Psychology*, **46**, 198–226.

Grossberg, S. & Mingolla, E. (1985a). Neural dynamics of perceptual grouping: Textures, boundaries, and emergent segmentations. *Perception & Psychophysics*, **38**, 141–171.

Grossberg, S. & Mingolla, E. (1985b). Neural dynamics of form perception: Boundary completion, illusory figures, and neon color spreading. *Psychological Review*, **92**, 173–211.

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.

Macknik, S. L., Martinez-Conde, S. & Haglund, M. M. (2000). The role of spatiotemporal edges in visibility and visual masking. *Proceedings of the National Academy of Sciences*, **97**, 7556–7560.

Petry, S., Grigonis, A. & Reichert, B. (1979). Decrease in metacontrast masking following adaptation to flicker. *Perception*, **8**, 541–547.

Purcell, D. G., Stewart, A. L., & Brunner, R. L. (1974). Metacontrast target detection under light and dark adaptation. *Bulletin of the Psychonomic Society*, **3**, 199–201.

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

Reeves, A. (1986). Pathways in type-B metacontrast. *Perception*, **15**, 163–172.

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

Snedecor, G. W. & Cochran, W. G. (1989), *Statistical Methods, Eighth Edition*, Iowa State University Press.

Stober, S. R., Brussell, E. M. & Komoda, M. K. (1978). Differential effects of metacontrast on target brightness and clarity. *Bulletin of the Psychonomic Society*, **12**, 433–436.

Weisstein, N. (1966). Backward masking and models of perceptual processing. *Journal of Experimental Psychology*, **72**, 232–240.

Weisstein, N. (1972). Metacontrast. In D. Jameson & L. Hurvich (Eds.) *Handbook of sensory physiology* (Vol. 7, No. 4, *Visual psychophysics*). Berlin: Springer-Verlag.

Weisstein, N. & Growney, R. L. (1969). Apparent movement and metacontrast: A note on Kahneman's formulation. *Perception & Psychophysics*, **5**, 321–328.

Figure Captions

Figure 1. Masking functions found by Kahneman (1967) show substantial overlap even as the target and mask duration varied. This finding led Kahneman to hypothesize an SOA law for backward masking. Reprinted with permission from Francis (1997).

Figure 2. Results that led to the development of the FM-ISI law. A shows simulation results generated by the model in Francis (1997). This model predicts that the ISI for maximal masking is a function of the mask duration, but does not vary with the target duration. B shows experimental data from Macknik & Livingstone (1998) that is consistent with the FM-ISI law. B is reprinted with permission from Macknik and Livingstone (1998).

Figure 3. Experimental data from Macknik & Livingstone (1998) that is consistent with an STA law. The STAs for maximal masking are indicated by the lines drawn down from the curves. The STA for maximal masking does not change very much even as the target and mask durations vary. Reprinted with permission from Macknik and Livingstone (1998).

Figure 4. The target and mask durations used in the current experiment. The durations used by Kahneman (1967) and Macknik & Livingstone (1998) are shown for comparison.

Figure 5. Schematics of the stimuli used in the experiment (in reverse contrast). The observer's task was to report the orientation of the flat side of the half circle in the target frame.

Figure 6. Percentage correct identifications of the target as a function of SOA for different target and mask durations in experiment 1 for averaged across multiple observers. For every target and mask duration, the masking function is u-shaped.

Figure 7. Global effects of target duration and mask duration in experiment 1. Each data point combines data across all SOAs for each target and mask duration. As target duration increased, observers correctly identified the target more often. Likewise, as mask duration increased, the percentage correct decreased.

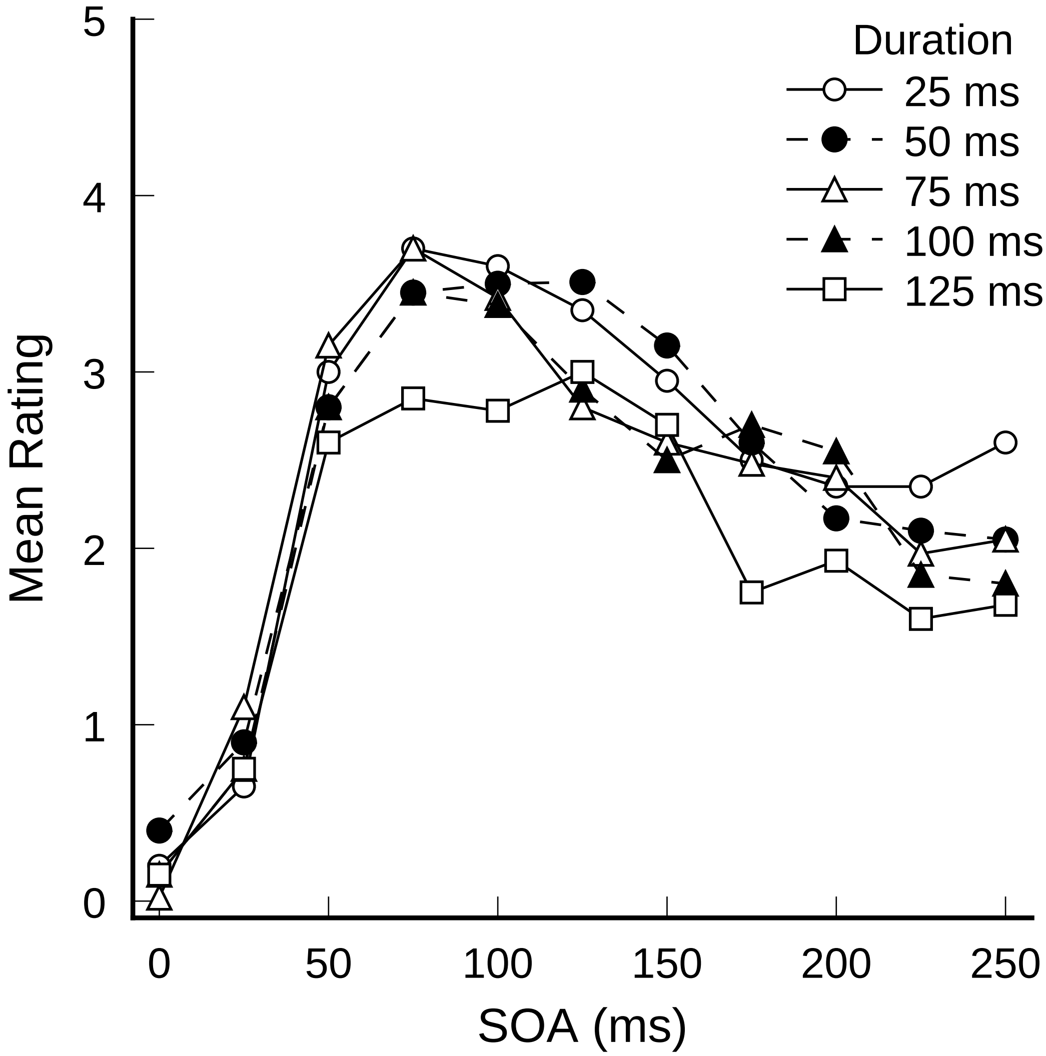
Figure 8. The data that test the ED-SOA law. A shows the masking functions for equal target and mask durations. If the ED-SOA law was true, the bottom of each curve would be at a common SOA. B shows the sampling distributions that were derived from the masking

functions in A. The sampling distributions were created with a bootstrapping process, and give an estimate of how much sampling variability exists in the SOA for maximal masking for each combination of target and mask durations.

Figure 9. The data from experiment 1 were used to compute the modal SOA, ISI, or STA for maximal masking from the bootstrapped sampling distributions. They are plotted as a function of the target and mask duration. The error bars show 95% confidence intervals for the point of maximal masking. A shows the SOA for maximal masking across the conditions where the target and mask have equal durations. Since the confidence intervals overlap, the data could be consistent with the ED-SOA law. B shows the ISI for maximal masking across all target and mask durations. Within each mask duration, the confidence intervals overlap, thereby indicating that the data could be consistent with the FM-ISI law. C shows the STA for maximal masking across all target and mask durations. Some of the confidence intervals do not overlap, thereby indicating that the data are not consistent with the STA law.

Figure 10. Percentage correct identifications of the target as a function of SOA for different target and mask durations in experiment 2 with a single observer. For every target and mask duration, the masking function is u-shaped.

Figure 11. The data from experiment 2 were used to compute the modal SOA, ISI, or STA for maximal masking from the bootstrapped sampling distributions. They are plotted as a function of the target and mask duration. The error bars show 95% confidence intervals for the point of maximal masking. A shows the SOA for maximal masking across the conditions where the target and mask have equal durations. Since the confidence intervals do not all overlap, the data are inconsistent with the ED-SOA law. B shows the ISI for maximal masking across all target and mask durations. Within each mask duration, the confidence intervals overlap, thereby indicating that the data could be consistent with the FM-ISI law. C shows the STA for maximal masking across all target and mask durations. Some of the confidence intervals do not overlap, thereby indicating that the data are not consistent with the STA law.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50 ms
75 ms
100 ms
125 ms
Mean Rating
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1
2
3
4
5
0
50
100
150
200
250
SOA (ms)

Figure 1:

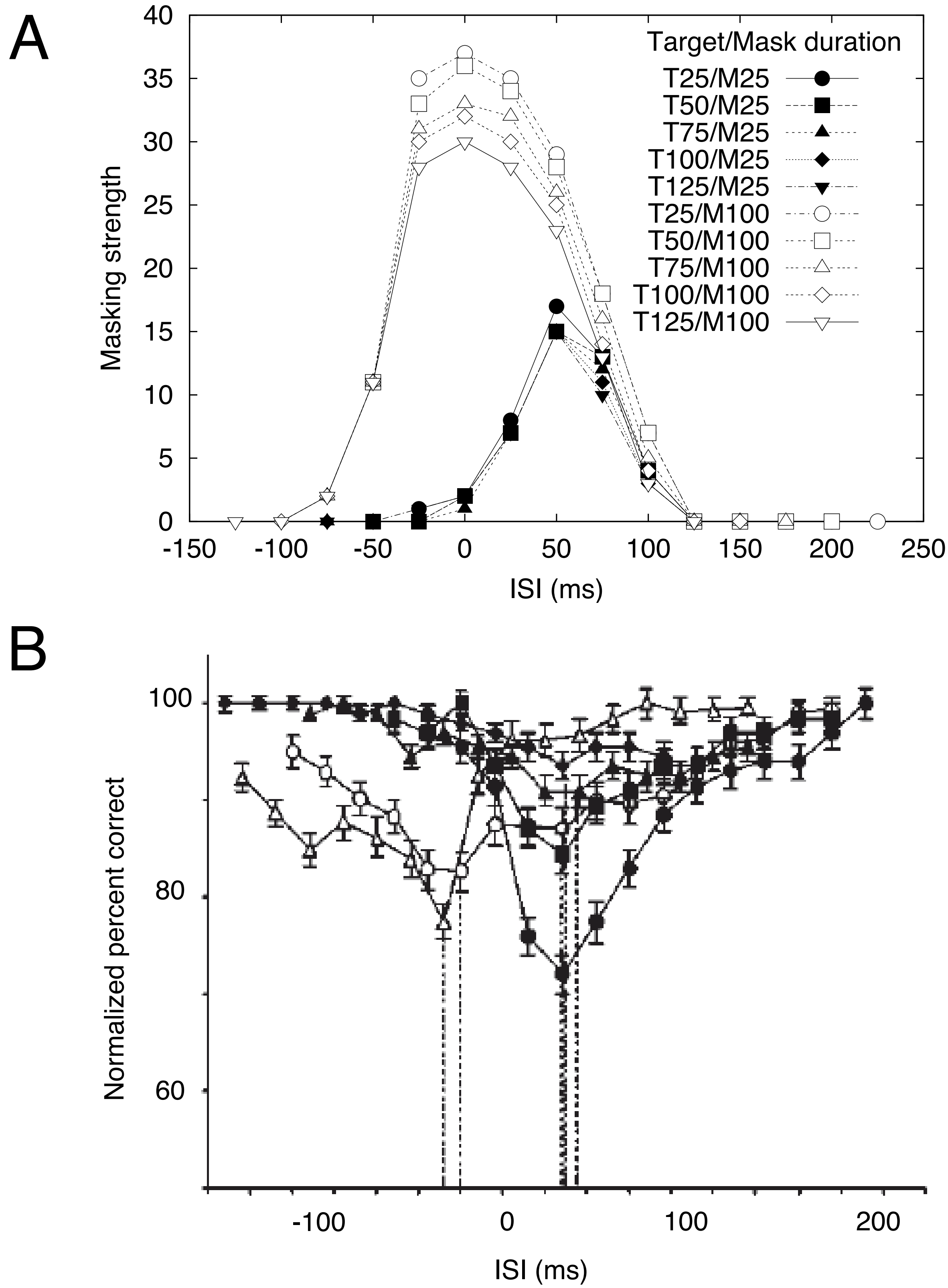

A
Masking strength
ISI (ms)
Target/Mask duration
T25/M25
T50/M25
T75/M25
T100/M25
T125/M25
T25/M100
T50/M100
T75/M100
T100/M100
T125/M100
0
5
10
15
20
25
30
35
40
-150
-100
-50
0
50
100
150
200
250
B
Normalized percent correct
ISI (ms)
60
80
100
-100
0
100
200

Figure 2:

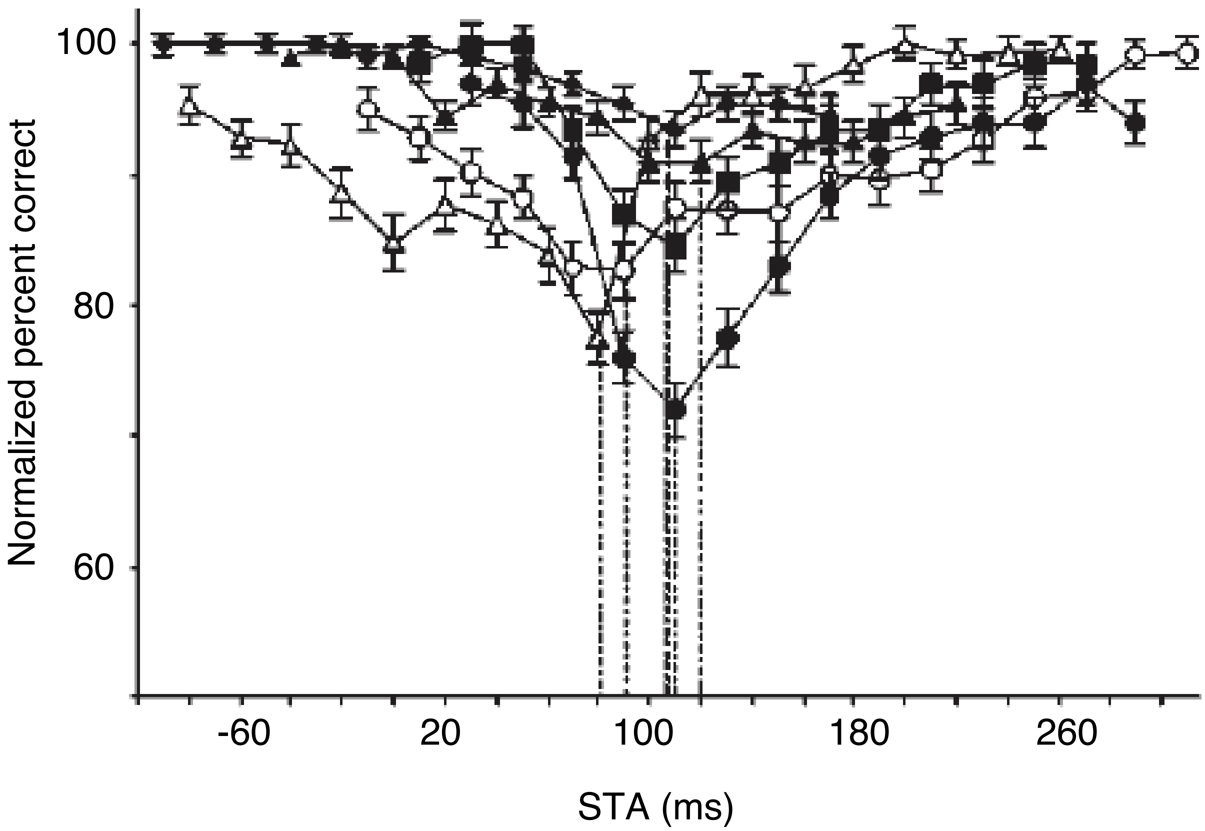


Figure 3:

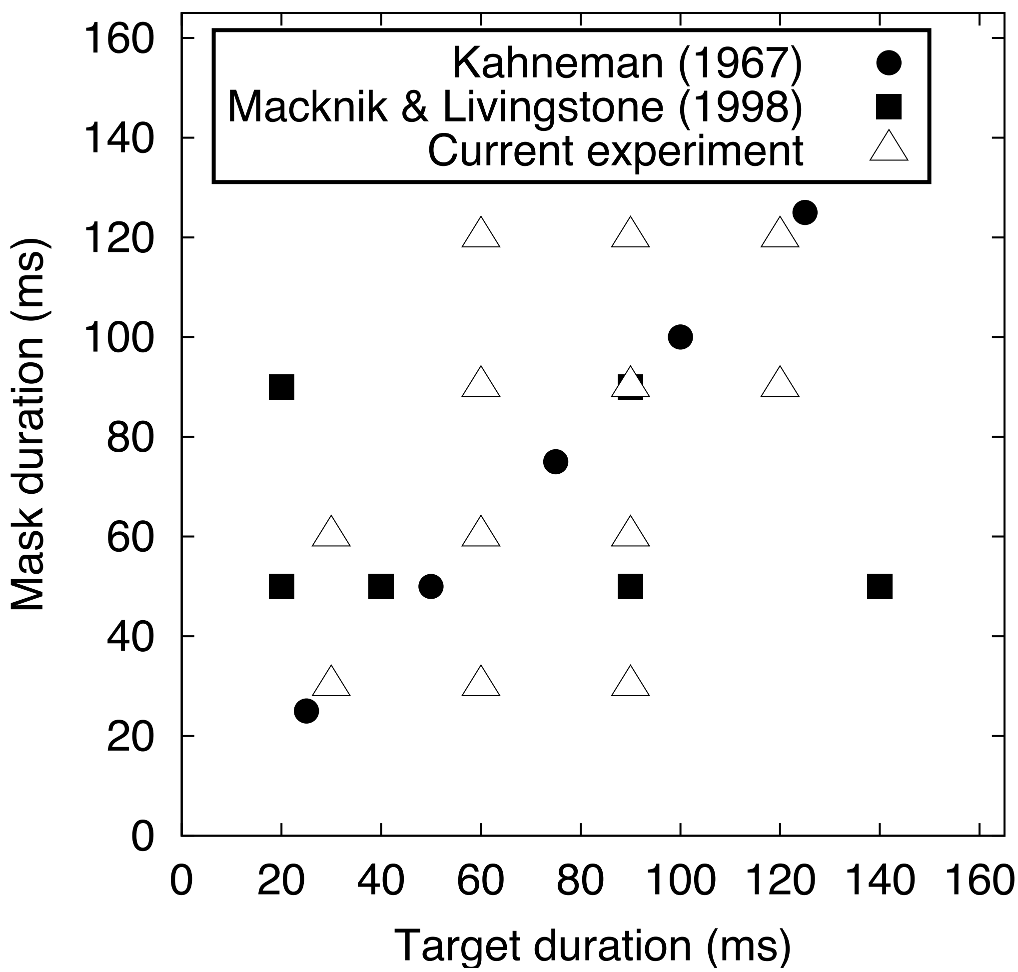
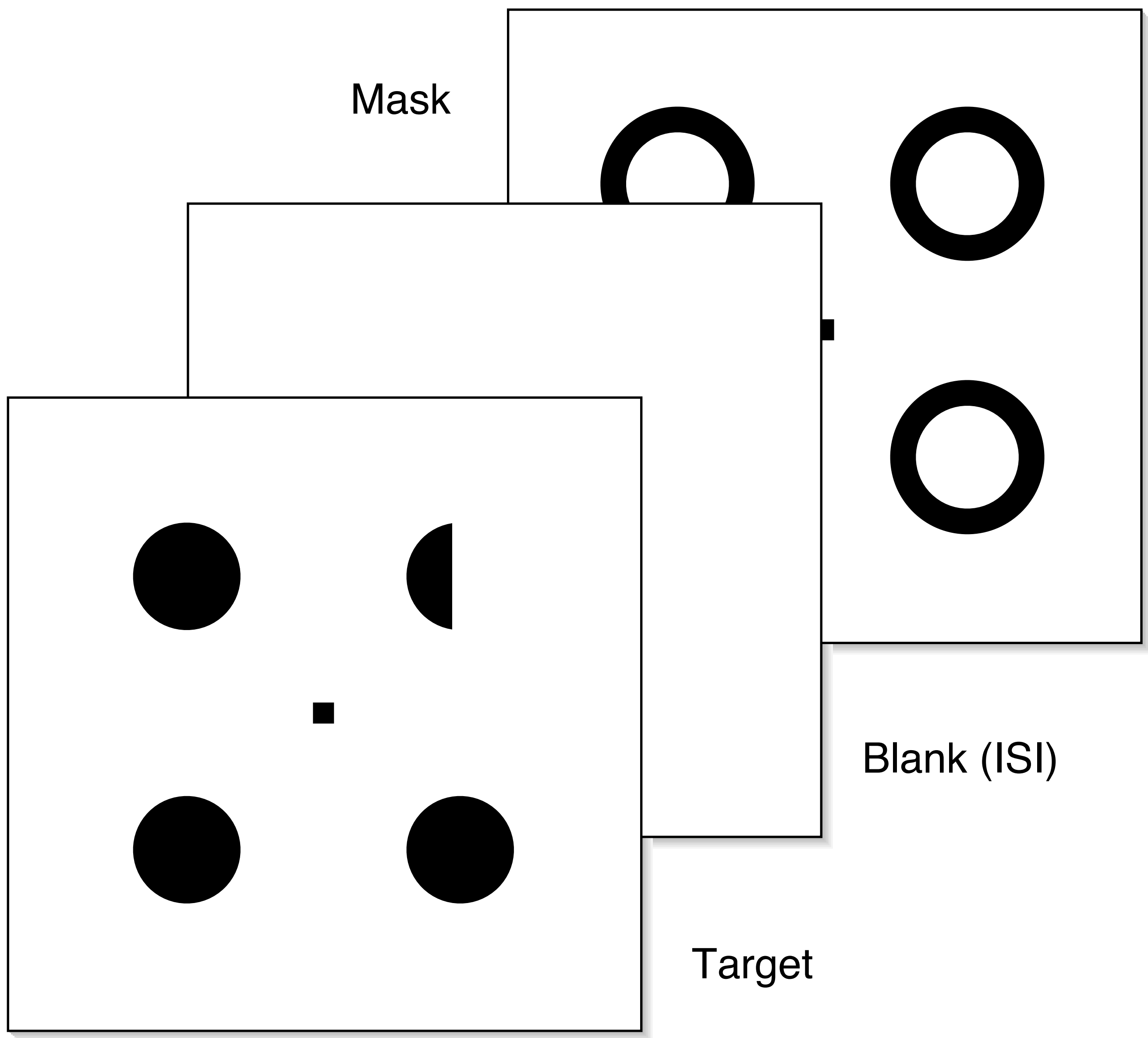

Kahneman (1967)
Macknik & Livingstone (1998)
Current experiment
160
140
120
100
80
60
40
20
0
Mask duration (ms)
0
20
40
60
80
100
120
140
160
Target duration (ms)

Figure 4:



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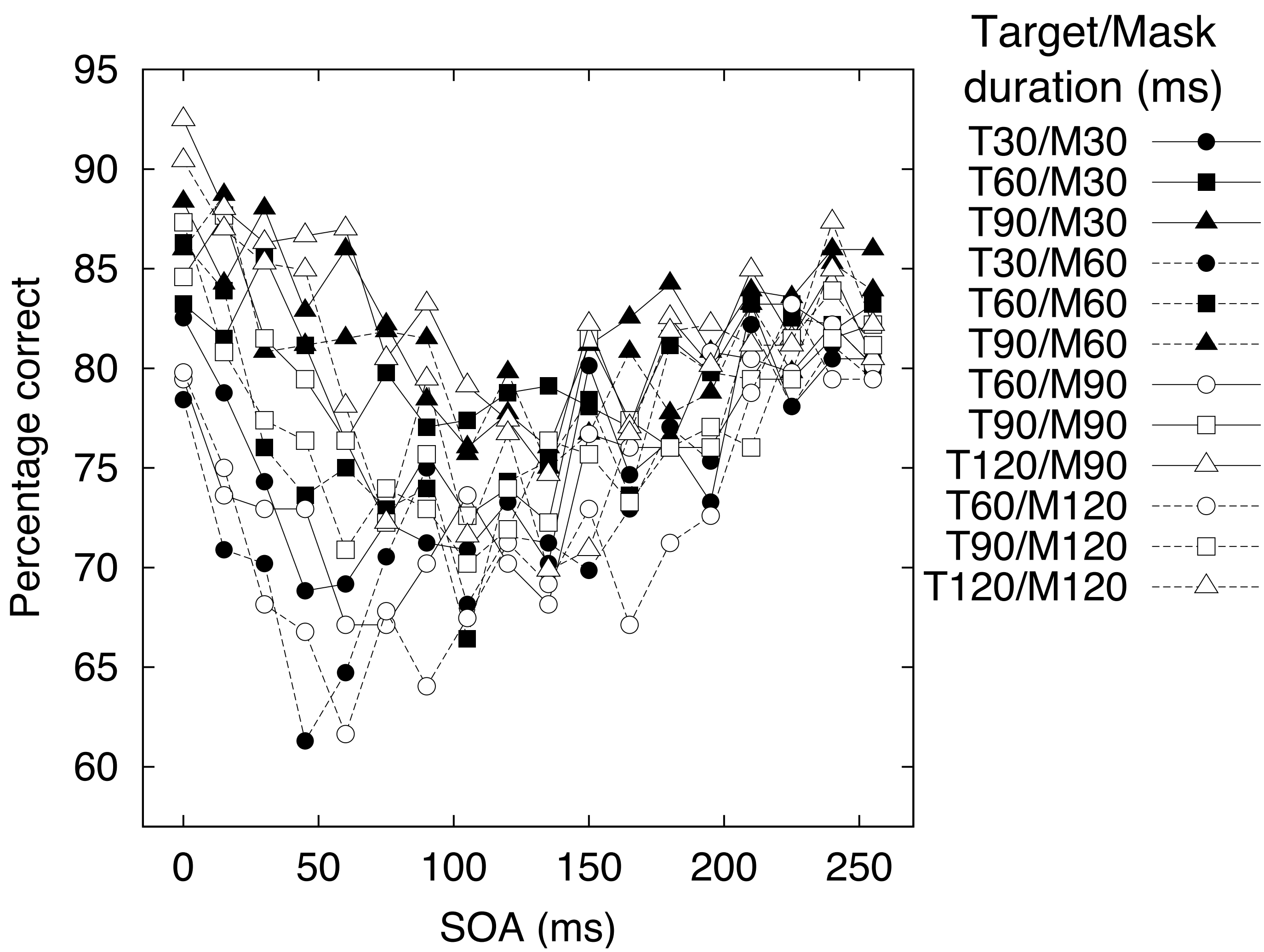
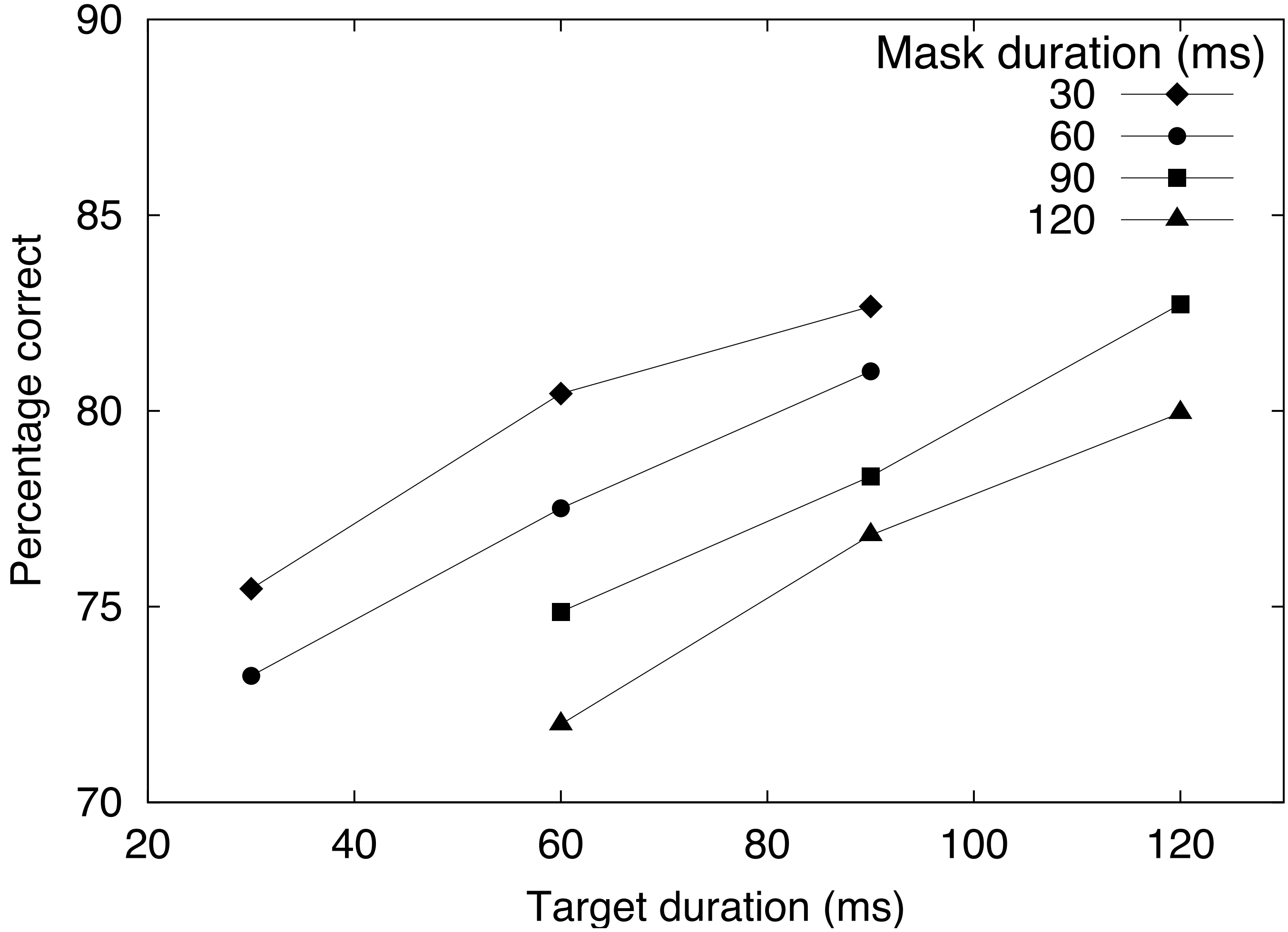

Target/Mask
duration (ms)
T30/M30
T60/M30
T90/M30
T30/M60
T60/M60
T90/M60
T60/M90
T90/M90
T120/M90
T60/M120
T90/M120
T120/M120
Percentage correct
95
90
85
80
75
70
65
60
0
50
100
150
200
250
SOA (ms)

Figure 6:



90
85
80
75
70
20
40
60
80
100
120
Percentage correct
Target duration (ms)
Mask duration (ms)
30
60
90
120

Figure 7:

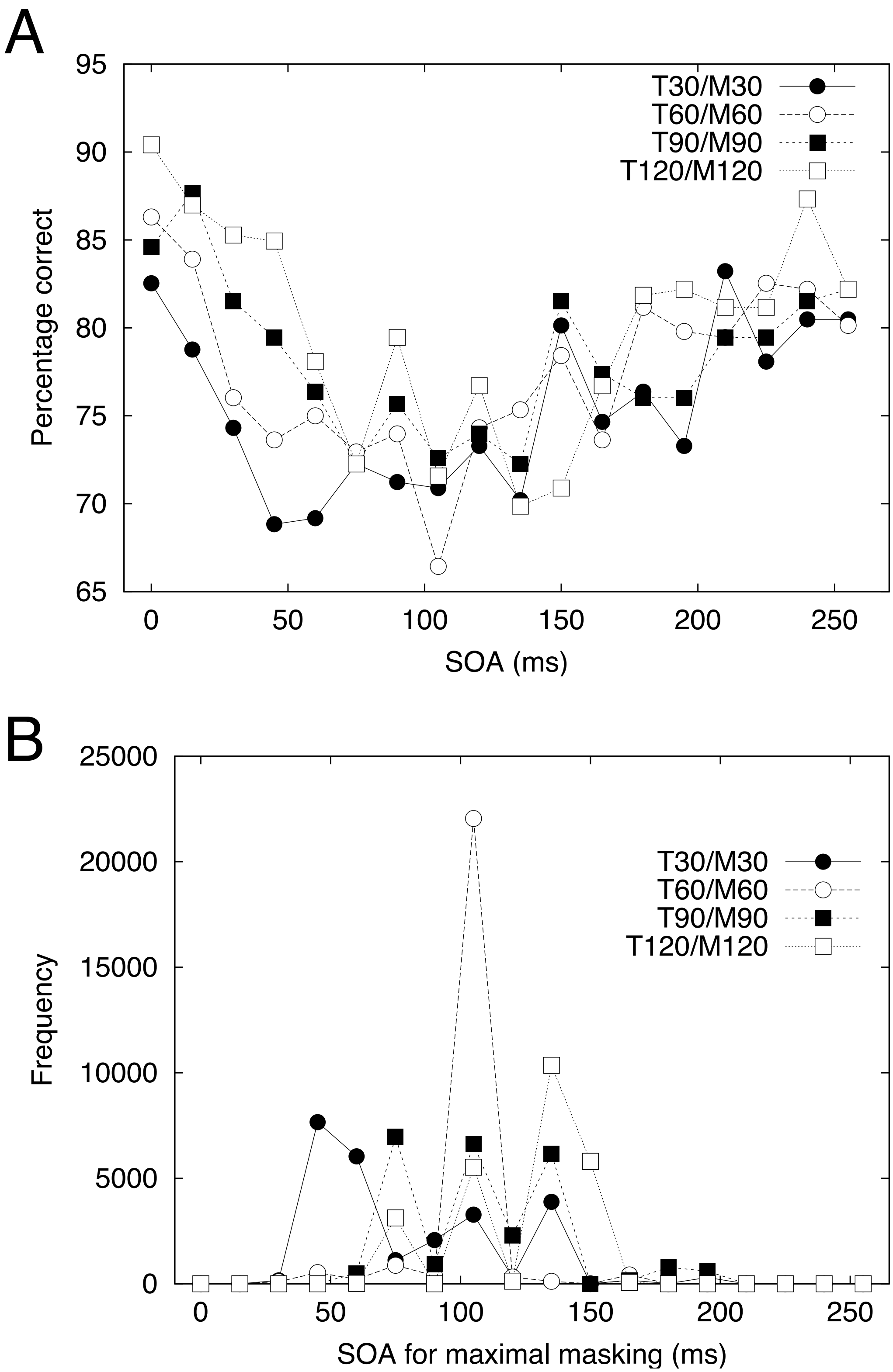

A
Percentage correct
SOA (ms)
T30/M30
T60/M60
T90/M90
T120/M120
B
Frequency
SOA for maximal masking (ms)
T30/M30
T60/M60
T90/M90
T120/M120

Figure 8:

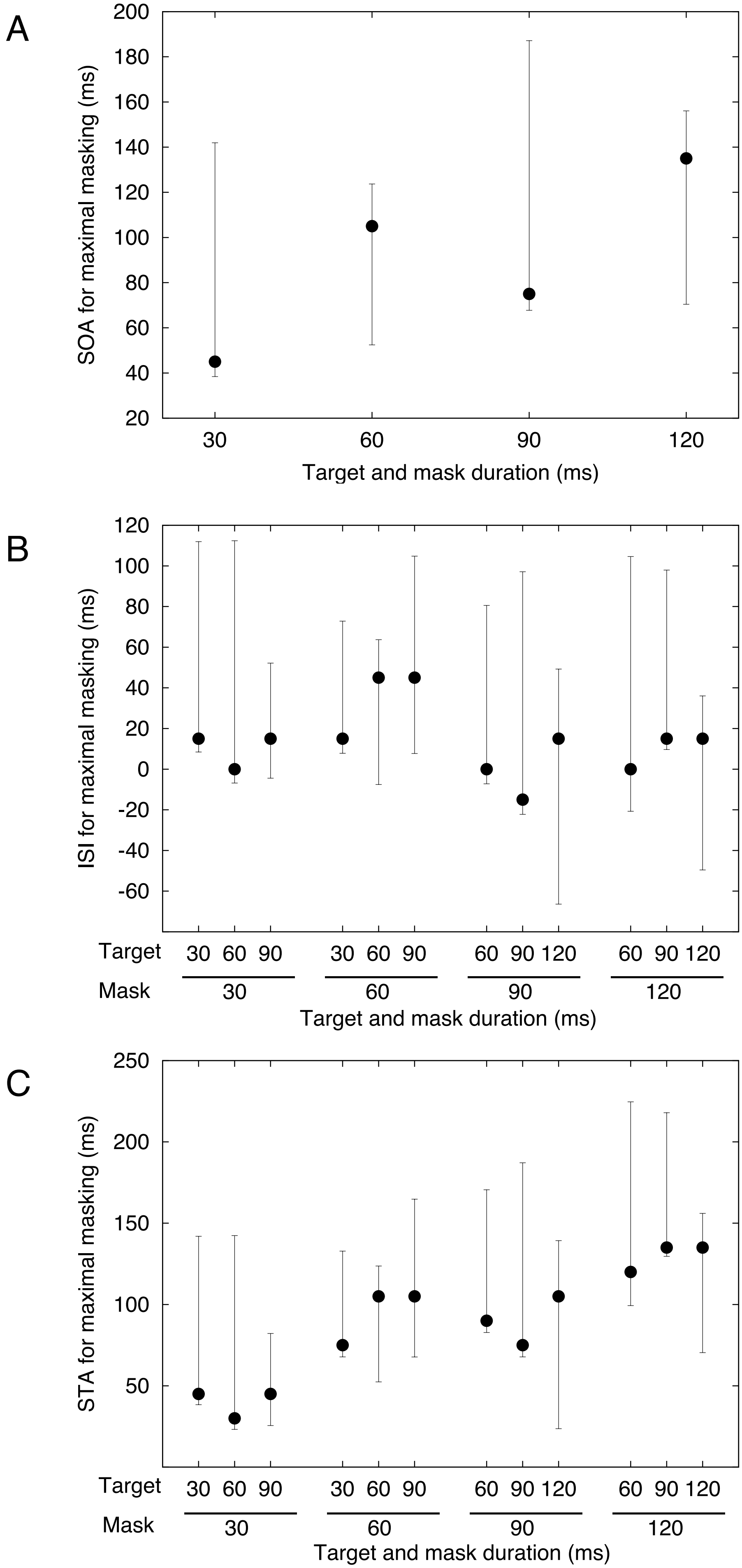

A
SOA for maximal masking (ms)
Target and mask duration (ms)
B
ISI for maximal masking (ms)
Target
Mask
Target and mask duration (ms)
C
STA for maximal masking (ms)
Target
Mask
Target and mask duration (ms)

Figure 9:

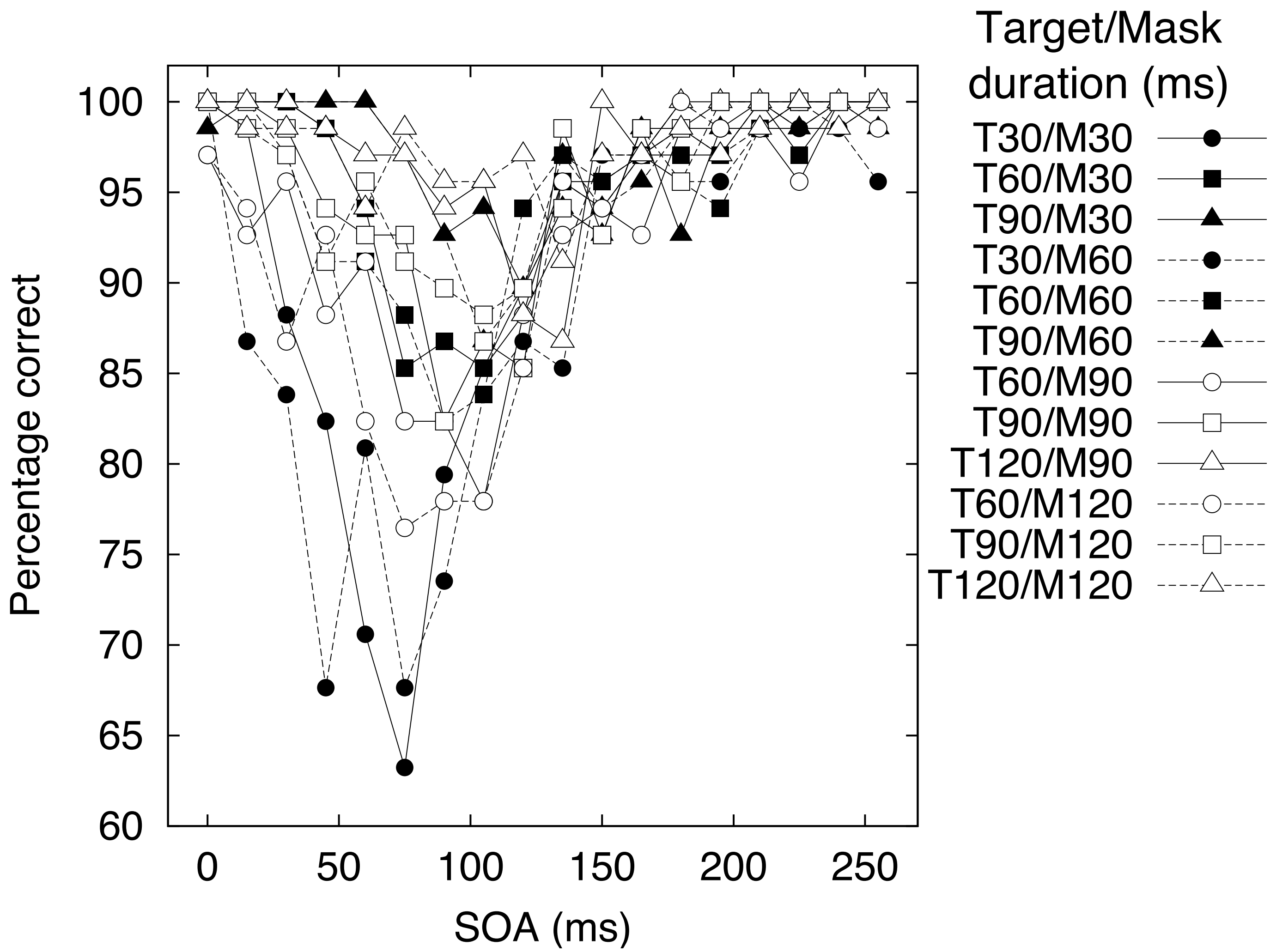

Target/Mask duration (ms)
T30/M30
T60/M30
T90/M30
T30/M60
T60/M60
T90/M60
T60/M90
T90/M90
T120/M90
T60/M120
T90/M120
T120/M120
Percentage correct
100
95
90
85
80
75
70
65
60
0
50
100
150
200
250
SOA (ms)

Figure 10:

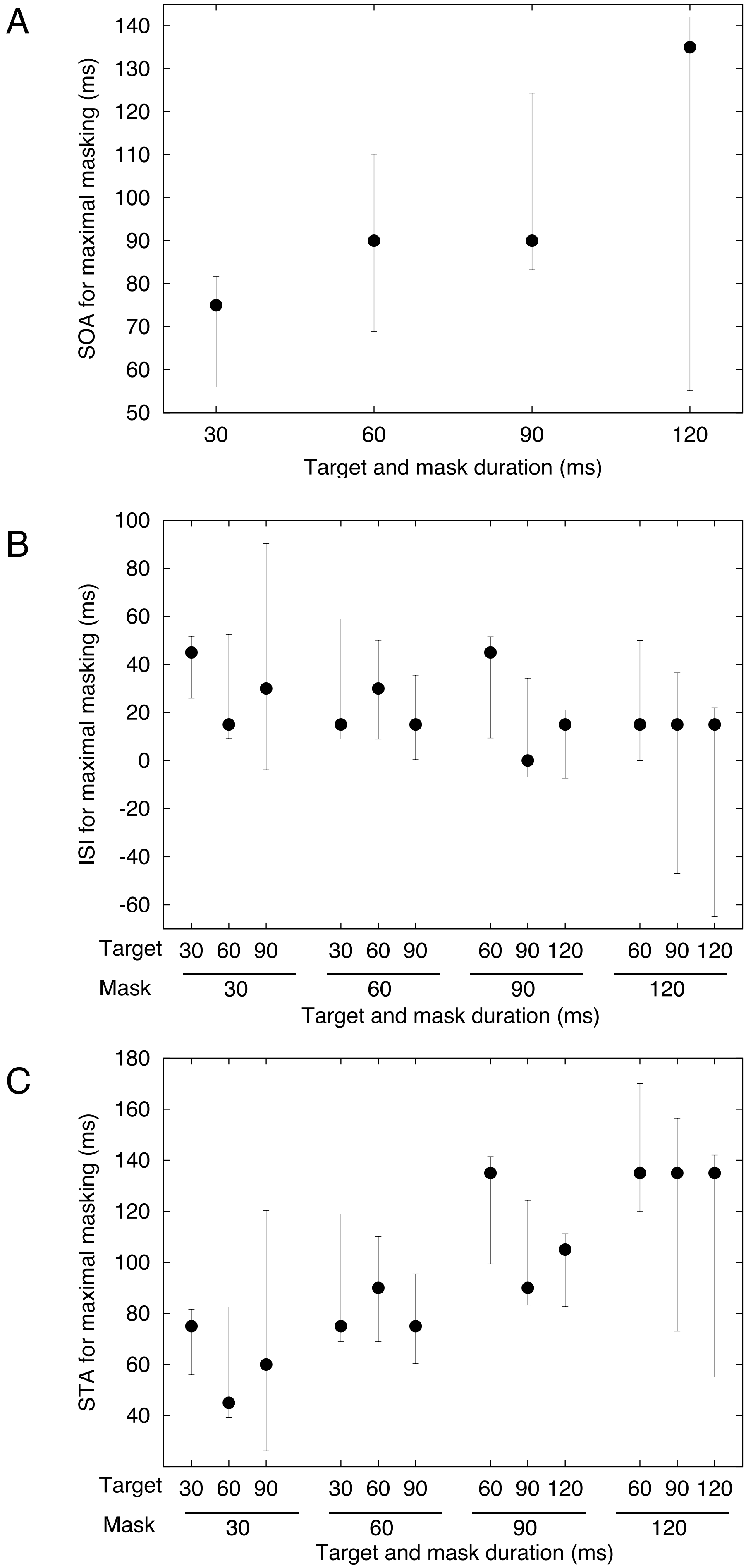

A
SOA for maximal masking (ms)
Target and mask duration (ms)
B
ISI for maximal masking (ms)
Target
Mask
Target and mask duration (ms)
C
STA for maximal masking (ms)
Target
Mask
Target and mask duration (ms)

Figure 11: