What is the strength of a mask in visual metacontrast masking?

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After more than a century of research, the mechanisms underlying visual masking are still hotly debated. One key characteristic of masking is that variations in the stimulus onset asynchrony (SOA) between the target and the mask can lead to either monotonic reductions in the effect of the mask on the target (A-type masking) or an increase in masking for intermediate SOAs and then a decrease in masking for longer SOAs (B-type masking). Past experimental and theoretical work suggested that the type of the masking function depends on the strength of the mask relative to the target. Usually, mask strength is related to energy (stimulus intensity × duration). Here, we show that the overall spatial layout of the mask is a much stronger factor than classical energy to explain the type of masking function.

Keywords: B-type masking, backward masking, verniers, spatial vision


Introduction

Perception is not immediate. After stimulus presentation, the brain undergoes a series of complex, dynamic processes before a percept or a behavioral response is elicited. Backward masking techniques are often used to study the dynamics of visual processing: After the presentation of a target, a mask stimulus is displayed, which impedes the explicit perception of the target. The time requirements for perception are revealed by the finding that judgments about a target can be impeded by a mask that follows the target by several hundred milliseconds in certain paradigms.

Backward masking is an integral part of many studies of cognition and perception. It has been used to study consciousness (e.g., Klotz & Neumann, 1999; Lachter, Durgin, & Washington, 2000; Macknik & Martinez-Conde, 2004; VanRullen & Koch, 2003; Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003), visuomotor processing (Schmidt, 2002), perceptual choice tasks (e.g., Brown & Heathcote, 2005), and many other topics. As Bachmann (1994) noted, masking as a topic or method of research is used in 14% of the articles related to vision research and psychology (see also Enns & Di Lollo, 2000).

Historically, one of the most puzzling properties of backward masking, and a clear indication for the complex dynamics of visual processing, is the phenomenon of B-type masking. Whereas performance improves with increasing stimulus onset asynchrony (SOA) in A-type masking, the worst performance is found for intermediate SOAs between the target and mask onset in B-type masking.

Most models of B-type masking focus on the temporal properties of the target and mask and try to provide a solution to how the neural representation corresponding to the mask can catch up to the one of the target. Breitmeyer and Ganz (1976) proposed that visual processing occurs in two visual channels: a fast transient system and a slower sustained system. In their theory, B-type masking occurs when the faster transient signal of the trailing mask catches up and inhibits the slower sustained signal of the target (for a recent review, see Breitmeyer & Ögmen, 2000). In the perceptual retouch model of Bachmann (1994), a slower noncortical signal, generated by the target, facilitates processing of the trailing mask rather than of the preceding target. Likewise, models by Anbar and Anbar (1982), Francis (2003), and Weisstein (1972) focus on the temporal rise and fall of target and mask.

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responses and their interactions in the visual system. Even model systems that inherently include a representation of spatial properties of visual stimuli (Bridgeman, 1978; Francis, 1997) have been shown to primarily depend on the temporal dynamics of the target and mask responses rather than on spatial properties of the stimuli (Francis, 2000).

Francis (2000) showed that almost all current quantitative models that account for B-type masking do so by a common kind of nonlinear interaction between representations of the target and mask. Francis called this interaction mask blocking. In a mask-blocking type of system, B-type masking occurs because at short SOAs, the target is strongly represented in the visual system and thereby blocks the weak inhibitory effect of the mask. At intermediate SOAs, the target representation has faded and the weak inhibitory effect of the mask has a strong impact on the remaining target signals. At very long SOAs, the mask arrives so late that it has very little effect on the target signals at all.

Francis and Herzog (2004) showed that all of the models that use mask blocking predict that the temporal properties of masking are dependent on the strength of the mask. In particular, B-type masking occurs for a relatively weak mask compared to the target. A-type masking occurs for a strong mask compared to the target because even at short SOAs, the strong inhibitory signals from the mask cannot be blocked by the target representation.

In the models, the strength of the mask can be directly measured as the value assigned to the model’s representation of the mask stimulus. Large numbers correspond to strong masks. However, it is less clear what corresponds to a strong mask in an experiment. Past research has focused on low-level stimulus “energy” properties such as luminance (Weisstein, 1972), duration (Breitmeyer, 1978), brightness (Di Lollo, von Muhlenen, Enns, & Bridgeman, 2004), or duration × luminance (Breitmeyer & Ögmen, 2006, p. 48). Consistent with the mask-blocking models, these studies find that as mask strength increases, the shape of the masking function usually goes from B type to A type.

In this contribution, we identify a situation where the shape of the masking function is more determined by the spatial layout of a metacontrast mask than by its overall energy. Specifically, we can change the masking function from A-type to B-type by changing the spatial layout of the mask, even with increases or decreases of traditional measures of energy.

General materials and methods

General setup

Stimuli were displayed on an X–Y display (HP 1332A) that was controlled by a PC via fast 16-bit D/A converters. Stimuli were composed of dots drawn with a dot pitch of 250–300 μm at a dot rate of 1 MHz. The dot pitch was selected so that dots slightly overlapped; that is, the dot size (or line width) was of the same magnitude as the dot pitch. Stimuli were greenish or bluish white on a black background. Luminance of a dot grid (same dot pitch as above) was approximately 80 cd/m². The background luminance was about 0.5 cd/m². Hence, contrast was close to 1.0. Subjects observed the stimuli from a distance of 2 m.

A vertical vernier target was presented simultaneously with or preceded a metacontrast mask of various types. Vernier segments were 600″ (arc seconds) long, oriented vertically, and separated by a vertical gap of 60″. Thus, total vernier length was 1,260″. The target vernier segments were offset in the horizontal direction either to the left or to the right. The vernier always appeared in the middle of the screen for a duration of 20 ms.

Metacontrast masks were single nonoffset flanking verniers or masks made up of a varying number of such verniers. The vernier segments were oriented vertically and separated by a vertical gap of 60″ without offset. Masks lasted for 20 ms and were presented at different SOAs from 0 to 150 ms, which correspond to simultaneous and backward, but not forward, masking. The target vernier was centered among the verniers of the metacontrast mask. The spacing between all elements was 200″. The length of mask vernier segments or number of mask elements was variable and is described in the methods section of each experiment.

We define the spatiotemporal energy of a mask as the sum of the energy over each element. The energy of an element is defined by its luminance × duration.

Observers

Data were obtained from four students at EPFL and from one of the authors. Each observer was informed about the general aim of the experiment, but most observers were naive regarding the exact purpose of the study. All observers had normal or corrected-to-normal visual acuity as tested by means of the Freiburg visual acuity test (Bach, 1996). To participate in the experiments, observers had to reach a visual acuity of 1.0 (corresponding to 20/20) in this test for at least one eye.

Task

On each trial, the target vernier was randomly offset either to the left or to the right. Observers had to discriminate, in a binary forced-choice task, this offset direction by pressing one of two push buttons. A tone produced by the computer followed incorrect responses.

Procedure

We determined thresholds by means of an adaptive staircase procedure and fit a cumulative Gaussian to the data via maximum likelihood or probit analysis (PEST;
Taylor & Creelman, 1967). In many conditions, subjective visibility of the preceding vernier can be strongly diminished (with “visibility,” we refer to the subjective reports by observers about the perception of the foregoing vernier). Adaptive strategies cannot properly handle such conditions because these strategies present increasingly larger offsets in search of the (nonexistent) discrimination threshold, defined as 75% correct responses. Therefore, we prevented the PEST procedure from offering offset sizes of the target vernier that exceeded 150 \(^{\prime}\) (twice the starting offset size of 75\(^{\prime}\)). If observers were unable to obtain 75% correct responses for an offset value below 150\(^{\prime}\), the condition was considered as “subthreshold” and an offset of 150\(^{\prime}\) was tabulated if, firstly, increasingly larger offsets were presented by PEST; secondly, an offset value of 150\(^{\prime}\) was offered by PEST at least once; and, thirdly, the hit rate for this value was below 75% correct responses. In ambiguous cases, the block was repeated. We emphasize that restricting the PEST procedure avoids increasingly large performance differences that would occur otherwise. For comparisons with other conditions with a “clear” vernier visibility, this procedure is rather conservative because extreme thresholds are avoided.

For each observer, every condition was measured twice. The order of conditions was randomized individually for each observer to reduce possible hysteresis or order effects in the averaged data. After every condition had been measured once, the order of conditions was reversed for the second round of measurements to, at least, partly compensate for possible learning effects. A block comprised 80 trials.

### Experiment 1: Flank length and number

We previously found that mask energy cannot explain pattern and simultaneous masking effects by varying the number of lines in the masks (e.g., Herzog & Fahle, 2002; Herzog & Koch, 2001; Malania, Herzog, & Westheimer, 2007). In the first experiment here, we investigated an analogous effect for a metacontrast mask, where the mask verniers do not overlap the target vernier, by varying the length and number of the mask verniers.

### Methods

We presented a target vernier flanked by one, two, or six mask verniers on each side.

In the one-flanking vernier condition, each mask vernier segment was half the length of a target vernier segment, the same length as a target vernier segment, 100\(^{\prime}\) longer than a target vernier segment, or twice as long as a target vernier segment. Hence, the length of the mask vernier segments was 300\(^{\prime}\), 600\(^{\prime}\), 700\(^{\prime}\), or 1,200\(^{\prime}\). Because the segments of the verniers were separated by a vertical gap of 60\(^{\prime}\), the total length of the mask verniers was 660\(^{\prime}\), 1,260\(^{\prime}\), 1,460\(^{\prime}\), or 2,460\(^{\prime}\). We will refer to these conditions as the one-flank conditions (1-F) and abbreviate these as 1-F 300, 1-F 600, 1-F 700, and 1-F 1,200 according to the number of mask verniers on each side of the target and the length of the mask vernier segments.

In the conditions with two (2-F) or six (6-F) masking verniers on each side, the length of the mask vernier segments was the same as the target vernier segments or twice as long. We abbreviate these conditions as 2-F 600, 2-F 1,200, 6-F 600, and 6-F 1,200. There was also one condition (12-F 1,200) with 12 mask verniers on each side of the target and with segment lengths twice as long as the target.

We also determined the threshold for an unmasked vernier target. Thresholds were determined in separate sessions for the 1-F, 2-F, 6-F, and 12-F conditions.

### Results and discussion

Masking is demonstrated by an increase in the vernier threshold compared to the unmasked condition. Figure 1 plots the thresholds as a function of SOA for the 1-F conditions. For SOAs up to 80 ms, the presentation of the mask results in a strong threshold elevation. For all masks, a B-type masking function occurs with the peak at about 40 ms. In some conditions with SOAs around 40 ms, some observers reported that the vernier offset is visible at one of the mask verniers, whereas the target vernier is largely invisible, i.e., a feature inheritance effect (e.g., Herzog & Koch, 2001; Hofer, Walder, & Groner, 1989; Otto, Ögmen, & Herzog, 2006; Stewart & Purcell, 1970; Werner, 1935; Wilson & Johnson, 1985). Any inheritance effect appears to be overwhelmed by the strong masking.

The main conclusion from Figure 1 is that all of the 1-F masks produce B-type masking (U-shaped masking functions). This is a replication of previous studies (e.g., Francis & Herzog, 2004) and is in notable contrast to the 2-F masks discussed below. Interestingly, it seems that the strongest masking occurs for the condition where the mask verniers have the same length as the target vernier (600\(^{\prime}\)). Weaker masking appears to occur for masks of less total energy (1-F 300) and for masks of higher total energy (1-F 700 and 1-F 1,200). Although there was insufficient data to make the effect statistically significant, the trend suggests that spatiotemporal energy does not solely determine the overall strength of masking for these stimuli.

Stronger evidence against a spatiotemporal energy explanation for masking strength is visible in Figure 2, which plots the vernier threshold as a function of SOA for the 2-F 600 and 2-F 1,200 conditions. For SOAs up to 80 ms, masking results in a strong threshold elevation compared to the unmasked condition. Unlike in the 1-F conditions, an A-type masking function occurs for the 2-F 600 condition. This is not unexpected given that the
spatiotemporal energy is increased in the 2-F 600 condition compared with the 1-F 600 condition. What is unexpected is that the 2-F 1,200 condition results in a weaker B-type masking function that peaks at an SOA of 40 ms. This condition has more spatiotemporal energy than the 1-F 600, 1-F 1,200, and the 2-F 600 conditions. Thus, an increase in spatiotemporal energy does not necessarily lead to A-type masking.

A similar conclusion is demonstrated in Figure 3 for the 6-F conditions. Strong A-type masking occurs for the 600” condition, whereas an almost flat masking function is found for the 1,200” condition. Once again, an increase in spatiotemporal energy leads to a reduction in the masking effect.

Thus, the traditional definition of spatiotemporal energy does not determine the overall strength of masking in our experiment. The 1-F 600, 2-F 600, and 6-F 600 masks have smaller total spatiotemporal energy than their corresponding 1,200” conditions, but the former stimuli produce stronger masking than the latter. Moreover, for the 2-F and 6-F conditions, the weaker energy masks produce A-type masking functions, whereas the stronger...
energy masks produce B-type or flat masking functions. This relationship is the opposite of what is reported for many other studies of masking that varied mask energy (e.g., Breitmeyer & Ögmen, 2006).

A similar conclusion can be drawn by comparing the masking functions for different numbers of mask verniers. Figure 4 plots the masking functions for masks that varied in the number of 1,200° flanks. The 1-F, 2-F, and 6-F curves were previously plotted in Figures 1, 2, and 3, whereas the 12-F condition is a new mask that has 12 flankers on each side of the target vernier. Masking strength is inversely related to the spatiotemporal energy of the mask. The mask with the highest spatiotemporal energy (12-F 1,200) showed the weakest masking, with thresholds barely above the no-mask condition. The thresholds for the 6-F 1,200 mask are elevated above the 12-F 1,200 mask thresholds but are still quite modest. The strongest masking occurs for the 1-F 1,200 and 2-F 1,200 conditions, although these conditions have the smallest amount of spatiotemporal energy.

Figure 3. A target vernier was flanked by six mask verniers to the left and right. Mask vernier segment length was 600° or 1,200°. For the 6-F 600 mask, A-type masking occurs. In the 6-F 1,200 condition, the shape is less clear, but masking is clearly weaker than in the 6-F 600 condition.

Figure 4. Results for masks with a segment length of 1,200°, which was twice the length of the target vernier. The masks varied in the number of flanking verniers. Only the 12-F 1,200 condition was not shown previously. The results show that as more flanks are presented, masking decreases although energy increases.
For current theories and models of backward masking to account for these findings, they need to characterize how the various masks give rise to different strengths of mask representation within their respective frameworks. Traditionally, such effects have been attributed to the overall spatiotemporal energy of the mask, but the current data suggest that this is not correct.

Rather than energy, we propose that the strength of masking is related to the tendency for the target vernier to be grouped within the structure of the mask, for short SOAs. When the target and mask group together, we propose that the properties of the target are more difficult to access because they are subsumed in the representation of the mask (see also He, Cavanagh, & Intriligator, 1996; Malania et al., 2007; Sharikadze, Fahle, & Herzog, 2005). Such grouping effects explain the influence of mask vernier length on the strength of masking. In the conditions with 600”-long mask vernier segments, the target vernier is the same length and, thus, easily groups within the mask structure. In contrast, the conditions with 300-, 700-, and 1,200”-long mask vernier segments introduce a spatial inhomogeneity that separates the target vernier from the mask. As a result, the target features can be accessed and masking is weaker.

A similar effect occurs when the target vernier is shorter than the mask verniers and when the number of mask verniers is varied (Figure 4). Here, increasing the number of mask verniers leads to stronger spatial inhomogeneity between the differently sized target vernier and the mask verniers by emphasizing the structural regularity of the mask. As a result, the target is less likely to be grouped with the mask and its features can be more easily accessed.

If true, this proposal suggests that other variations in the spatial structure of the mask should lead to changes in masking function shape and strength in predictable ways. This is the purpose of the following experiment.

### Experiment 2: Varied layouts

The grouping hypothesis suggests that masking strength at the shortest SOAs depends on the spatial inhomogeneity of the target and mask elements. Weak masking occurs with high spatial inhomogeneity, whereas strong masking occurs for low spatial inhomogeneity. In the second experiment, we varied the spatial homogeneity by introducing variations in the mask vernier lengths.

### Methods

The 20-ms target vernier was presented with six flanks to the right and left. In the 6-F 700+ condition, the mask vernier segments increased in length outward from 700” to 1,200”, in steps of 100” as a function of the distance from the target. Hence, the extreme segments of this mask and the 6-F 1,200 mask have the same length. In the 6-F 1,200–700 condition, the mask vernier segments decreased in length from 1,200” to 700”, in steps of 100” (Figure 5).

The two layouts of the mask elements are visible in Figure 5. Note that the global spatiotemporal energy is the same in both masks; only the arrangement of the mask verniers is varied. As in Experiment 1, we varied the SOA between the target and the mask.

![Figure 5](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/933517/) Six mask verniers to the left and right of the vernier target continually increased or decreased in length. A-type masking is found in both conditions, with stronger masking in the 6-F 700+ condition.
Results and discussion

On the basis of the grouping hypothesis, we predicted that, for short SOAs, the target would group with the mask in the 6-F 700+ condition because the target length continues the mask’s spatial pattern. Such grouping should make the target features difficult to access and lead to strong masking. On the other hand, there should be little or no grouping for the 6-F 1,200–700 condition because of the strong spatial inhomogeneity between the target vernier and the surrounding mask verniers.

Both masks resulted in a threshold elevation above the unmasked threshold, particularly for SOAs up to 80 ms. Figure 5 plots the threshold elevations for the 6-F 700+ and the 6-F 1,200–700 masks. The 6-F 1,200–700 mask resulted in weaker masking at the shortest SOAs, which is consistent with the prediction of the grouping hypothesis. There was some heterogeneity across observers. For example, in the 6-F 700+ condition, two observers produced a B-type masking function.

General discussion

Masking a vernier target with flanking verniers can yield strong masking that depends on the spatial layout of the mask. Thresholds can be elevated by more than a factor of 6 compared to the unmasked condition.

The experimental results demonstrate that, in our study, the spatiotemporal energy of the mask is not the main determinant of masking effectiveness or the type of the masking function (A vs. B). This is contrary to all quantitative and most qualitative models of masking, where both the strength of masking and the shape of the masking function are related to the ratio of target and mask energy (e.g., Breitmeyer & Ögmen, 2006; Francis, 2000; Weisstein, 1972).

It might be argued that our definition of energy (duration $\times$ stimulus intensity $\times$ space) does not correspond to the classical one (duration $\times$ stimulus intensity) because it includes a spatial component. However, removing the spatial component from the energy calculation simply emphasizes that energy is not solely related to masking effects because our results demonstrate a strong influence of spatial layout. Moreover, we obtained weaker masking by making the flanking lines longer, which certainly did not decrease energy according to the classical definition.

One might also be tempted to argue that completely different energy measures should be used. For example, if the visual system prefers some spatial frequencies over others, then an increase in mask vernier number or length might decrease rather than increase the strength of the mask signal in the visual system and thereby lead to a reduction in the masking effect. This is not a viable explanation for current quantitative models of masking because Francis and Herzog (2004) showed that the current quantitative models of masking all predict that the strength of masking is connected to the type of the masking function. In the models, A-type masking functions only appear for strong masks, whereas B-type masking functions only appear for weak masks. This means that, for a fixed target, task, and SOA, a point on a B-type masking function curve should never show stronger masking than a corresponding point on an A-type masking function curve. Figure 6 plots the curves for

![Figure 6](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/933517/ on 10/16/2018)
the F 600 conditions. The 2-F 600 and 6-F 600 conditions produce A-type masking functions, whereas the 1-F 600 condition produces B-type masking. That the masking function types are not tied to overall mask strength is easily demonstrated by noticing that, for different SOAs, the B-type curve has both stronger and weaker masking than the A-type curves. This result is impossible in the current quantitative models and strengthens the conclusion in the studies of Francis and Herzog (2004) and Francis and Cho (2006; in press) that models of B-type masking need to include more elaborate spatial processing of stimuli.

The experimental results suggest that a key aspect of masking is how the target and mask are grouped together for very short SOAs. At longer SOAs, the temporal distinctions between the target and mask prevent such grouping, and this explains why all the curves in our study converge on weak masking for long SOAs. The kind of grouping we propose is different from any kind of integration masking such as camouflage or montage (for a recent interpretation, see Enns, 2004) because the target and mask stimuli do not overlap and because the target’s location is known to the observer.

The mask stimuli were deliberately chosen to avoid “simple” spatial effects that may be explained by local contour interactions (e.g., Kolers, 1962; Werner, 1935) or lateral inhibition (e.g., Bridgeman, 1971; Growney, 1977). While local contour effects may influence masking in some conditions, such effects are apparently overwhelmed by the grouping effects in our stimuli. For many of the conditions in our experiments, the contours of the directly flanking mask verniers were identical even as performance varied dramatically (e.g., Figures 4 and 6). Moreover, increases in local contour sometimes lead to weaker masking (Figures 1, 2, and 3).

Our experimental results on mask size are related to a long-standing confusion in the field of masking regarding the impact of changing the mask size. Previous studies with pattern masks (Herzog & Fahle, 2002; Herzog & Koch, 2001; Kolers, 1962; Macknik & Haglund, 1999; Schiller & Greenfield, 1969; Sturr, Fromkes, & Veneruso, 1965) have observed that increasing the size of the mask leads to weaker masking. In contrast, studies with metacontrast masks generally find that increases in mask size lead to stronger masking (e.g., Kao & Dember, 1973; Matteson, 1969). Our results now show, in a single paradigm, that varying the size of metacontrast masks can increase or decrease the strength of masking and can change the shape of the masking function. We propose that what matters for masking strength is how the spatial properties of the target and mask contribute to the target’s tendency to group with the mask at short SOAs. This hypothesis may be able to provide a single explanation for the properties of the different types of masks.

Spatial aspects, except for mask size, flank–target distance, and types of pattern masks, are largely neglected in masking research, but there have been a few exceptions. Several studies have found that both the amount and spatial distribution of mask contour affect the strength of masking (Francis, 1997; Gilden, MacDonald, & Lasaga, 1988; Kahan & Mathis, 2002; Moore & Lleras, 2005; Sherrick & Dember, 1970; Werner, 1935). Williams and Weisstein (1984) found that performance improves when the target can be integrated with the mask into a 3-D structure. This result is contrary to our findings where performance is worse when the target is grouped within the mask for short SOAs. This may suggest differences between 2-D grouping (in the present study) and 3-D grouping (in Williams & Weisstein, 1984). Similar to the present findings, Enns (2004) found that different types of masks had different masking effects at the shortest SOAs. Enns hypothesized that the different masking effects were related to camouflage effects when the target and mask integrated together. Such an explanation is unlikely to be applicable to our data because the target and mask do not overlap and because the location of the target vernier is known by the observer. Our results are in good accordance with findings in simultaneous masking, which show that detection deteriorates when targets are grouped with distracters (e.g., Prinzmetal & Banks, 1977).

Although our experimental results verify the importance of spatial grouping for masking, we do not deny that other effects also play a role. For example, our spatial grouping hypothesis would predict that when the target and mask verniers are of the same length, the 6-F mask should produce stronger masking than the 2-F mask because the larger number of mask elements would make the target properties more difficult to discern. However, the data are the opposite of this prediction, as shown in Figure 6. This finding implies that there must be additional masking mechanisms because it is inconsistent with both our current understanding of spatial grouping and spatiotemporal energy effects.

Because there appear to be many different influences on masking, one goal of research on masking must be to characterize the different mechanisms. Our experimental results demonstrate that, at least for these stimuli and conditions, spatial grouping has an important influence on masking. Whether spatial grouping always dominates spatiotemporal energy and other factors remains an open question that needs to be explored with other stimuli, tasks, and conditions.

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