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On the relations between crowding and visual masking

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To study the question of which processes contribute to crowding and whether these are comparable to those of visual temporal masking, we varied the stimulus onset asynchrony (SOA) between target and flankers in a crowding setting. Monotonically increasing Type A masking functions observed for small spacings and large eccentricities indicate that the integration of information from target and flankers underlies crowding. Decreasing masking functions obtained for large spacings and small eccentricities relate processes of crowding to those contributing to Type B masking. In addition, Type B masking was more frequent with letter-like nonletter flankers than with letter flankers, suggesting that Type B masking, just like crowding over large areas, is due to higher level interactions. The rapid decrease of the effects of interletter spacing and eccentricity with increasing SOA indicates that positional information is transient.

Letter recognition declines in the visual periphery (Aubert & Foerster, 1857), which is attributed to visual acuity. The decline in performance is much stronger when adjacent characters or flankers are presented (e.g., Bouma, 1970). This effect is referred to as *crowding*, or the *lateral masking effect*. Acuity and crowding are commonly thought of as the basic sensory factors underlying visual word recognition (e.g., Massaro & Cohen, 1994; Massaro & Klitzke, 1979; Paap, Newsome, McDonald, & Schvaneveldt, 1982). The most often replicated findings concerning crowding are that it increases with an increase in target eccentricity and with a decrease in spacing between a target and flankers. Both factors interact; as target eccentricity increases, so does the critical spacing between a target and a flanker.

The processes underlying crowding are still unknown. The notion of lateral masking suggests that the processes underlying crowding are similar to those of ordinary masking. However, the appropriateness of these terms is already under discussion. Some authors have used both terms, *crowding* and *lateral masking*, synonymously (e.g., Townsend, Taylor, & Brown, 1971; Wolford & Chambers, 1983); some have defined *lateral masking* as the broader term, to describe interactions between any close contours, whereas *crowding* refers to interactions between letters only (e.g., Chung, Levi, & Legge, 2001). Others have preferred the usage of *crowding* only (e.g., Levi, Klein, & Aitsebaomo, 1985; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001), due to the assumption that crowding effects are distinct from masking phenomena. For completeness, it should also be mentioned that some authors have avoided both terms and have talked about *interaction effects* (e.g., Bouma, 1970; Legge, Pelli, Rubin, & Schleske, 1985). The goal of the present study was to examine the relations of crowding and visual temporal masking.

There have been several recent studies in which the relation of crowding and ordinary masking has been investigated (e.g., Chung et al., 2001; Parkes et al., 2001; Pelli, Palomares, & Majaj, in press), which have arrived at various answers. Chung et al. have presented data showing that some properties of masking can also be observed in crowding. For example, both effects are spatial frequency specific and are weaker for low-contrast masks. Therefore, Chung et al. suggested that whereas masking is concerned with pooling information over time, crowding is probably concerned with pooling information over space. However, arguments have also been made that crowding and visual masking do not share the same properties. Parkes et al. have observed that information about a flanked target is combined with information from the flankers, rather than lost. Pelli et al. have also observed that integration between target and flanker information contributes to crowding. Both studies came to the conclusion that crowding is distinct from ordinary masking, where, according to the authors, the signal disappears instead of being integrated with the mask. It must be added

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that Pelli et al. suggested that the main difference between crowding and masking should be regarded as being that the former (crowding) scales with eccentricity independently of size, whereas the latter (masking) scales with size independently of eccentricity.

The term *masking* itself is adopted for a wide range of visual phenomena, which are explained by various theoretical approaches. In order to gain, via this comparison, insight into the processing of underlying crowding, one central issue is the conception of *ordinary* visual masking. Hence, it is necessary to look not only into the details of the processes contributing to crowding, but also into those contributing to visual masking. In the present exploratory study, we do this by focusing on visual temporal masking.

Visual temporal masking refers to the disturbances in target recognition performance when a second stimulus, the mask, is presented at the same location as the target, either before (forward masking) or after (backward masking) the target has been displayed. There are indeed some intriguing analogies between crowding and temporal masking. Whereas crowding describes disturbances in target recognition performance when flankers (masks) are presented at the same time as the target in close spatial proximity, masking describes disturbances when masks are presented at the same location as the target in close temporal proximity. And whereas crowding increases when the spatial proximity is decreased (e.g., Bouma, 1970), masking increases when the temporal proximity is decreased (e.g., Turvey, 1973). In addition, temporal masking also increases with decreasing spatial distance (e.g., Growney, 1977). The effects of temporal distance on crowding are unknown. Studying the effects of temporal distance on crowding should contribute some important arguments to the discussion of whether crowding and masking phenomena share underlying properties.

Visual temporal masking is not a unitary process. One can differentiate not only between forward and backward masking, but also among different types of backward masking. Up to four different kinds of backward masking have been distinguished: masking by light, masking by noise, masking by structure or pattern, and masking by metacontrast (e.g., Breitmeyer, 1984; Turvey, 1973). Nevertheless, it is unclear whether these distinctions, based on the kinds of masking stimuli, uniquely correspond to certain visual mechanisms. Rather, visual mechanisms contributing to masking might be inferred by means of the function of recognition performances. Here, one can differentiate between Type A and Type B masking. We will now turn to the discussion of basic conditions and explanations of Type A and Type B masking to figure out how crowding effects might be related to either form of temporal masking.

Type A masking refers to monotonically increasing performance with increases in the stimulus onset asynchrony (SOA) between a target and a mask. That is, recognition performance benefits from increasing the delay between a target and a mask. Type A masking is often observed in masking by structure or pattern—when the perception of a target is impaired by a spatially overlapping masking stimulus consisting of a field of structured contours. To explain Type A masking functions in pattern masking, two processes underlying the masking effect have been assumed: the integration of information about target and mask contours and the interruption of target processing (e.g., Kahneman, 1968; Scheerer, 1973; Turvey, 1973). Integration means that information about a target and a mask is combined into a unitary percept. Integration is assumed to be strongest with the simultaneous presentation of a target and a mask and to become weaker with increasing SOA, which can explain the monotonic growth in recognition performance. Interruption means that the processing time for the target is reduced by the onset of the mask. For typical crowding tasks, interruption of target processing by a subsequently presented mask cannot be relevant, since there is usually no stimulus displayed after the presentation of the target.

The distinction between interruption and integration might be of importance when evaluating the conclusion of Parkes et al. (2001) and Pelli et al. (in press) that crowding does not share any properties with masking. What Parkes et al. observed was that the orientation of a target contributed to the estimation of the mean orientation of the whole stimulus configuration—that is, an integration of target and mask information. Also, Pelli et al. found that integration of feature information underlies crowding. As was just mentioned, such integrative processes are assumed to be essential components of Type A masking. Therefore, one might conclude from their results that crowding and visual temporal masking do share some underlying properties.

Taken together, if one assumes similar processes to be responsible for crowding and for Type A masking, the integration of a target and a mask should occur in crowding. That is, there might be spatial summation or integration when the target and the flankers are presented in close spatial proximity and reduced integration with increasing spatial distance. When varying the SOA between target and flankers in a typical crowding task, one should, therefore, expect crowding to be strongest when the target and the flankers are presented simultaneously and to monotonically decrease when the temporal distance is increased.

However, as was already mentioned, there is also another form of masking—namely, Type B masking. Type B masking refers to U-shaped masking functions. At very brief and very long SOAs, the target can be clearly perceived. At intermediate SOAs of about 50–150 msec, target recognition is impaired. This is also known as the *onset–onset law* (Kahneman, 1968) or the *SOA law* (Breitmeyer, 1984; but see Francis, 1997). Type B masking is often observed in metacontrast masking. Masking by metacontrast refers to situations in which a target and a subsequent mask are presented in close spatial proximity—for example, when flanking characters are presented on each side of the target (e.g., Fehrer & Raab, 1962). Like crowding, metacontrast masking increases with decreasing spatial separation between a target and a mask (e.g., Growney, 1977) and with increasing eccentricity of the stimulus (e.g., Kolers & Rosner, 1960; Stewart & Purcell, 1970). In this sense, when subsequently presenting target and flankers in a usual crowding task, one might also talk about paracontrast and metacontrast masking, instead of forward and backward masking. By the way, if assuming that metacontrast masking belongs to ordinary visual masking phenomena, the fact that it decreases with eccentricity argues against the assumption of Pelli et al. (in press) that masking does not scale with eccentricity.

The processes underlying Type B masking are less clear than those underlying Type A masking. The increase in masking with increasing SOA and the decrease in masking when further increasing the SOA have been attributed to various processes (see Breitmeyer & Ogmen, 2000, Di Lollo, Enns, & Rensink, 2000, and Francis, 2000, for examples; but see Francis & Herzog, 2004). One recent account of Type B masking has been provided by Di Lollo et al. (2000). This account was based on the assumptions of interactive activation, which is also preferred in letter and word recognition models (e.g., McClelland & Rumelhart, 1981; Sanocki, 1987) and might, therefore, be of special interest for the crowding effects between letters at issue in the present study. That is, the processing of information is assumed to be hierarchically organized, and information at higher levels is assumed to reenter (i.e., to feed back to) lower levels. Di Lollo et al. suggested that temporally delayed feedback from higher level to low-level processes concerning the first stimulus interferes with the incoming information about the second stimulus. For Type B masking, this interference might be assumed to cause the decrease in recognition performance at a certain delay after target onset. That is, higher level processing is assumed to contribute to Type B masking.

The increase of metacontrast Type B masking with decreasing spatial distance between a target and a mask and with increasing eccentricity suggests that crowding—where interference also increases with decreases in the spatial proximity between target and flankers and with increases in target eccentricity—works analogously to Type B masking. This leads to the hypothesis that when the SOA between a target and flankers in a crowding setting is increased, the function of recognition performance should be U-shaped. That is, performance should be lower for intermediate SOAs than for simultaneous presentation and for longer SOAs. According to the results found for metacontrast masking (Growney, 1977; Kolers & Rosner, 1960; Stewart & Purcell, 1970), one might expect Type B masking functions to occur, especially when spacing is small and eccentricity is large.

On the basis of this review, one might expect either a monotonically increasing or a U-shaped function of recognition performance with increasing SOA in a crowding setting. A monotonically increasing masking function would indicate that a process of integration or a summation of target and mask information contributes to crowding, as has already been indicated by the observations of Chung et al. (2001), Parkes et al. (2001), and Pelli et al. (in press). A U-shaped Type B masking function would suggest that mechanisms in crowding work analogously to metacontrast masking. One might hypothesize that Type B masking will be especially pronounced under conditions of small spacing and large eccentricities.

In the present study, the effects of the SOA between a target and flankers (masks) on crowding effects are investigated. The often replicated findings that spatial factors affect crowding (i.e., interletter spacing and target eccentricity) and that there are higher level effects of kinds of flankers were studied when the flankers were displayed at various times before, during, and after target presentation. In Experiment 1, flankers on each side of the target were displayed with various spacings between the target and the flankers at various times before, during, and after target presentation. In Experiment 2, the effects of target eccentricity were analogously established. In Experiment 3, the effects of the kinds of flankers (masks) were assessed under various temporal conditions.

GENERAL METHOD

Stimuli

All 26 letters of the alphabet served as targets. The characters were typed in uppercase, using the Windows 3.11 Arial font. The width and height of the letters were 3 × 4 mm, corresponding to a visual angle of 0.38° × 0.51° at a viewing distance of 45 cm. Targets were displayed at 4° of eccentricity on the horizontal meridian. The flankers on each side of the target were randomly chosen out of a set of eight letter flankers of the same width (B, E, H, K, N, P, R, and U). The flankers were chosen with the restrictions that three different letters were exposed in one string and the letters formed no words and no common abbreviations. The flankers were presented to the left and right of the target with a spacing of 1°, measured from center to center of the stimuli. The stimuli were black on a light gray background, resulting in a Michelson-contrast of 1.05. The monitor (14-in. CRT, Philips 4CM4270) had a refresh rate of 60 Hz and a resolution of 600 × 800 pixels. The experiment was controlled by ERTS (Experimental Run Time System; Beringer, 1993) Version 3.0, which ran on an IBM-compatible 486 PC. ERTS ensures the synchronization of exposure time and refresh rate. The keyboard was situated between the monitor and the participant.

Procedure

To ensure fixation, the stimuli were presented randomly in the right or the left visual field. The presentation duration of the targets and the flankers was 50 msec. SOAs between the target and the flanker were varied. The flankers were presented 150, 100, and 50 msec before (negative SOAs), simultaneously with (SOA = 0), or 50, 100, and 150 msec after (positive SOAs) the target. So that the experimental session for each participant would not be longer than necessary, the conditions were presented in two subexperiments. Experiments A consisted of all negative asynchronies plus an SOA of 0. Experiments B consisted of the positive SOAs plus an SOA of 0. Thus, in each subexperiment, there were three independent variables—visual field (2), SOA (4), and target letter (26)—plus the respective variable of interest (e.g., interletter spacing, eccentricity, or kinds of flankers), yielding a multiple of 208 trials per participant. Within each experiment, all the trials were presented in random order. The dependent measure was percentage of correct responses.

The participants viewed the screen binocularly. A keypress started the presentation of a fixation cross, which appeared in the center of the screen and remained visible until the last character disappeared from the screen. Eight hundred milliseconds after the onset of the fixation cross, in Experiments A, the flankers were displayed for 50 msec. After the respective SOA (150, 100, 50, or 0 msec), the target was displayed for 50 msec. In Experiments B, the sequence started with a presentation of the target for 50 msec, and after the respective SOA (150, 100, 50, or 0 msec), the flankers were displayed. In both experiments, the participants were instructed to report the central letter of the string by pressing the appropriate key on the keyboard. In case of uncertainty, the participants were instructed to guess. Every 52 trials, the word PAUSE was displayed on the monitor, encouraging the participants to take a short break. Each participant was familiarized with the task in an initial practice session consisting of about 60 trials. During practice, all the SOA conditions and all the target letters presented in the experimental session were displayed at least two times.

EXPERIMENTS 1A AND 1B

One of the key properties of crowding is that crowding increases as the spacing between a target and flankers decreases. In Experiment 1, the effects of letter spacing were assessed when flankers (masks) were displayed at various times before, during, or after target presentation. The main question was whether Type A or Type B masking functions would be observed. Whereas Type A masking functions would indicate that the integration of information about a target and flankers contributes to crowding, as is also assumed for pattern masking, Type B masking would suggest that processes also relevant in metacontrast masking underlie crowding. By hypothesis, Type B masking functions were expected especially when the spacing between the target and the flankers was small.

Method

In addition to the design described above, the flankers were presented with a spacing of 0.4º (normal spacing), 1º (medium spacing), and 2º (large spacing), measured from center to center of the stimuli. This led to a total of 624 trials per participant in each of the subexperiments. Ten graduate students participated in Experiment 1A, and 10 in Experiment 1B. The participants were naive with respect to the experiment and received course credits.

Results and Discussion

The mean proportion of correct responses as a function of SOA is depicted in Figure 1. As is obvious in Figure 1, for simultaneous presentation of the target and the flankers, recognition performance increased with increases in spacing, thus replicating the usual crowding findings (e.g., Bouma, 1970).

The main question of interest was whether an increase in SOA would produce a monotonically increasing (Type A) or a U-shaped (Type B) function of recognition performance. As can be seen in Figure 1, whereas Type A masking functions were observed for the small spacing, Type B masking functions were apparent when spacing was increased. Since mean functions can derive from various individual functions, functions were analyzed separately for each observer (see Table 1). The functions were classified into three categories; both strictly monotonically increasing and monotonically increasing functions are referred to as Type A masking, and whenever there was a decrease with an increase in SOA, the functions are referred to as Type B masking. Taking into consideration that some of the answers might have been right or wrong by chance, the established recognition performance ±2.5% was regarded as the “true” value. This tolerance of 5% corresponds to 2.6 of 52 answers.

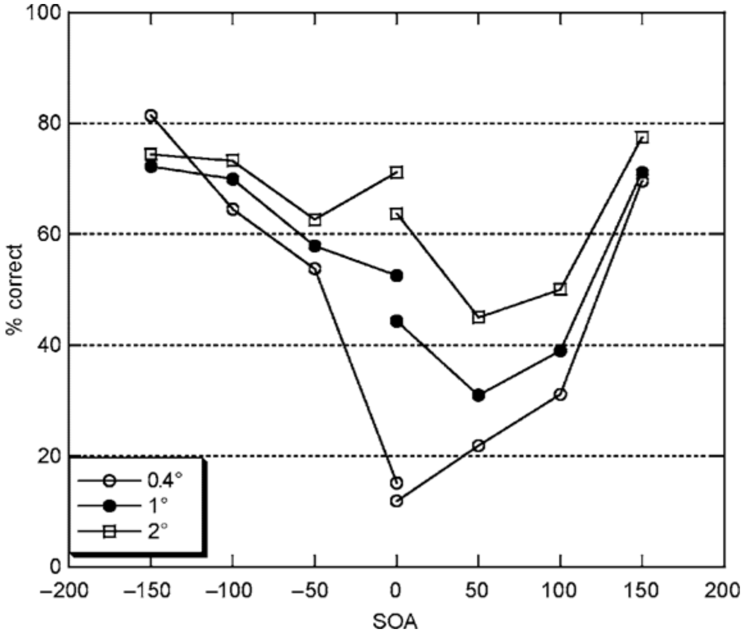

Figure 1. Mean percentage of correct responses as a function of target–mask stimulus onset asynchrony (SOA) separately for the three spacing conditions of 0.4º (normal), 1º (medium), and 2º (large), as observed in Experiment 1A (negative SOAs) and Experiment 1B (positive SOAs).

Table 1
Frequency of Monotonically Increasing (Type A) and Decreasing (Type B) Masking Functions in Experiment 1 Depending on Spacing and on the Sequence of Presentation of Target and Mask (Negative SOAs, Experiment 1A; Positive SOAs, Experiment 1B)

	Negative SOAs		Positive SOAs	
Spacing	(Strictly) Monotonically Increasing	Decreasing	(Strictly) Monotonically Increasing	Decreasing
Small	9 (7)	1	7 (4)	3
Medium	6 (1)	4	1 (0)	9
Large	4 (2)	6	0 (0)	10

Note—A function was classified as decreasing when, with increasing SOA, performance was reduced by more than 5%. The number of functions that did strictly monotonically increase is given in parentheses.

Strictly monotonically increasing functions were those for which all the values increased more than tolerance with increases in SOA. Functions were categorized as monotonically increasing when performance increased or fell within the tolerance interval. All other functions were classified as decreasing.

As can be seen in Table 1, for both negative and positive SOAs, the frequency of Type A masking functions decreased with increases in spacing. On the basis of the assumption that Type A masking functions indicate an integration of information, the data show that integration increased with decreases in spacing between the characters. One might argue that increasing Type A masking functions were observed only because of floor effects for the smallest spacing, but mean performance was clearly above chance performance (1/26, or 3.85%, of the answers). In addition, Type A masking functions were also evident for observers whose performance was better than mean performance. One might further argue that the keypress required some additional search time, which might have interfered with the measurement of perceptual processes. However, in an unpublished experiment, we compared oral responses with the procedure used here. This change of the task did not change the pattern of the data.

The decreasing number of Type A masking functions with increases in spacing also means that Type B masking becomes more probable with increases in spacing. This result seems to contradict the usual metacontrast masking findings, which have shown that metacontrast masking becomes weaker with increases in the distance between the target and the surround (e.g., Growney, 1977). But indeed, at each SOA, performance increased, and thus masking decreased with increased spacing. That is, when only the masking effect is looked at, the results replicate the findings that masking becomes weaker with increasing spacing. However, they provide evidence that increasing the spacing also changes the form of the masking function from Type A to Type B masking.

One might interpret the present findings in terms of reentrant visual processes (Di Lollo et al., 2000). Di Lollo and co-workers assumed that Type B masking results from interactions between temporally delayed feedback from higher level to low-level processes concerning the first stimulus and the incoming information from the second stimulus. Obviously, higher level information can be fed back only if it has been computed. For the small spacing, where information is difficult to analyze, no such higher level information can be computed and fed back. With increases in spacing, higher level information becomes more available. Then interference with incoming information can be observed. Hence, in terms of Di Lollo and co-workers, the counterintuitive finding that Type B masking increases with increased spacing between a target and a mask indicates effects of higher processing levels.

As is also evident in Figure 1, the effect of spacing decreased with increases in the SOA. For inferential testing of this effect, arcsine-transformed correct responses were entered into an analysis of variance (ANOVA) for repeated measures. For the negative SOAs in Experiment 1A, recognition performance depended on SOA [$F(3,27) = 9.38, p < .001$], on spacing [$F(2,18) = 17.0, p < .001$], and on the interaction of SOA and spacing [$F(6,54) = 14.80, p < .001$]. In Experiment 1B for positive SOAs, effects of SOA [$F(3,27) = 14.35, p < .001$], of spacing [$F(2,18) = 133.29, p < .001$], and of SOA × spacing [$F(6,54) = 14.90, p < .001$] also were observed. For both negative and positive SOAs, spacing effects decreased as the temporal distance between the target and the flankers increased. For the largest SOAs of 150 msec, effects of spacing even disappeared. That is, the information about the positions of the characters presented first is less available the longer the processing of the characters continues. This is of importance for current models of visual letter and word recognition (e.g., McClelland & Rumelhart, 1981). But on the basis of the present data, it cannot be ruled out that at least after 150 msec of processing the first character, target and flankers no longer interact with each other. We will come back to this issue in Experiment 3.

To sum up, the question of whether crowding shares properties with Type A or Type B masking led to some unexpected findings. For the small spatial separation between target and flankers, recognition performance increased monotonically with increasing SOA, suggesting that underlying processes are related to processes involved in pattern masking. U-shaped functions of recognition performance, which are assumed to indicate that underlying processes are related to those contributing to metacontrast masking, were observed more frequently the larger the spacing. The functions of performance show a smooth transition between Type A and Type B masking.

EXPERIMENTS 2A AND 2B

Crowding is characterized not only by its increase with decreases in spacing, but also by an increase with increases in eccentricity. Whereas in Experiment 1 spatial–temporal interactions were assessed when the spacing between the target and the flankers was varied, in Experiment 2 these interactions were established analogously with varying target eccentricity. With regard to the expected masking functions, one might derive two hypotheses. Since Type B masking is known to increase as stimuli are moved away from the fovea (e.g., Kolers & Rosner, 1960; Stewart & Purcell, 1970), one might expect U-shaped masking functions to be observed especially for targets presented in the far periphery. However in Experiment 1, U-shaped masking functions were obtained especially when crowding was weak (i.e., for the large spacing). Hence, one might analogously expect Type B masking to be more pronounced the smaller the eccentricity.

Method

The method was the same as in Experiment 1, with the following changes. Flankers were presented with a medium spacing of 1º only. The target was presented at 1º, 4º, or 7º of eccentricity. Twenty students, 10 in Experiment 2A and 10 in Experiment 2B, took part in Experiment 2. None of them had participated in this kind of experiment before.

Results and Discussion

The data of 1 participant in Experiment 2A were not readable, due to a computer error; the analysis is, therefore, based on 9 observers. Mean target recognition performances are shown in Figure 2.

Replicating the observations in Experiments 1A and 1B, both Type A and Type B masking functions were observed. Type A masking was observed for the larger eccentricities, whereas Type B masking was evident for the smallest eccentricity of 1º. The analysis of the masking functions for each participant is given in Table 2. As can be seen in Table 2, the frequency of Type B masking functions decreased with increasing eccentricity. Again, there were more decreasing Type B masking functions with positive than with negative SOAs.

To summarize, U-shaped masking functions were observed at each eccentricity, but contrary to our expectation, the portion of U-shaped masking functions decreased with increasing eccentricity. That is, as in Experiment 1, Type B masking was most pronounced under spatial conditions producing small crowding effects, and Type A masking was most pronounced under spatial conditions producing large crowding effects.

In terms of interactive activation accounts of metacontrast masking, the U-shaped masking functions suggest that temporally delayed higher level information from the first stimulus that feeds back to low levels of processing interacts with low-level information (Di Lollo et al., 2000). The present results indicate that if higher level information can be successfully computed (as is the case when targets are presented with large separations to adjacent characters or at small eccentricities), it interferes with incoming information about a second stimulus, resulting in Type B masking functions. If, however, higher level information is hardly available for feedback (as can be assumed for letters presented at large eccentricities and with small separations between neighboring characters), no such interference is obtained. Instead, in these conditions, monotonically increasing masking functions suggest that information from adjacent characters is in-

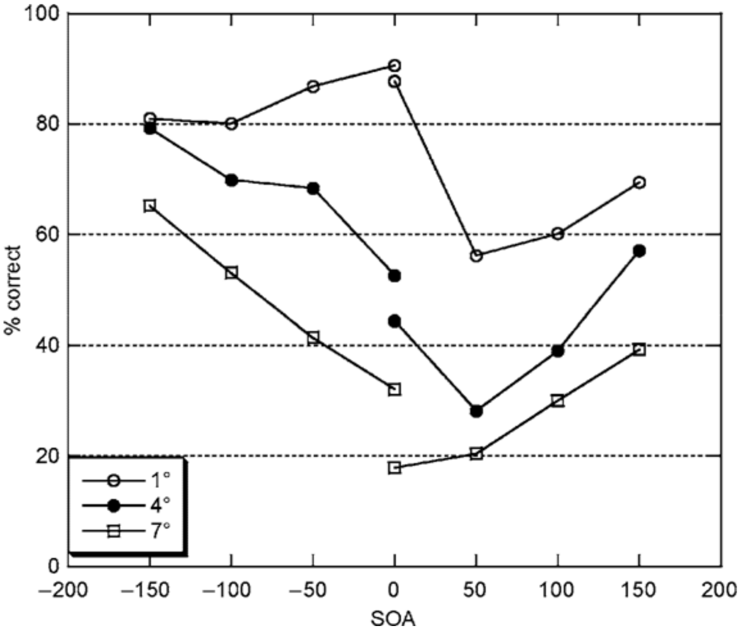

Figure 2. Mean recognition performance as a function of target–mask stimulus onset asynchrony (SOA) separately for the three target eccentricities of 1º, 4º, and 7º, as observed in Experiment 2A (negative SOAs) and Experiment 2B (positive SOAs).

Table 2
Frequency of Monotonically Increasing (Type A) and Decreasing (Type B) Masking Functions in Experiment 2 Depending on Eccentricity and on the Sequence of Presentation of Target and Mask (Negative SOAs, Experiment 2A; Positive SOAs, Experiment 2B)

	Negative SOAs		Positive SOAs	
Eccentricity	(Strictly) Monotonically Increasing	Decreasing	(Strictly) Monotonically Increasing	Decreasing
Small	2 (2)	7	0 (0)	10
Medium	5 (1)	4	0 (0)	10
Large	6 (3)	3	4 (2)	6

Note—A function was classified as decreasing when, with increasing SOA, performance was reduced by more than 5%. The number of functions that did strictly monotonically increase is given in parentheses.

tegrated. This supports the hypothesis that crowding is composed of an integration or summation of information at small interletter distances and at large eccentricities. When the spatial separation between characters is enlarged and when the eccentricity is decreased, higher level interactions become more important.

As can be seen in Figure 2, as in Experiment 1, spatial and temporal factors showed interactive effects on recognition performance. Whereas for simultaneous presentation of a target and flankers, effects of eccentricity were very large, they decreased with increasing SOA. For negative SOAs in Experiment 2A, recognition performance depended on SOA [$F(3,24) = 3.38, p < .05$], on target eccentricity [$F(2,16) = 77.80, p < .001$], and on the interaction between eccentricity and SOA [$F(6,48) = 8.77, p < .001$]. For positive SOAs (i.e., Experiment 2B), recognition performance depended on target eccentricity [$F(2,18) = 95.91, p < .001$] and on the interaction between eccentricity and SOA [$F(6,54) = 8.70, p < .001$]. This suggests that positional information increasingly disappears with increases in processing duration. However, it might also be that at least after 150 msec of processing the first character, target and flankers are processed separately and, thus, no longer interact with each other.

When the mean effects of Experiments 1 and 2 were compared, there were also some differences. Whereas in Experiment 1 there was an overall increase in recognition performance with increasing SOA, no such main effect of SOA was found in Experiment 2B. The absence of a statistically significant main effect of SOA in Experiment 2B can be attributed to the larger variation of performance with the chosen eccentricities than with the chosen interletter spacings. In addition, the decrease of the effects of spatial characteristics with increasing SOA was smaller for eccentricity than for spacing. The remaining effect of eccentricity even for the largest SOAs might be plausibly interpreted as an effect of visual acuity. Since increasing eccentricity is associated with reduced visual acuity, effects of eccentricity that stem from visual acuity must be assumed to occur independently of SOA. Only the portion of eccentricity effects that comes into play when a target is flanked should be reduced by increasing the temporal distance between a target and flankers.

EXPERIMENTS 3A AND 3B

The masking functions observed in Experiments 1 and 2 were interpreted in terms of the interactive activation account of masking (Di Lollo et al., 2000). This account attributes Type B masking to interactions between feedback higher level information and incoming low-level information. But the nature of the information that has been fed back in the present experiments is still unclear. Proceeding from interactive letter and word recognition models, one might suppose three levels for the processing of letter strings: a feature, a letter, and a word level (e.g., McClelland & Rumelhart, 1981). If it is assumed that integration of information takes place on a feature level, the next higher level information that might provide top-down feedback is letter-level information. Hence, if letter-level information can hardly be computed, higher level feedback should be reduced, thus decreasing the probability of Type B masking. To examine this assumption, in Experiment 3, the effects of letter, as well as nonletter, flankers were studied with various SOAs.

It is already known that recognition performance for a temporally masked target depends on the kind of mask. For example, masks consisting of letter segments, letters, or words produce different recognition performances for the same target letters (e.g., Massaro & Cohen, 1994; Taylor & Chabot, 1978; Turvey, 1973). Also, crowding effects depend on the kinds of flankers/masks (Bouma, 1970; Huckauf, Heller, & Nazir, 1999; Styles & Allport, 1986). One example is that letter-like nonletter flankers produce more crowding than letter flankers do (Huckauf et al., 1999). This so-called *letter superiority effect* seems paradoxical, since one would expect a facilitation when presenting flanking characters of a set different from the target. The suggested interpretation for this letter superiority effect is that the processing of unfamiliar flankers slows down the identification process. Proceeding on this hypothesis, increasing the temporal distance between target and flankers should lead to a decrease of the letter superiority effect.

Moreover, the letter superiority effect provides evidence that higher level processes contribute to crowding effects. If one assumes that Type B masking functions derive from higher level feedback, one might suppose that information from the letter level is fed back to the feature level. Since nonletter flankers should produce weaker letter-level activation than do letter flankers, one might expect less top-down feedback and, thus, also less pronounced Type B masking for nonletter than for letter flankers.

Another question was raised by Experiments 1 and 2. Both experiments showed a reduction of spatial effects with increasing SOA. After 150 msec, no effects of character spacing and only a small effect of target eccentricity was observed. Nevertheless, it was unclear whether these findings were due to the fact that, with increasing SOA, target and flankers are processed increasingly separately, or whether they indicated a loss of spatial information with increases in processing time. It has often been suggested that position information is lost during processing (e.g., Mozer, 1989; Treisman & Paterson, 1984). Moreover, there are already some indications that crowding effects arise because of positional uncertainty (e.g., Chung et al., 2001; Fine, 2001; Huckauf & Heller, 2002). Also, Di Lollo et al. (2000) have claimed that one reason for the reentering of higher level signals into lower levels of processing is the fact that sensitivity to location is reduced during higher level coding. However, in current interactive activation models of letter and word recognition (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; McClelland & Rumelhart, 1981), processing is assumed to be position specific. To examine this question, in Experiment 3 isolated letters were also presented. If there were to be no interactions between characters after a certain amount of time, the performance for flanked letters should equal the performance for isolated letters. If, however, the performance of flanked letters is still lower than that for isolated letters, one would have to conclude that there were still interactions among the target and the flankers and that the nonexistent spatial effects were due to the transience of the spatial information.

In addition in Experiment 3, there was only one block of trials including negative and positive SOAs. So far, the comparison of effects of negative and positive SOAs was problematic because of possibly different baseline performances at an SOA of 0 produced by various groups of participants. The procedure in Experiment 3 allowed us to directly compare forward and backward masking, or paracontrast and metacontrast masking, respectively.

Method

Flankers were either selected out of a set of eight letter-like nonletters or out of a set of eight letters. Details of the stimuli are given in Huckauf et al. (1999). All the characters were of the same height and width and consisted of a vertical bar on their left-hand side and additional strokes to the right. Targets were presented at 4º of eccentricity, either with nonletter or with letter flankers on each side. Flankers were presented with a spacing of 1º. The SOA between target and flankers was −150, −75, 0, 75, or 150 msec. This yields a total of 26 (target letters) ∗ 2 (visual fields) ∗ 2 (kinds of flankers) ∗ 5 (SOAs) = 520 trials. In addition, each target letter was presented in isolation, which adds 26 (target letters) ∗ 2 (visual fields) = 52 trials per participant. All the trials were presented in random order. Ten naive students participated in this experiment.

Results and Discussion

Mean recognition performances are depicted in Figure 3. Whereas with nonletter flankers, a monotonic increase of mean performance was obtained with increasing SOA, with letter flankers a rather U-shaped masking function was observed. The dominance of Type B masking for recognition of targets flanked by letters over that for nonletter flankers also becomes evident when one looks at each observer separately (see Table 3). For the interpretation of the differences, one must take into account the fact that both kinds of flankers are visually very similar, so that even the nonletter flankers might have produced some amount of activation within the letter level. The more pronounced Type B masking for letter than for nonletter flankers indicates that interactions of higher level letter and incoming feature information can be regarded as a critical mechanism for producing Type B masking.

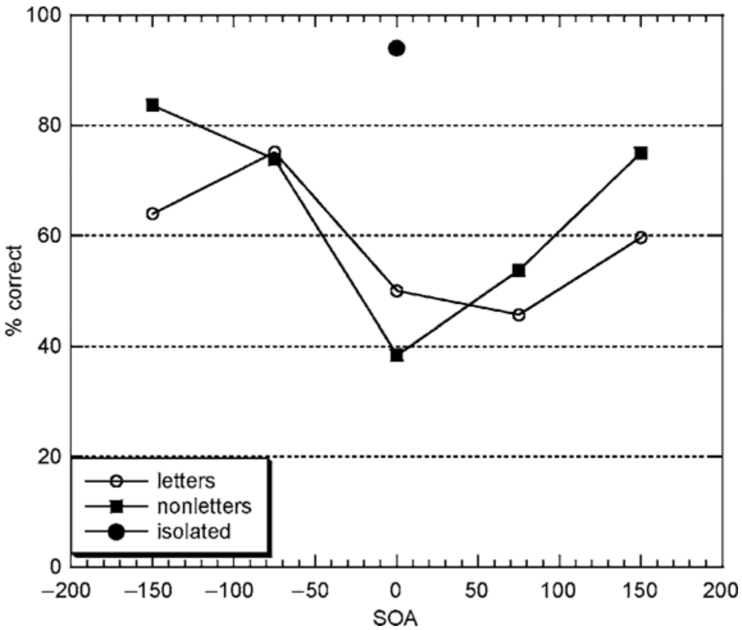

Figure 3. Recognition performance for letters flanked by letter-like nonletters and by letters, depending on target–mask stimulus onset asynchrony (SOA) as observed in Experiment 3. In addition, recognition performance for isolated letters is depicted.

Table 3
Frequency of Monotonically Increasing (Type A) and Decreasing (Type B) Masking Functions in Experiment 3 Depending on the Kind of Flankers/Masks and on the Sequence of Presentation of Target and Mask

	Negative SOAs		Positive SOAs	
Flankers	(Strictly) Monotonically Increasing	Decreasing	(Strictly) Monotonically Increasing	Decreasing
Letter	3 (3)	7	4 (4)	6
Nonletter	7 (7)	3	8 (5)	2

Note—A function was classified as decreasing when, with increasing SOA, performance was reduced by more than 5%. The number of functions that did strictly monotonically increase is given in parentheses.

As can be seen in Figure 3, even with a spatial distance of 1° and a temporal delay of 150 msec between a flanker and a target, performance was lower for flanked than for isolated targets. That is, even when a target and flankers with a spacing of 1° and a temporal delay of 150 msec were presented, they clearly interacted with each other. This indicates that also in Experiments 1 and 2, the reduction of spatial effect with increasing SOA should be attributed to the transience of the spatial information. The result also shows that the processing of the characters continues for more than 150 msec and still interferes with successively presented stimuli.

To compare forward, or paracontrast, with backward, or metacontrast, masking, arcsine-transformed correct responses for flanked targets (except those for simultaneous presentation with an SOA of 0) were entered in a ANOVA for repeated measures, with the factors of SOA (short vs. long), masking direction (presentation of flankers before vs. after target presentation), and kinds of flanker (letters vs. nonletters). Recognition performance was better when the temporal delay between the target and the flankers was larger [main effect of SOA: $F(1,9) = 11.12$, $p < .01$]. Backward masking was marginally stronger than forward masking [main effect of masking direction: $F(1,9) = 4.93$, $p = .053$]. Whereas for the smaller SOA of 75 msec, backward masking was clearly stronger than forward masking, there was only a small difference between forward and backward masking for the large SOA of 150 msec [interaction of SOA and masking direction: $F(1,9) = 17.97$, $p < .005$]. The stronger masking effect for backward, or metacontrast, than for forward, or paracontrast, masking, at least for SOAs shorter than 150 msec, provides evidence that also in Experiments 1 and 2 the differences between negative and positive SOAs should not be ascribed to differences between participants. Instead, they should be regarded as effects of the experimental context. Importantly, the fact that there was no difference between forward and backward masking at the large SOA of 150 msec cannot be attributed to ceiling performance, as the comparison with performance for isolated targets reveals.

Within the SOA conditions (other than an SOA of 0), targets flanked by letter-like nonletters were, in the mean, recognized better than targets flanked by letters [$F(1,9) = 9.30$, $p < .02$]. This advantage for nonletter flankers was more pronounced for the larger SOA of 150 msec than for the shorter SOA of 75 msec [interaction between SOA and kinds of flankers: $F(1,9) = 5.68$, $p < .05$], as is shown in Figure 3. The results indicate that the letter-like nonletters need more than 75 msec of processing before they are identified as nonletters.

A second ANOVA only for an SOA of 0 showed that the effect of kinds of flankers was reversed when the flankers were displayed simultaneously with the target [$F(1,9) = 6.94$, $p < .05$]. As is depicted in Figure 3, for an SOA of 0, recognition performance for targets flanked by nonletters was worse than that for targets flanked by letters, thus replicating the letter superiority effect.

The results of Experiment 3 support the assumptions that flankers are automatically processed and that letter-like nonletters are processed more slowly than letters. When there was enough time to process the target and the flankers, nonletter flankers produced less interference with target recognition than did letter flankers. This indicates that for higher level processing, temporal factors are more important than spatial factors are known to be.

In all the experiments, there were some conditions that could be directly compared. Presentation conditions for letter flankers in Experiment 3 were comparable to the medium spacing in Experiment 1 and the medium eccentricity in Experiment 2. For positive SOAs, the U-shaped function of mean recognition performance was replicated in all the experiments. For negative SOAs, however, the decrease of performance at the largest SOA of −150 msec, which was clearly observed in Experiment 3, was only slightly pronounced in Experiment 1 and was not found in Experiment 2. To clarify the form of the masking function, this eventual decline in performance with increases in the negative SOAs should be studied further by increasing the SOA to more than 150 msec. Then, however, eye movements would have to be monitored to ensure fixation.

Experiment 3 provided evidence that the kinds of flankers/masks interact with SOA, not only for forward, or paracontrast, but also for backward, or metacontrast, masking. It further confirmed the observations that negative SOAs lead to better recognition performance than do positive SOAs. This stronger backward, or metacontrast masking, however, was restricted to SOAs up to about 100–150 msec. Thereafter, there was nearly no difference between forward (paracontrast) and backward (metacontrast) masking. The fact that there was no difference between positive and negative SOAs at 150 msec cannot be attributed to a ceiling effect in performance, as the comparison with performance for isolated letters revealed. That is, even with a spatial distance of 1° and a temporal delay of 150 msec between the flanker and the target, performance was lower for flanked than for isolated targets. This shows that the processing of the pseudoletters and letters continues for more than 150 msec and still interferes with successively presented stimuli. Type B masking was more pronounced with letter than with nonletter flankers. This supports the interpretation that impaired information at higher levels of processing leads to less top-down feedback, thus reducing the probability of Type B masking functions.

GENERAL DISCUSSION

To examine the question of whether processes underlying visual temporal masking contribute to crowding, effects of spatial distance on target recognition were assessed when the temporal distance (SOA) between a target and flanking letters was varied. Joint mechanisms underlying crowding and masking were expected to concern either processes of integration of information, as in Type A masking, or processes underlying Type B masking. The results gave evidence that varying the temporal dynamics of crowding results in Type A, as well as Type B, masking functions. As was shown in Experiments 1 and 2, the probability of Type A masking decreased and that of Type B masking increased with increases in interletter spacing and with decreases in eccentricity. That is, for conditions known to produce strong crowding effects (targets presented in the far periphery and with flankers displayed close to the target), Type A masking predominated. Contrary to the expectations derived from the metacontrast masking literature, for targets presented close to fixation and with widely spaced flankers (i.e., conditions known to produce relatively weak effects of crowding), there was a preponderance of Type B masking functions. Experiment 3 further revealed that Type B masking was more pronounced when letters flanked/masked the target, relative to letter-like nonletters.

If the integration of information about target and mask features results in Type A masking, the present results confirm the hypothesis that integration of features plays an important role in crowding, replicating earlier work (e.g., Wolford, 1975), as well as recent studies (Chung et al., 2001; Parkes et al., 2001; Pelli et al., in press). But the data strongly suggest that integration of feature information is restricted to small spatial separations between targets and flankers and large target eccentricities. The notion of integration or summation of information leaves open the question of what information is integrated in Type A masking. On the basis of the assumption that letter recognition is a hierarchically organized process preceding from feature to letter analysis (e.g., McClelland & Rumelhart, 1981; Sanocki, 1987), one might assume that information about features is pooled. This hypothesis can be related to the notions of contour interaction (Flom, Weymouth, & Kahneman, 1963) or feature perturbation (Wolford, 1975) in the crowding literature. Central to these concepts is the assumption that adjacent features are combined to form a unitary stimulus. The probability of wrongfully combining features of neighboring characters is assumed to increase with decreases in spacing and with increases in eccentricity.

However, for crowding effects that are observed at small eccentricities or over large retinal distances, other mechanisms have to come into play. As the present study indicates, these processes are analogous to those contributing to Type B masking. Unfortunately, which mechanisms underlie Type B masking is unclear. One recent account suggests that higher level information from the first stimulus feeds (temporally delayed) back to low levels of processing and interacts with incoming information about the new stimulus (Di Lollo et al., 2000). This can explain the lower recognition performance for successive than for simultaneous presentations. But which processes can be assumed to cause crowding in simultaneously presented characters? One might speculate that for simultaneous presentation, higher level information about the target interacts with higher level (instead of incoming) information about the flankers. In this sense, the data indicate that higher level information is more available the larger the spacing and the smaller the eccentricity, or in other words, that integration of information in conditions of small spacing and large eccentricities perturbs the processing of higher level information and thus prevents higher level interactions.

To further examine the hypothesis that Type B masking was due to interactions on the letter level, in Experiment 3, letter-like nonletters were presented as flankers. The underlying logic was that if Type B masking is based on top-down feedback from the letter level, nonletters should produce less activation at the letter level and, therefore, less top-down information and, consequently, less Type B masking. This has been confirmed. The frequency for U-shaped functions was larger with letter than with nonletter flankers, resulting in mean U-shaped masking functions for letter flankers and monotonic functions for nonletter flankers. Since nonletter and letter flankers were similar in terms of their spatial extension, as well as their feature structure, it must be assumed that even nonletter flankers may have produced some activation at the letter level. Hence, the results are in line with the suggested interpretation of higher level information as information at a letter level.

However, the assumption of interactions between a target and flankers on a letter level of processing implies that letter information is only minimally spatially organized. Otherwise, one cannot explain why letters that can be clearly separated interact with each other. This missing spatial organization of letter information was impressively shown in Experiments 1 and 2. Both experiments revealed that with increases in processing time, spatial factors became more and more irrelevant. Already, 50 msec after presentation of the first character, the effects of interletter spacing and eccentricity were largely reduced. After 150 msec, there was no effect of spacing and only a weak effect of eccentricity, which might be ascribed to visual acuity. Thus, the results are in conflict with models of letter and word recognition (e.g., Coltheart et al., 2001; McClelland & Rumelhart, 1981), which are based on the central assumption that the processing of letters in a string is position specific.

With respect to the main question of which processes underlie crowding and whether these processes can be observed in other forms of visual temporal masking, the present study suggests that crowding effects result from an integration or summation of information of adjacent features and from interactions at a higher letter level of processing. One might further assume that whereas interactions among the features result from position-specific processing, interactions among the letters result from position-independent processing. The missing spatial information during higher level coding can account for the large regions in which crowding between letters occurs. Pelli et al. (in press) termed these regions *integration fields*. The present data indicate that whereas integration over small spatial separations and at large eccentricities is based on the processing of features, integration over large spatial separations and at small eccentricities is based on higher level letter processing. Whether such higher level interactions are subsumed under the term *masking* strongly depends on the theoretical account of masking. At least for visual temporal masking, the processes contributing to crowding and masking seem to be strongly related.

In each experiment, a smooth transition between Type B and Type A masking functions was observed. This argues against a strict differentiation between these kinds of masking (see also Francis & Herzog, 2004). Instead, the findings lead to the hypothesis that all masking effects observed in the present study might be based on the same processes (e.g., integration of information about target and mask features and interactions during higher level processing), which change in weight depending on the spatial and the temporal distance between the target and the flankers/masks and on the kind of information to be processed (e.g., letters vs. nonletters).

If various kinds of masking result from the same underlying processes, the relation between forward and backward masking becomes of interest. Current frameworks of masking model mainly backward-masking effects. Although the present study was not intended to investigate commonalities and differences between forward and backward masking, the experiments revealed that after about 100–150 msec, no difference between recognition performance for forward- or backward-masked targets was observed. For the first 100 msec, however, the mechanisms contributing to differential effects in forward and backward masking are unclear. The principal paradigm of presenting a character as a target as well as a mask might provide further insight into the processes underlying both forms of masking.

In conclusion, crowding—at least crowding in letter strings—shares some processes in common with temporal masking. It may, therefore, be referred to as *lateral* masking. Concerning the question of which processes underlie crowding effects, one likely mechanism is the position-specific integration of information about adjacent character features. But whenever the spatial and temporal distance between stimuli is sufficient to keep them apart, thus prohibiting the integration process, interference between the stimuli seems to be due to conflicting information at higher levels of letter processing. This kind of interaction can be assumed to start at about 50 msec after presentation of the characters, when abstract position-independent information becomes more and more available, and lasts for more than 150 msec.

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