Running title: Asymmetric substitution masking

Asymmetric object substitution masking

Yuhong Jiang Marvin M. Chun

Yale University Vanderbilt University

Under Review: JEP:HPP (Version of July, 2000)

Send correspondence to:

Yuhong Jiang

The John B. Pierce Laboratory

290 Congress Avenue

New Haven, CT 06519

E-mail: yuhong.jiang@yale.edu

Phone: (203)-562-9901-ext. 232

Fax: (203)-624-4950

Abstract

Object substitution masking occurs when a lateral mask persists beyond the duration of a target, reflecting reentrant processes in vision (V. Di Lollo, J. Enns, & R. Rensink, in press). We studied whether substitution masking is location-specific and whether it is symmetric around the target. We presented a brief circular display of letters along with a mask that designated the target. The mask was centered on the target or 1.1° to the central or the peripheral side. Substitution masking was found even when the target and the mask were at different locations. Substitution masking was asymmetric. It was stronger when the mask was to the peripheral side of the target than the central side. Asymmetric substitution was observed using varieties of masks. It could not be explained by retina acuity gradients and was not attenuated by focused attention. We propose that target selection triggers an asymmetric inhibitory surround that is stronger towards the central side of the target.

Asymmetric object substitution masking

Visual perception occurs across multiple cortical areas (Felleman & Van Essen, 1991), which are extensively connected with one another. The earlier cortical areas not only send forward projections to the later areas, but also receive backward projections from the later areas (Van Essen & Maunsell, 1983). Although it is intuitively clear what the forward projections are for, the role of the backward projections is not well understood. Several early theories of visual cognition have proposed that the backward projections provide top-down modulation of the ascending perceptual input (Broadbent, 1958; Hebb, 1949). Yet it was not clear whether such modulations occur after the completion of forward processing or whether forward processing and backward processing interact in an iterative manner during the first wave of visual processing.

One specific role of backward projections may be to modulate early visual processing through selective attention. The receptive field (RF) properties of neurons are affected by whether the RF falls within the focus of attention (Luck, Chelazzi, Hillyard, & Desimone, 1997; Moran & Desimone, 1985; Maunsell, 1995; Motter, 1993), and reentrant processes serve to enhance the gain of visual responses and to inhibit distractor activity.

More broadly, cortical feedback mechanisms may serve to match top-down perceptual hypotheses with incoming visual information. Such reentrant processing can be studied psychophysically using a new masking effect, introduced as object substitution masking by Di Lollo, Enns, and colleagues (Di Lollo & Enns, 1998; Di Lollo, Enns, & Rensink, in press). In a typical object substitution masking task, observers were presented with a brief visual display of geometric objects. One object was enclosed by four small dots. Observers were to report the shape of this object as accurately as possible. The search display and the four-dot cue were presented simultaneously for about 30 ms before the search display was erased. A sample of the four-dot cue and the target (a circle) similar to that used by Di Lollo and Enns (1998) is shown in Figure 1. Accuracy to report the target was high if the four-dot cue was simultaneously erased with the offset of the rest of the search display. Performance was severely impaired when the offset of the four-dot cue was delayed for 100 ms relative to the offset of the search array. It is as if the presence of a lingering stimulus at the target location substituted the target. The masking is called *object substitution masking* (Enns & Di Lollo, 1997), or *common onset masking* (Di Lollo, Enns, & Rensink, in press).

Insert Figure 1 here

Several features of object substitution masking make it a unique masking phenomenon. First, complex contour interactions between the target and the mask are not required to observe substitution masking. For example, the four-dot mask used in Di Lollo et al. (in press) has minimal contour and does not resemble the shape of the target. This feature makes the paradigm different from traditional backward pattern masking that operates through integration of the target and the mask contours (Kahneman, 1968). Second, delayed offset of the mask, rather than delayed onset of the mask, signifies the time course of substitution masking. Object substitution masking can be observed even when the onset of the mask and the onset of the target are simultaneous. The interruption form of backward pattern masking, on the other hand, relies on the mask onset to interrupt target processing (Turvey, 1973). The common onset nature also differentiates substitution masking from traditional metacontrast masking. In metacontrast masking, strict temporal succession of the target and the mask onset is essential (Breitmeyer, 1984; Kahneman, 1967). Finally, object substitution masking is modulated by focused attention. Substitution masking is reduced when the target location is pre-cued so that attention can be allocated to it in advance (Di Lollo et al., in press). This indicates that at least a major component of the substitution masking operates at relatively high levels of processing that are modulated by visual attention. This makes substitution masking different from low level sensory masking (Breitmeyer, 1984).

To account for object substitution masking, Di Lollo et al. (in press) proposed a computational model using the notion of *reentrant visual processing*. Specifically, they propose that there are multiple levels of visual processing, with both feed-forward and feedback projections. The feedback projections allow the higher levels to check back with input from the lower levels. Target identification is completed only when information from the lower levels is consistent with processing at the higher levels. When the target (e.g., a circle) and the mask (the four-dot cue) are erased simultaneously, there is no inconsistent input from the lower levels. Thus the processing of the target is successful. In contrast, when the four-dot mask lingers on the display, the representation of a four-dot mask at the lower levels is inconsistent with the representation of a circle at the higher levels. Processing of the target is thus disrupted. Focused attention at the target location reduces the disruption because the target can be identified more quickly. This reduces the amount of reiteration necessary to identify the target, and hence reduces substitution masking (Di Lollo et al., in press; Enns & Di Lollo, 1997).

In this study, we use the object substitution masking paradigm as a tool to study visual reentrant processing. We ask three questions. First, is iterative reentrant processing location-specific? That is, can we find masking when the target and the mask are at different locations? Second, is reentrant processing sensitive to the similarity between the target and the mask? Finally, when the target and the mask are at different locations, is the reentrant process sensitive to the spatial arrangement of the target and the mask? The first question will be addressed in Experiment 1, and the other questions will be addressed in the remaining experiments.

The first question taps into the mechanism of the postulated reentrant process. It is not clear whether substitution masking is location-specific. On the one hand, a non-specific reentrant process is inefficient. During reiterative processing between different levels, the higher levels should restrict their reentrant feedback modulation to the regions surrounding the target. The reentrant process of one object should not be applied all over the visual field because at any given moment, there may be many objects scattered about. A non-selective reentrant process will confuse information from different locations (or objects) and will never permit a coherent representation of any object. Thus, to minimize confusion, the visual system must restrict reentrant processing to an appropriate location (or object). On the other hand, the accuracy and resolution of location-specific reentrant processing is limited by the physiological properties of the visual system. Because the receptive fields of cells get larger in higher visual areas (Desimone & Duncan, 1995), the exact location of the target inside the receptive field of a cell becomes ambiguous as information ascends the visual system hierarchy. So the reentrant process may extend beyond the target location to its neighboring locations. If so, inconsistent input at a location near the target should also disrupt visual processing during the reentrant process, producing object substitution masking for targets and masks appearing in different, but neighboring locations.

Previous studies have not systematically examined whether substitution masking can be obtained when the mask is at a different location than the target. In previous studies of substitution masking, the target and the mask were centered on the same location. Di Lollo et al. (in press) argued that in their four-dot masking paradigm, the masking object should be considered as the surface produced by modal completion of the four-dot mask (Kanizsa, 1979). Thus, although there was no physical overlap between the target figure and the four-dot mask, the mask surface and the target were positioned at the same location. Results showed that masking was effective under such conditions. A notable exception to the same-location design is an experiment reported by Enns and Di Lollo (1997). In one condition of their Experiment 1, Enns and Di Lollo presented the four-dot mask and the target at different locations. The separation between the neighboring contours of the target and the mask was 0.35°. No substitution masking was found in this condition.

Although Enns and Di Lollo's (1997) result suggests that the reentrant process is location specific, it cannot exclude the possibility that under appropriate conditions substitution masking may be observed when the mask and the target are at different locations. The parameters used in Enns and Di Lollo’s (1997) study may not have been optimal to observe strong substitution masking. For example, target location uncertainty was small because only three possible locations were used. So attention was not completely diffuse. In addition, the set size of the search display was one, with no distractors presented. Substitution masking is stronger with increasing display set sizes (Di Lollo et al., in press). It is possible that if one tests conditions that optimize the chances to observe a robust substitution effect, one may find significant substitution masking even when the target and the mask are presented at different locations. Thus, our first experiment tests whether substitution masking can be observed when the target and the mask are at different locations. We optimized masking conditions by increasing target location uncertainty (8 possible target locations compared to 3 used by Enns & Di Lollo) and display set size (set size 8 compared to 1). In addition, we used a slightly smaller separation between the closest contours of the target and the mask (0.30° compared with 0.35°) and a more eccentric search array (3.13°

compared with 3.00°). These variations should increase the strength of substitution masking (see Di Lollo et al., in press). If substitution masking is strictly location-specific, we should replicate the null result of Enns and Di Lollo (1997) in the different location condition.

Experiment 1: Is substitution masking location-specific?

We used alphabetic letters as search elements and the four-dot figure as the mask. Pilot studies in our lab have shown that letters are highly susceptible to substitution masking, despite their frequent use. The degree of masking for letter targets is comparable to that obtained for the geometric figures used in Di Lollo and Enns (1998). The main questions that we ask in Experiment 1 are (1) whether substitution masking is modulated by the location of the mask and (2) whether focused attention can attenuate masking.

Three factors were manipulated in a within-subject design to answer these questions. First, the location of the mask was either the same as that of the target or different. Figure 2 shows a sample of the same location (Figure 2A) and different location (Figure 2B, 2C) trials. The different location condition was partitioned into two types: central mask and peripheral mask, as illustrated in Figures 2B and 2C. In this paper, "central" and "peripheral" always describe the relative location relationship between the target and the mask, using the center of fixation/display as the reference point. A central mask is closer to the fixation point than the target is. A peripheral mask is farther away from the fixation point than the target is.

Insert Figure 2 here

The second factor of interest is the time course of mask offset. In the simultaneous offset condition, the mask was erased simultaneously with the offset of the search array. In the delayed offset condition, the mask remained on the screen for 160 ms after the offset of the search display. The difference between these two conditions is a measure of substitution masking.

The last factor manipulated is whether the target location was indicated by a valid pre-cue. In the valid cue condition, a pre-cue was flashed at the target’s location for 107 ms. Briefly afterwards the search display was presented. In the neutral cue condition, the pre-cue was flashed at the center of the display. Figure 3 shows a schematic sample of presentation sequence. As demonstrated by Di Lollo et al. (in press) and Enns and Di Lollo (1997), substitution masking is attenuated by focused attention. However, the modulation of attention has been shown only in conditions in which the target and mask were presented at the same location. We are also interested in the attentional effect when the target and the mask are presented at different locations. If the reiterative process underlies object substitution in both the same location and the different location conditions, we should expect an attentional attenuation in both conditions. When the target and the mask are at different locations, focused attention can reduce substitution in two ways. First, attention enhances target identification and thus reduces substitution masking in general, whether the mask is at the same location as or at a different location from the target. Second, attention helps to localize the target (Luck, Girelli, McDermott, & Ford, 1998). Because the target is detected sooner when the pre-cue is valid rather than neutral, the amount of reiteration is reduced. Therefore, substitution masking should be smaller.

Insert Figure 3 here

Hence, if substitution masking is strictly location specific, we should find a significant masking effect only when the target and the distractors are at the same location. In addition, masking should be reduced in the valid pre-cue condition. On the other hand, if substitution masking applies to locations around the target, we should find significant masking for both the same location and the different location conditions. Masking should be reduced by the valid pre-cue in the different location condition also.

Method

Participants

In most of the experiments reported in this article, participants were recruited from Yale University's graduate and undergraduate subject pool. Seven naïve observers from Vanderbilt University's undergraduate subject pool participated in Experiment 5B. The participants were 18 to 26 years old. All had normal or corrected-to-normal visual acuity and normal color vision. One author (Y.J.) participated in all but the last experiment. The pattern of her performance was not noticeably different from those of the naïve observers'.

Seven naïve observers and one author (Y. J.) were tested in this experiment.

Materials and Procedure

A sample search display is shown in Figure 2. In the search display, 8 white letters (A, S, D, and F, each presented twice) were regularly spaced on the periphery of an imaginary circle (3.13° X 3.13°). The letters were printed using Helvetica font with a point size of 24 (0.75°). The target was defined by being closest to the four-dot mask. The four white dots were arranged in a square configuration (0.81° X 0.81°), each dot subtended 0.13° X 0.13°. On half of the trials, the four-dot mask was centered at the same position as the target on the imaginary circle. On the other trials, the center of the four-dot mask was shifted along the same radius as the target by 1.10°. The four-dot mask appeared either to the peripheral or to the central side of the target equally often. In the different location condition, the closest contour distance between the letter and the four-dot mask was approximately 0.30°. The target was presented at equal frequency in each of the eight positions.

Observers pressed the space bar to initiate each trial. The fixation point was presented for 400 ms at the center of the display. It was followed by a green square (0.47° X 0.47°) flashed either at the center of the display (neutral cue) or at one of the eight locations on the imaginary circle (valid cue). The green square was flashed for 107 ms followed by a blank interval that lasted 53 ms. Observers were instructed to shift their attention to the pre-cue location if the pre-cue was presented on the imaginary circle because the target would be there. Following the blank interval, the search display along with the four-dot mask was presented for 13 ms. Then the whole display was erased on half of the trials (simultaneous offset condition). On the other half of the trials, the letter array was erased, but the four-dot cue stayed for another 160 ms (delayed offset condition). Observers were instructed to identify the target as accurately as possible and enter their response on the keyboard. Sound feedback was immediately provided following correct responses.

Each participant carried out 16 practice trials and 384 experimental trials. The trial components were: 384 = 2 (mask offset – simultaneous offset vs. delayed offset) X 2 (pre-cue – valid cue vs. neutral cue) X 2 (location – same mask-target location vs. different locations, the latter is further divided into equal proportion of central and peripheral masks) X 48 (cases). The trial sequences were randomized.

Apparatus

The experiment was conducted on a Macintosh computer with a 17" screen. The experiment was programmed with MacProbe software (Hunt, 1994). Participants were tested individually in a room with normal interior lighting. The unrestricted viewing distance was about 57 cm.

Results

Figure 4 shows the results averaged across the 8 participants.

Insert Figure 4 here

Overall ANOVA tests

We entered mask location, mask offset and cue validity into repeated-measures ANOVA. The main effect of mask location was not significant, F (1, 7) = 1.54, p > .25. This suggests that performance was comparable between the same location and the different location trials. The main effect of mask offset was highly significant, F(1, 7) = 134.25, p < .001. Accuracy was significantly poorer in the delayed offset condition, showing an overall substitution masking effect. The main effect of cue validity was significant, F(1, 7) = 46.11, p < .001. Performance was better when the cue was valid.

For the two-way interactions, we found a significant interaction between pre-cue and mask offset, F(1, 7) = 17.44, p < .004. This reflects the fact that the substitution masking (the difference between delayed offset and simultaneous offset) was attenuated by valid attentional pre-cues. In addition, there was a significant interaction between mask location and cue validity, F(1, 7) = 8.17, p < .025, indicating that performance in the different location condition was facilitated by the valid pre-cue more than that in the same location condition. This is understandable because without the valid pre-cue, the target was difficult to localize in the different location condition. A valid pre-cue helped the localization process. On the other hand, the target was not difficult to localize in the same location condition even without the valid pre-cue. The benefit of the pre-cue was thus smaller. Lastly, the interaction between mask location and mask offset was not significant, F < 1, ns.

Follow-up tests: neutral trials and valid trials

Although the three-way interaction was not significant, F(1, 7) = 1.73, p > .20, we think it is necessary to break trials down into neutral cue trials and valid cue trials. To answer whether substitution masking is location-specific, one needs to look at the valid cue trials, not the neutral trials. The reason is as follows.

In the neutral cue trials, two factors determined the observed substitution masking effect. One is a location-specific mechanism. Suppose that substitution masking is somewhat location-specific, then the masking effect should be larger in the same location than the different location condition. The other factor, however, produces the opposite effect. This factor concerns the efficiency of target localization. The more efficient the target is localized, the fewer the number of reiterations required, and hence smaller substitution masking is obtained. The neutral cue condition forced observers to rely on the mask to localize the target. The mask was a better localization cue when centered on the target than when centered away from the target. This reduced the number of reiterations needed for the same location trials compared with the different location trials. When the two factors were combined, one may not find any difference between the same and the different location conditions.

In fact, when data are restricted to the neutral cue condition, the interaction between mask offset and mask location was not significant, F < 1. Substitution masking was 42% when the target and the mask had different locations and 40% when the target and the mask had the same location.

Because we are mainly interested in the first factor – the location-specific mechanism – we should try to minimize the difference in the efficiency of target localization. The valid cue condition allowed us to do so. When the cue was valid, observers could rely on the pre-cue to localize the target. Therefore the target was localized with the same efficiency in the same and different location conditions. The comparison between these two conditions would then be a relatively pure measure of the location-specific mechanism.

When data are restricted to the valid cue trials, the interaction between mask offset and mask location was significant, F (1, 7) = 9.84, p < .016. Substitution masking was smaller in the different location condition (M = 15%) than the same location condition (M = 23%). Therefore, we found evidence for a location-specific component of substitution masking.

Follow-up tests: same location trials and different location trials

Our novel finding is that substitution masking was significant when the mask and the target were presented at different locations. To show this point, we restricted the analysis to the same location and the different location conditions separately. In the same location condition, we replicated results from Di Lollo et al. (in press) and found a significant substitution masking (p < .001), a significant cueing effect (p < .002) and a significant modulation of masking by attention (p < .02). Results from the different location condition gave the same pattern: significant masking, significant cueing and significant attentional modulation, all ps < .007. This clearly indicates that substitution masking is not completely tied to the target location.

Follow-up tests: Peripheral vs. Central masks.

Insert Table 1 here

In the last analysis, we compared trials when the mask was peripheral and when it was central. The mean for these different location trials is shown in Table 1. We entered mask location (peripheral or central), mask offset and pre-cue validity into repeated-measures ANOVA. We will only report effects related to the comparisons between peripheral and central masks. The main effect of mask location was significant, with better performance in the central mask condition, $F(1, 7) = 5.64$, $p < .05$. The interaction between mask location and mask offset was not significant, $F(1, 7) = 1.79$, $p > .20$, indicating comparable substitution masking for peripheral and central masks. The interaction between mask location and pre-cue validity was not significant either, $F(1, 7) = 2.19$, $p > .15$. However, the three-way interaction approached significance, $F(1, 7) = 4.95$, $p < .061$. This is explained by the fact that attention seems to attenuate substitution masking more when the mask was central than when it was peripheral. However, this trend was not significant in later experiments (e.g., Experiments 8 and 9), so we will not discuss this result any further.

Discussion

In this experiment, we tested whether substitution masking was strictly location-specific and whether substitution masking was modulated by attention when the target and the mask were at different locations. Results show that substitution masking is somewhat, but not completely, location-specific. The location-specific component was revealed most clearly in the valid cue condition, which did not have a target location uncertainty confound. There, substitution masking was significantly larger in the same (target-mask) location condition than in the different location condition.

However, substitution masking is not completely location-specific. Robust substitution masking was obtained even when the mask appeared in a different location than the target. In addition, different location masking was reduced when attention was directed to the target's location by a peripheral cue. This suggests that masking by a nearby mask has similar characteristics to masking by an overlapping mask. If the substitution masking is caused by reentrant processing (Di Lollo et al., in press), then the feedback loop does not merely compare information from the same location as the target, but also from neighboring locations. As we suggested in the introduction, this is probably due to the size of the receptive fields in higher visual areas. Because the cells have very large receptive fields, it is difficult to accurately localize the input stimulus within the receptive field of a cell (Desimone & Duncan, 1995). Thus, the reentrant process is carried out over regions surrounding the target. This finding is different from that of Enns and Di Lollo (1997), who found no substitution masking in the different location condition. As discussed earlier, our study used parameters that optimized substitution masking. Enns and Di Lollo's null result may be explained as due to lack of testing power.

In addition to elucidating the effect of location in substitution masking, different location masking allows us to extend the original four-dot figure masking paradigm to tasks with various different types of masks without worrying about physical overlap between the target and the mask. The four-dot mask was a good stimulus in the original substitution masking partly because it had no contour overlap with the target, even when the four-dot mask was centered at the same location as the target. Other stimuli, such as letters, would not be good stimuli because they would overlap with the target, and thus add additional low-level effects into the masking phenomenon. Now, since robust substitution masking can be observed when the mask is at a different location than the target, we can use a wider variety of masks that may reveal other properties of substitution masking.

Experiment 2: Letter masks and asymmetric substitution masking

In this and all later experiments we tested different location substitution masking. In most experiments, the pre-cue was not presented. The target was indicated by the neighboring mask.

In this and the next three experiments, we try to answer two main questions about the reentrant process. First, is the reentrant process sensitive to the form similarity between the target and the mask? Second, is the reentrant process affected by the spatial arrangement between the target and the mask?

Results from Experiment 1 paved the way for us to examine these two questions. By using different varieties of masks, we examine whether the reentrant process is sensitive to the nature of the mask. As postulated by the reentrant theory of Di Lollo et al. (in press), identification is disrupted when there is an inconsistency between the representation of the target at later visual areas and the representation of the mask at earlier visual areas. One unspecified issue here concerns what counts as an inconsistency. The four-dot mask used in the original study was inconsistent with the target in several aspects. First, its time course was longer than that of the target's. The temporal fate alone may indicate to the visual system that a different object was on the display. Second, the four-dot mask was not a letter. So its category was inconsistent with the letter target. Third, the four-dot mask did not contain any features such as line and line junctions. So its form features were inconsistent with the features of the letter target. Any of these inconsistencies may be considered by the reentrant process as sufficient evidence for disruption.

In Experiment 2, we used two types of mask: the four-dot mask and a letter 'N' mask. These two masks have a common time course, which is different from that of the target's. If time course alone is important, then both types of mask should produce substitution masking of the same magnitude. In addition, the letter 'N' mask belongs to the same category as the target, and it shares more common features with the target such as lines and line junctions. Thus, the four-dot mask is more inconsistent with the target letter than the letter 'N' mask is. It is not clear from the original reentrant theory how inconsistencies are treated by the visual system. If the visual system rejects the target more easily when there are more inconsistencies, then the four-dot mask should produce larger substitution masking. However, a similar but non-identical mask may be more confusing. Thus, a letter 'N' may substitute the representation of the target letter more easily. This will lead to larger substitution masking with the letter 'N' mask. The empirical data will reveal whether the visual system rejects a target more easily with a more inconsistent mask (the four-dot) or with a more similar (confusable) mask (the letter 'N').

The second purpose of this experiment is to compare the effect of a peripheral and a central mask. Here, "peripheral" and "central" characterizes the relative location relationship between the target and the mask, using the center of fixation display as a reference. A peripheral mask appears towards the peripheral side of the target (further away from center fixation), and a central mask appears towards the central side of the target (closer to center fixation). Is the reentrant process affected by such spatial arrangement? The answer to this question will tell us whether substitution masking is symmetric or anisotropic around the target.

Method

All procedures used in this experiment were the same as in Experiment 1 except where noted. Just like Experiment 1, the target array contained eight letters ('A', 'S', 'D', and 'F', each presented twice). The experiment had three factors. (1) Mask type (four-dot or the letter ‘N’). (2) Mask location (the mask is to the peripheral or the central side of the target); and (3) Mask offset (simultaneous offset vs. delayed offset). Attentional pre-cues were not used in this experiment. Each trial started with a fixation point (400 ms) followed by the search array (13 ms). The mask was either erased simultaneously with the search array or lingered on the screen for 160 ms longer. The letter ‘N’ was white printed in Helvetica font with a point size of 24.

Fifteen new naïve observers and Y. J. were tested in this experiment. Each observer did 16 practice trials and 256 experimental trials (256 = 2 mask type X 2 mask location X 2 mask offset X 32 cases). The trial order was randomized.

Results

Mean accuracy is plotted in Figure 5 as a function of mask type, mask location and mask offset. We entered the three factors into repeated-measures ANOVA.

Insert Figure 5 here

The main effect of mask type was significant, with poorer performance when the mask was the letter ‘N’ than the four-dot, F(1, 15) = 36.96, $p < .0001$. The main effect of mask location was also significant, with poorer performance when the mask was peripheral than when it was central, F(1, 15) = 45.85, $p < .0001$. In addition, there was a significant main effect of mask offset, showing substitution masking, F(1, 15) = 750.68, $p < .0001$.

The significant two-way interaction between mask type and mask offset indicated that substitution masking was larger for the letter ‘N’ mask than the four-dot mask, F(1, 15) = 9.17, p

< .008. Substitution masking was 32.5% with the four-dot mask, $F(1, 15) = 353.88$, $p < .0001$, and it increased to 46.3% with the letter mask, $F(1, 15) = 295.33$, $p < .0001$.

Unexpectedly, there was a significant interaction between mask location and mask offset, $F(1, 15) = 14.65$, $p < .002$. Substitution masking was stronger when the mask was towards the peripheral side of the target ($M = 50\%$) than when it was towards the central side of the target ($M = 32\%$). The interaction between mask type and mask location was not significant, $F(1, 15) = 1.41$, $p > .25$, nor was the three-way interaction significant, $F(1, 15) = 2.74$, $p > .10$. The asymmetric substitution masking pattern was significant with the four-dot mask, $F(1, 15) = 8.72$, $p < .01$, as well as with the letter mask, $F(1, 15) = 20.43$, $p < .0001$.

Discussion

We compared substitution masking produced by the four-dot mask and the letter ‘N’ when these masks were presented at a location different from that of the target. Substitution masking was found for both the letter mask and the four-dot mask, but was stronger with the letter mask. Although the four-dot mask was more inconsistent with the target letter than the letter mask was, it produced weaker substitution. This indicates that during reentrant processing, the visual system does not reject the target with more inconsistencies in form and identity. Rather, the more consistent but more confusable mask (the letter mask 'N') produced larger substitution.

It is not clear, however, whether the visual system is truly sensitive to the identity of the mask. The letter 'N' differs from the four-dot mask in at least three aspects. First, it is a letter. Second, it shares common features with the target. Third, it is a more visually dense mask than the four-dot mask because the letter 'N' is composed of more pixels. The next three experiments will test each factor in turn.

Another interesting result from our experiment is that substitution masking was stronger when the mask was peripheral than when it was central, relative to the location of the target from fixation. This pattern only applied to the delayed offset condition. Performance was comparable between the peripheral and the central mask conditions when the mask was erased simultaneously with the offset of the search array. So the asymmetric pattern was restricted to substitution masking, not to lateral masking in general. Because this result was not expected, it needs to be replicated. The asymmetric pattern will be tested again in the next three experiments.

To determine what aspect of the mask the reentrant process is sensitive to, Experiment 3 tested the categorical status of the letter mask. We compared the masking effect between letter masks (‘E’ and ‘S’) and rotated or reflected letters. A mask letter in its canonical orientation may be more confusable with the target than a rotated or reflected letter may be. Experiment 4 tested the effect of feature similarity between the mask and the target. The mask was either a ‘+’ or random dots. Only the ‘+’ shared features (lines and line junctions) with the targets. If substitution masking depends on feature similarity between the mask and the target, we should find weaker substitution for the random dot mask. In Experiment 5 we tested the effect of the mask density. The mask was composed of 85, 50, 15 or 4 random dots. If substitution masking depends on the density of the mask, we should find attenuation of substitution masking as the mask density is reduced.

Experiment 3: Letter mask vs. rotated or reflected letter mask

In this experiment, we contrasted upright letter masks with rotated or reflected letters (non-letters). The letters and the rotated/reflected letters had the same low level physical features. Figure 6 shows these two types of masks. (A sample of the masks used in Experiment 4 and Experiment 5 are also shown in Figure 6.) The only difference was that the letters were in their canonical orientation. They can be easily categorized as belonging to the same set as the target.

Insert Figure 6 here

Method

Six naïve observers and Y. J. participated in this experiment. Three factors were manipulated in a within-subject design: mask type (letter vs. rotated letter), mask location (peripheral vs. central) and mask offset (delayed offset vs. simultaneous offset). The masks were ‘E’ and mirror image of ‘E’ for 4 observers and were ‘S’ and 90-degree rotated (clockwise) ‘S’ for the other 3 observers (Figure 6). The search letters were selected from ‘A’, ‘B’, C’, and ‘D’. Each participant did 16 practice trials and 256 experimental trials. All other aspects of the experiment were the same as those of Experiment 2.

Results and Discussion

Since the results showed no difference between ‘E/reflected E’ and ‘S/rotated S’ masks, accuracy was averaged across all observers and is plotted in Figure 7.

Insert Figure 7 here

It is clear from Figure 7 that accuracy patterns were similar when the mask was a letter and when it was a rotated or reflected letter. Repeated-measures ANOVA showed that none of the effects (main effect or interactions) associated with mask type was significant, all Fs < 1. Beside the mask type factor, we found a significant main effect of mask location, with better performance for central masks than peripheral masks, $F(1, 6) = 11.84$, $p < .014$. There was also a significant main effect of mask offset, $F(1, 6) = 25.57$, $p < .002$, showing robust substitution masking. Moreover, there was a significant interaction between mask location and mask offset, $F(1, 6) = 23.28$, $p < .003$, with larger substitution masking for peripheral mask than central mask. This replicated the asymmetric substitution masking pattern found in Experiment 2.

Thus, whether the mask was an upright letter or a reflected or rotated letter did not influence (1) substitution masking or (2) the asymmetric masking between peripheral and central masks. The first result suggests that the reentrant process is not sensitive to the categorical relation between the target and the mask. It does not matter whether the mask is a letter or a rotated letter. As long as the mask is inconsistent with the target input in its time course, it produces disruption. The second result suggests that asymmetric masking is not restricted to letter masks per se. Rotated letter masks can also produce asymmetric substitution masking.

One difficulty in interpreting results from this experiment is that a rotated or reflected letter may have been treated as a letter by observers. Because the same mask was used throughout the experiment, observers might have mentally rotated the letters to their canonical orientation. Studies have shown that such computations can be easily performed with letters (Hommel, 1995). However, we note that search performance is strongly modulated by whether letter stimuli are presented in their familiar, canonical orientation or in their unfamiliar orientations or handedness (Wang, Cavanagh, & Green, 1994). Hence, even though participants may have readily categorized the rotated or reflected letter as a letter at a cognitive level, their visual performance should have been sensitive to the distinction regardless. As visual performance was unaffected in this masking task, we tentatively conclude that substitution masking is not sensitive to similarity in stimulus category. Future experiments should further confirm that substitution masking can be observed with masks that are non-letters. The next experiment will further test the effect of mask-target category similarity as well as their feature similarity.

Experiment 4: ‘+’ mask vs. random-dot mask

Although the mask category does not have any effect on substitution masking or asymmetry, a second difference between the letter mask and the four-dot mask may have an effect. The difference lies in the feature similarity between the target and the mask. The letter masks (or rotated letters) shared similar features with the search elements, such as lines and line junctions, whereas the four-dot mask did not share such features with the target. Substitution masking and asymmetric masking patterns may be sensitive to feature similarity.

In this experiment, we compared a '+' shaped mask with a random-dots mask. We controlled mask density in the two types of masks by using the same number of dots to form the masks. The '+' mask shared features with the letter target because both contained lines and line junctions. The '+' mask also belongs to the same category as the target at the level of "symbols". These differences made the '+' mask more confusable with letter targets than the random dot mask.

Method

Both masks were composed of 17 white dots (0.10° X 0. 10°). The dots were arranged into a cross configuration in one condition and were randomly positioned in a 9 X 9 invisible matrix (each cell was 0.10° X 0. 10°) in the other condition. Only the ‘+’ mask shared line and line junctions with the target letters. Figure 6 shows a sample of the masks used in this experiment. We tested 10 observers (9 naïve + Y.J.) in this experiment. The same design and procedure used in Experiment 4 were adopted here, except that the mask types were different. In addition, the target elements were selected from ‘A’, ‘S’, ‘D’ and ‘F’, as in Experiment 1.

Insert Figure 8 here

Results and Discussion

Figure 8 shows mean accuracy obtained from this experiment. ANOVA test showed that none of the effects (main effects or interactions) associated with mask type (cross vs. dots) were significant, all Fs < 1.05, ns. Overall, there was a significant main effect of mask offset, showing substitution masking, F(1, 9) = 133.28, $p < .001$; a significant main effect of mask location, with higher performance when the mask was central than when it was peripheral, F(1, 9) = 33.66, $p < .001$; and the interaction between mask offset and mask location approached significance, F(1, 9) = 5.07, $p < .051$, indicating stronger peripheral substitution masking than central substitution masking. Thus, both substitution masking and the asymmetric pattern were obtained with these masks, but none of the results were affected by whether the mask was a cross or just random dots. Thus, neither mask category (symbol vs. non-symbol) nor mask feature similarity (lines vs. random dots) had an effect on the visual reentrant processing mechanism that underlies substitution masking.

Experiment 5: The density of the mask

In Experiments 3 and 4, we found that substitution masking and the asymmetric masking pattern were not affected by whether the mask was associated with the same response category as the target, or whether the mask shared visual features with the target. These results indicate that the reentrant process is not sensitive to similarity in the categorical and form dimension between the target and the mask. The question then is why did we find a larger substitution masking for the letter 'N' mask than the four-dot mask in Experiment 2? We note that the letter 'N' has more density than the four-dot mask. This experiment is to test whether the reentrant process is sensitive to the density of the mask.

Method

The mask was produced by filling in different number of cells in an invisible 10 X 10 matrix that subtended 0.81° X 0. 81°. Two versions of the experiment were tested on different observers. In experiment 5-A , there were three levels of mass: 15-cell filled, 50-cell filled and 85-cell filled. In Experiment 5-B, there were two levels of mass: 15-cell filled and 4-cell filled. The two versions were otherwise identical. A sample of the masks can be seen in Figure 6. The density of the mask increased as more cells were filled. Eight observers (7 naïve + Y.J.) were tested in 5-A, and 12 observers (11 naïve) were tested in 5-B. Each observer was tested in 16 practice and 384 experimental trials (384 = 3 mask mass X 2 mask location X 2 mask offset X 32 cells). The procedure used in this experiment was similar to that of Experiment 4.

Results

Version A: 85, 50, and 15-cell filled:

Figure 9 shows the average accuracy of the 8 observers. Again, none of the factors associated with mask density were significant, all Fs < 1.76, ps > .20. And again, substitution masking was significant overall, F(1, 7) = 94.54, $p < .001$; performance was better in the central mask condition, F(1, 7) = 277.81, $p < .001$; and substitution masking was smaller with central masks than peripheral masks, F(1, 7) = 5.57, $p < .05$, showing an asymmetric masking pattern.

Insert Figures 9, 10 here

Version B: 15 and 4-cell filled:

Before concluding that substitution masking and the asymmetric pattern were not affected by mask density at all, we need to rule out the possibility that the 15-dot used in version A was already too dense. Modulation by mask density may be observed at the lower end when 15-dot and 4-dot masks are compared.

Figure 10 shows the results from 12 observers tested in version B. Unlike version A that found no effect of mask density, version B revealed a significant main effect of mask density, F(1, 11) = 23.10, $p < .001$, with better performance with 4-dot than 15-dot masks. The main effect of mask location was significant, F(1, 11) = 109.18, $p < .001$, with higher performance for the central mask than the peripheral mask. The main effect of mask offset was also significant, showing robust substitution masking, F(1, 11) = 184.20, $p < .001$.

In addition, mask density modulated substitution masking. This is reflected by the significant interaction between mask density and mask offset, F(1, 11) = 25.42, $p < .001$. Substitution masking was smaller for the four-dot mask (M = 28.9%) than for the 15-dot mask (M = 42.8%). Note that the magnitude of substitution masking found here was similar to that obtained in Experiment 2. In Experiment 2, the letter 'N' mask produced a substitution masking effect of 46.3%. The four-dot mask produced a masking effect of 32.5%. The masking effect and the difference in masking with the two types of masks were similar across the two experiments. The reduction in substitution by the four-dot mask compared with the letter 'N' mask appears to be completely accountable by mask density.

There was also a significant interaction effect between mask density and mask location, F(1, 11) = 9.99, $p < .009$. This is explained by the fact that the asymmetry of lateral masking was more pronounced with the 15-dot mask. Importantly, there was a significant interaction between mask location and mask offset, showing the asymmetric substitution masking, F(1, 11) = 13.83, $p < .003$. In addition, the three-way interaction was not significant, $F < 1$, ns. This last finding suggests that the asymmetric substitution pattern was not modulated by mask density.

In follow-up tests we performed analyses on the 4-dot mask and the 15-dot mask conditions separately. For trials that used the 15-dot mask, there was a significant substitution masking effect, F(1, 11) = 474.92, $p < .001$; a significant main effect of mask location, F(1, 11) = 48.32, $p < .001$, and a significant interaction effect, F(1, 11) = 9.17, $p < .011$, showing asymmetric substitution. A similar pattern of results was found for trials that used the 4-dot mask: a significant substitution effect, F(1, 11) = 59.99, $p < .001$; a significant main effect of mask location, F(1, 11) = 20.48, $p < .001$; and a significant interaction effect, F(1, 11) = 6.66, p <

.026. Thus, substitution masking and the asymmetric substitution masking effect held up for both the 15-dot and the 4-dot masks.

Discussion

When the density of the mask was directly manipulated, we found a modulation effect of mask density on substitution masking. This was only observed in Experiment 5-B which contrasted 15-dot and 4-dot masks. When the density exceeded 15-dots, as tested in Experiment 5-A, no further modulation was observed with increased mass. Thus, we conclude substitution masking is partly modulated by the density of the mask, but only in the lower range of minimal density levels.

Experiments 2 to 5 indicated that the reentrant process was not sensitive to the categorical similarity or the feature similarity between the target and the mask. It was sensitive to the density of the mask, but only at the lower end of mask density. Larger substitution was observed when the density of the mask was high. We believe that the reentrant process shown here is insensitive to the semantics of the mask. It appears that the reentrant process does not consider what the mask is. Informal observations showed that the mask could be the same exact letter as the target, yet observers reported that they did not see anything at the target's location. The reentrant process only considers the inconsistency in the time course of the mask and the target. Such temporal cues strongly indicate that a different object is presented (Kahneman, Treisman, & Gibbs, 1992). The goodness of the object seems to be modulated by the density of the object. If the density of the mask is too low, the visual system may reject its status as a good object to substitute the target. The threshold for the visual system to accept the mask as a good object is low. Beyond 15-dots, further increases in the density of the mask did not induce larger substitution.

Overview of Experiments 6 - 10

We were intrigued by the asymmetry between peripheral and central masks because it may enrich an understanding for substitution masking and reentrant processing mechanisms in general. The asymmetric substitution effect was consistently observed in the last four experiments. The effect was robust and was observed with varieties of different masks. The original reentrant theory (Di Lollo et al., in press) does not account for asymmetric masking between peripheral and central masks. Thus, we conducted 5 additional experiments to explore the possible mechanisms for asymmetric substitution masking. These experiments tested three possible hypotheses.

In the first section, we tested the acuity gradient hypothesis for lateral masking proposed by Banks and his colleagues (Banks, Larson, & Prinzmetal, 1979). Banks and colleagues have extensively studied asymmetries in lateral masking. They found that peripheral masks were more effective than central masks in lateral masking, even when the target was presented at a fixed eccentricity (Banks et al., 1979). They proposed that retinal acuity to identify a target is determined not by the eccentricity of the target, but by the eccentricity of the combined target plus mask configuration. When target eccentricity is fixed, the “mask + target” as a whole is at a more peripheral location in the peripheral mask condition. Thus, the peripheral mask is more effective because the target falls on a lower retina acuity gradient when it is combined with a peripheral mask.

On first thought, the asymmetry of substitution masking found in Experiments 2-5 was strikingly similar to the asymmetry reported in previous lateral masking studies. However, one aspect of our paradigm suggests that the asymmetry found in our study reflects a different mechanism than the asymmetry in lateral masking. Specifically, the asymmetry was found to be much larger in the delayed offset condition than the simultaneous offset condition. If the asymmetry was produced by the acuity reduction of the “mask + target” group, we should have found similar asymmetry for the delayed offset and the simultaneous offset conditions.

Of course, the acuity gradient of “mask + target” may take the duration of the items into account. If a higher weight is assigned to an item that is presented longer, then it is still possible that the acuity factor should be more salient for the “delayed offset” condition than the “simultaneous offset” condition. Thus, to test the retina acuity gradient hypothesis more decisively, we carried out Experiment 6. In this experiment, we put the mask at a fixed eccentricity, but the target was presented in either the central or the peripheral side of the mask. When the target was more central, the “mask + target” was located at a higher acuity gradient. The acuity gradient hypothesis predicts smaller masking for central targets than peripheral targets. On the other hand, if asymmetric masking is found when the mask is relatively peripheral compared with the target, we should find smaller masking for the peripheral target (or, central mask) than the central target.

Experiments 7-9 tested the attention hypothesis. According to this hypothesis, peripheral masking is stronger either because the mask attracts more attention when it is peripheral or the target gets less attention when it is central. First, peripheral masks may attract attention more effectively than central masks due to perceptual closure. Specifically, the peripheral mask was outside the imaginary circle of the search array. The perceptual closure of the search elements may have rendered the central mask less salient. Second, the central target may get less attention than the peripheral target as a result of attentional momentum carried over by orienting to the mask. This idea will be explained in more detail later. In brief, larger peripheral substitution masking is predicted if attentional momentum causes the target to receive less attention under peripheral masking than central masking.

We carried out three experiments to test the attention hypothesis. In Experiment 7 we tested substitution masking with a set size of 1. The removal of the distractors eliminates the perceptual closure effect, making central and peripheral masks equally salient. Asymmetric masking should be eliminated according to the perceptual closure hypothesis. Experiment 8 tested the effect of attentional pre-cues and Experiment 9 tested the effect of target singleton pop out. Asymmetric masking should be reduced by valid pre-cues or target pop out if attention asymmetry was the underlying mechanism for the asymmetric substitution masking pattern.

To preclude, none of the hypotheses proposed above turned out to be responsible for the asymmetric substitution masking we observed. By process of elimination, we narrowed down the list of plausible mechanisms to a third hypothesis – asymmetric inhibition. According to this hypothesis, tested in Experiment 10, higher visual areas not only check back to lower levels for information comparison, but they also send an inhibitory projection to the lower levels. This inhibitory mechanism is centered on the target letter and projects an inhibitory surround around the target letter, with stronger inhibition towards the central side of the target than the peripheral side. The inhibition renders the central mask less effective than the peripheral mask and hence, reduces substitution masking. This hypothesis is conjectured based on data from Experiments 1 to 9 in the substitution masking paradigm. To provide independent support for the asymmetric inhibition mechanism, we designed Experiment 10 using a modified visual search task that has been successfully used to measure inhibition (Cave & Zimmerman, 1997; Kim & Cave, 1995, 1999; Klein, 1988). In this task, observers searched for a uniquely colored target letter among distractor letters and reported its identity. On a small proportion of trials, a tiny probe dot was presented next to the target. Observers pressed the space bar to report the detection of the probe dot as fast as possible. If the asymmetric inhibitory mechanism can be generalized to this paradigm, probe detection should be slower if the dot was towards the central side of the target than the peripheral side. Experiment 10 also allowed us to determine under which conditions the asymmetric inhibition mechanism may (or may not) be triggered.

Experiment 6: Can asymmetric masking be explained by the retina acuity gradient hypothesis?

In this experiment we examine whether the asymmetric substitution masking pattern can be explained by extant theories in the lateral masking literature. Lateral masking refers to the phenomenon that target identification accuracy is reduced when the target is surrounded by distractors. Several earlier studies have shown that lateral masking tends to be larger when the mask appears on the peripheral rather than on the central side of the target (Banks, Bachrach, & Larson, 1977; Banks, Larson, & Prinzmetal, 1979; Banks & White, 1984; Bouma, 1973; Chastain & Lawson, 1979; Chambers & Wolford, 1983; Wolford & Chambers, 1983; Wolford & Hollingsworth, 1974). We will consider two theories that have been proposed to explain asymmetric lateral masking.

According to the feature-perturbation model of visual masking (Wolford, 1975), features of the letter mask drift over time. Lateral masking occurs when the features of the target combine with those of the mask. Feature drifting is asymmetric, with more mask features drifting towards the center than towards the periphery. This results in larger lateral masking from peripheral masks. Although asymmetric feature drifting successfully accounts for asymmetric lateral masking found in other studies, it does not seem to apply to our displays. First, Wolford and Chambers (1984) proposed that feature perturbation occurred only when the distance between the target and the mask was very close. In our display, the center-to-center distance between the target and the mask was 1.1°. At the presentation eccentricity of 3.13°, this distance was clearly too far apart for feature perturbation to arise based on results from Wolford and Chambers (1984). In fact, the feature similarities between target and mask have no effect on substitution masking or asymmetric pattern in our study (Experiment 4). This indicates that asymmetric feature perturbation is not the underlying mechanism for the asymmetric substitution masking observed in our study.

A different theory proposed by Banks et al. (1979) may be more relevant here. According to the retina acuity gradient theory (Banks et al. 1977, 1979; Banks & White, 1984), the retina gradient of the target is determined by the cluster formed by the target plus the mask. Although the target itself may be presented at a fixed eccentricity in the central and the peripheral mask conditions, target acuity is not determined by the exact eccentricity of the target, but by the eccentricity of the "target + mask" configuration. When the mask is on the peripheral side, the acuity gradient to the target is lower because the center of the configuration is more peripheral. Thus, lateral masking is larger for peripheral than for central masks. Banks et al. (1979) further postulated that if multiple masks were added on the display in a column array, perceptual grouping may segregate the mask away from the target. Since the acuity gradient of the target would not be pulled away by peripheral masks when these masks were grouped, lateral masking by a column of peripheral masks was smaller than masking produced by a single mask.

In our study, since the mask was presented next to the target, lateral masking must have occurred. Our simultaneous offset condition corresponds to a traditional lateral masking condition. A trend for asymmetric lateral masking was indeed found in Experiments 1, 3, 4 and 5, but not in Experiment 2. However, we are mainly concerned with the much stronger asymmetry observed for delayed offset masks. Since the retina acuity gradient theory is agnostic about the mask offset time, it cannot explain asymmetric substitution masking without additional assumptions. The additional assumptions are not too hard to postulate, of course. For example, the acuity gradient may be a weighted average of item eccentricity and duration. Such an adjustment would predict larger asymmetry in the delayed offset condition.

Instead of just proposing and qualifying additional assumptions, we directly tested whether retina acuity gradient theory could explain asymmetric substitution masking. In Experiment 6, we used a fixed mask eccentricity, but positioned the target either to the peripheral or to the central side of the mask. Since "target + mask" configuration was closer to the center when the target was central (i.e., mask was peripheral, see Figure 11B) than when the target was peripheral (see Figure 11A), retina acuity gradient theory predicts smaller peripheral than central masking in this experiment. On the other hand, if asymmetric substitution masking is produced by the relative peripheral-central relationship between the target and the mask independent of the retina acuity gradient, we should still find larger substitution masking from the peripheral mask.

Insert Figure 11 here

Method

A within-subject design with two factors was tested. The factors were (1) target location (peripheral vs. central target) and (2) mask offset time (delayed vs. simultaneous). The mask was always located on an imaginary circle with a radius of 3.13°. The search array was located on an imaginary circle with a radius of either 2.19° or 4.06°. The center-to-center separation between the target and the mask was 0.93°. Note that when the target was peripheral (Figure 11A), the mask was relatively central compared with the target. Each of the eight observers (7 naïve + Y.J.) participated in 16 practice trials and 128 experimental trials (128 = 2 mask locations X 2 mask offset X 32 cases). Other aspects of the experiment were the same as in Experiment 2.

Results

Insert Figure 12 here

Mean accuracy is plotted in Figure 12. It is clear that asymmetric substitution masking was determined by the relative peripheral-central relationship between the target and the mask. The results were opposite to that predicted by retina acuity gradient theory. Substitution masking was stronger when the target was central (Figure 11B) than peripheral (Figure 11A), even though the central target (or target + mask) was much closer to the center of fixation and should benefit from higher retina acuity. The observation was confirmed by statistical analysis. The two main effects were both significant. Performance was better when the target was more peripheral, $\underline{F}(1, 7) = 28.62$, $\underline{p} < .001$, and was better in the simultaneous offset than delayed offset condition, $\underline{F}(1, 7) = 188.88$, $\underline{p} < .001$. An important observation was the significant interaction between mask offset and mask location, $\underline{F}(1, 7) = 9.13$, $\underline{p} < .018$, showing larger substitution masking when the target was central (i.e., mask was peripheral) than peripheral.

Discussion

When the letter mask was presented at a fixed eccentricity, identification of a letter target to the central side of it was much poorer than identification of a letter target to the peripheral side of the mask. This happened only when the mask offset was delayed, however, as performance was comparable between these two conditions when the mask was erased simultaneously with the search array. The acuity gradient mechanism proposed by Banks et al. (1979) cannot explain these results. The asymmetric substitution pattern is not retina-based. Note that the target is much closer to the center of fixation in the peripheral mask (target eccentricity = 2.19°) than the central mask condition (target eccentricity = 4.06°). Any mechanism based on an explanation of retina acuity would have difficulty explaining this result.

To further demonstrate that the asymmetric substitution pattern does not originate from the retina, we performed two follow-up studies. These are not presented in detail because the results of Experiment 6 have already spoken decisively against the retina acuity hypothesis. Nevertheless, to provide converging evidence, we presented the search array and the mask to separate eyes in one follow-up study. If the asymmetric pattern is produced in a visual center earlier than the optic chiasm where the optic nerves from the two eyes cross (Palmer, 1999), we should not find asymmetric substitution. Conversely, strong asymmetric substitution under dichotic viewing conditions suggests that the phenomenon may arise in higher levels (i.e., no earlier than the lateral geniculate nucleus). Results based on 3 observers showed that both substitution masking and the asymmetric pattern could be observed under dichotic viewing conditions. Thus, unlike what is implied in the retina acuity gradient theory, the asymmetric substitution obtained here does not originate from the retina. Furthermore, Di Lollo et al. (in press) suggested that whereas low-level visual masking was absent in dark-adapted viewing (Bischof & Di Lollo, 1995), high-level visual masking such as substitution masking was observable in scotopic vision. To find out whether the asymmetric substitution masking was a low-level or a high-level effect according to this criterion, two observers (Y.J. & X.J.) were tested under dark adapted conditions. Both substitution masking and the asymmetric pattern were found under these conditions. This provides additional support to the notion that at least a major component of the asymmetric pattern resides in high-level vision. The exact physiological locus, however, is unclear.

Having ruled out the retina acuity gradient hypothesis, we will now turn to the attention hypothesis.

Experiments 7-9: Asymmetric substitution and the attention hypothesis

It is possible that a delayed peripheral mask attracts attention more effectively than a delayed central mask. It is also possible that the target gets less immediate attention when it is on the central side than on the peripheral side of the mask. Both of these may contribute to asymmetric substitution masking. There are two reasons for the asymmetric attentional distribution. First, it may be produced by the perceptual closure of the circular search array (Palmer, 1992). Since the target and the distractors occupied an imaginary circle, a central mask was always positioned inside the circle and a peripheral mask outside it. Because of perceptual closure, the peripheral mask may stand out as a separate object from the search array while the central mask may not. If peripheral masks attract more attention than central masks, it may produce stronger substitution masking.

Second, asymmetric substitution masking may reflect attentional momentum. Independent of perceptual closure of the search array, the target may not get immediate attention when the mask is peripheral. The attentional momentum hypothesis is illustrated in Figure 13. To localize the target, one must first localize the mask. Suppose that a delayed mask orients attention from the center to the mask location and carries some momentum with it. Then attention must be re-directed from the mask to the target. When the mask is central, attentional momentum follows the same direction from the mask as it is re-directed to the target, and the target benefits from immediate attentional allocation. When the mask is peripheral, attention must reverse its direction (momentum) to orient to the target. Attention to the target is thus delayed in the peripheral masking compared with the central masking condition, producing poorer performance. The effect of attentional momentum has been demonstrated in studies of Inhibition of Return (Pratt, Spalek, & Bradshaw, 1999) and may apply to our experiments.

Insert Figure 13 here

We carried out three experiments to test the attention hypothesis. Experiment 7 tested the effect of search distractors that influence perceptual grouping of the search array. Experiments 8 and 9 tested the effect of attentional momentum.

Experiment 7: Reducing peripheral mask saliency

To investigate the effect of perceptual closure produced by the search array, we tested observers on search displays with no distractors. The target and the mask were the only items on the display. The absence of distractors eliminated grouping cues that produced perceptual closure. If asymmetric substitution was produced by perceptual closure, it should not be found in this experiment.

Method

Six observers (5 naïve) were tested in this experiment. The target letter (‘A’, ‘S’, ‘D’ or ‘F’) was presented on one of the eight locations on an imaginary circle (radius = 3.13°). It was accompanied by the mask letter ‘N’ that was presented either to the central or peripheral side. Hence, except for the absence of all seven distractors, the display was the same as in Experiment 2. Two factors were manipulated: mask location (peripheral or central) and mask offset (delayed or simultaneous). Each observer was tested in 16 practice and 128 experimental trials (128 = 2 mask location X 2 mask offset X 32 cases).

Results and Discussion

Table 2 shows mean accuracy data.

Insert Table 2 here

In the ANOVA test, we found a significant main effect of mask offset, F(1, 5) = 18.42, p < .008; a significant main effect of mask location, F(1, 5) = 24.49, p < .004; and a significant interaction effect, F(1, 5) = 64.00, p < .001. Thus, asymmetric substitution masking was robust in displays with no distractors. This clearly rules out an explanation based on peripheral mask salience due to perceptual closure of distractors.

Does set size have any effect on substitution masking and the asymmetric pattern? To find out, we compared results from this experiment (set size = 1) with those from Experiment 2 (set size = 8, letter 'N' mask). We combined data from the 15 naïve observers in Experiment 2 with data from all 6 observers in the current experiment. Set size (between-subject), mask offset time (within-subject) and mask location (within-subject) were entered into a mixed-design ANOVA test. We found that accuracy dropped significantly as set size increased, F(1, 19) = 43.72, p < .001. In addition, there was a significant interaction between set size and mask offset time, showing larger substitution masking as set size increased, F(1, 19) = 10.52, $p < .004$. However, the set size factor did not interact with mask location, $F < 1$. Nor was the three-way interaction significant, $F < 1$. At set size 8, substitution masking was 56.5% with a peripheral mask and 34.9% with a central mask. At set size 1, substitution masking was 40% with a peripheral mask and 13.3% with a central mask.

Therefore, substitution masking increased as the display set size increased, replicating Di Lollo et al.'s (in press) finding. However, the asymmetric substitution pattern was not affected by set size, suggesting that asymmetric substitution may have a different underlying mechanism than substitution masking.

Finally, we note that the target was always presented in a circular array in all of the experiments reported so far. The presence of the distractors on the circular display cannot account for the asymmetric substitution, as shown by Experiment 7. Still, in Experiment 7 the target location was selected from an imaginary circle. Observers may have learned that the display was circular, so there might have been perceptual closure in their imagery. To find out whether the circular display was critical for the asymmetric substitution effect, two observers (Y.J. and F.L.) were tested using linear search arrays. The target locations were selected either from the horizontal meridian or the vertical meridian in separate blocks. A clear asymmetric substitution effect was found in both observers. Thus, the circular display used in the experiments reported here was not critical for asymmetric substitution.

Experiment 8: Minimizing attentional momentum

In Experiment 7, we ruled out the perceptual closure argument of the attention hypothesis. The remaining two experiments examine the second version of the attention hypothesis. As illustrated in Figure 13, asymmetric substitution may be produced by attentional momentum that is carried over by orienting from the fixation to the mask cue. In the peripheral masking condition, the attentional momentum is disrupted because it must reverse its direction for a central target, while in the central masking condition, the momentum can be maintained along the same direction to a peripheral target. Thus, target processing benefits in the central mask condition, resulting in asymmetric substitution.

The premotor theory of attention generates similar predictions (Rizzolatti, Riggio, Dascola, & Umilta, 1987). This theory predicts that in order to attend to a target, a central command directs both covert attention and overt eye movement towards the target. Not only attentional shifts but also motor programming commands have momentum. Although the brief duration of the display (13 ms search array) precludes eye movements, the premotor command may carry momentum that asymmetrically favors central mask displays.

If this hypothesis is correct, then pre-cueing the target location should eliminate or at least attenuate asymmetry. Pre-cueing the target location makes it unnecessary to move covert attention or premotor eye movement commands twice: from the fixation to the mask and from the mask to the target. Rather, attention can be allocated to the target directly and thus avoid a reversed swing in attentional momentum. On the other hand, if asymmetric substitution is not sensitive to attentional cueing, we should not find an attenuation of the asymmetry.

The attentional pre-cue manipulation was also used in Experiment 1. There we found that valid pre-cues seemed to increase asymmetric masking rather than attenuate it. However, that experiment used the four-dot as the mask and the asymmetric pattern was not significant. The current experiment provides a stronger test of the pre-cue effect.

Method

We compared substitution masking when a valid pre-cue of the target location was provided versus when it was not. In one block, a pre-cue (the same as the pre-cue used in Experiment 1) was presented to the target location for 107 ms. After a brief blank of 53 ms, the search display was presented. In another block, the pre-cue was flashed at the center of fixation instead of the target's location. The attentional pre-cue factor was blocked in this experiment (it was not blocked in Experiment 1) to maximize the effect of attentional pre-cues. In each block, two factors were manipulated: mask offset and mask location. The mask was the letter 'N'. Other aspects of the experiment were the same as in Experiment 2.

Eight observers (7 naïve) participated in 16 practice trials and 128 experimental trials in each block. Six observers were also tested in two other blocks in the same session. We will only briefly mention these two blocks because data from these two blocks did not differ qualitatively from the target pre-cue block. In one block, the pre-cue was directed to the location of the mask. In another block, the pre-cues (two squares) were directed to both the target and the mask. The order of the blocks was randomized for each participant.

Results

Mean accuracy in the target pre-cue and neutral cue conditions is plotted in Figure 14.

Insert Figure 14 here

We entered pre-cue validity, mask location and mask offset into repeated-measures ANOVA. The main effect of pre-cue validity was significant, with better performance under the valid pre-cue condition, F(1, 7) = 23.52, p < .001. The main effect of mask location was significant, with better performance for central masks, F(1, 7) = 51.14, p < .001. The main effect of mask offset was also significant, F(1, 7) = 74.71, p < .002, showing robust substitution masking.

Substitution masking was significantly larger for peripheral masks than central masks, showing an asymmetric pattern, F(1, 7) = 12.09, p < .01. Substitution masking was attenuated by the valid pre-cue, showing a significant interaction between pre-cue validity and mask offset, F(1, 7) = 13.79, p < .008. The interaction between pre-cue and mask location was not significant, F < 1, ns. The three-way interaction was not significant either, F < 1, indicating that asymmetric substitution was not affected by attentional pre-cueing. Follow-up tests showed that asymmetric substitution was significant both when the pre-cue was neutral [F(1, 7) = 5.86, p < .046] and when it was valid [F(1, 7) = 16.30, p < .005]. Clearly, the results are inconsistent with the attentional momentum hypothesis postulated above.

Experiment 9: Asymmetric substitution and feature pop out

To provide converging evidence to the idea that asymmetric substitution is not attenuated by focused attention at the target location, we used another attention manipulation. In this experiment, the target had a unique color (e.g., black target among white distractors or vice versa). A pilot experiment showed that colors generally resist substitution masking. The unique color of the target was quite salient and could be identified at very high accuracy (above 90%). The pop out target had several features that may affect substitution masking and the asymmetric pattern. First, identification of the target does not rely on the mask. Attention can be directly allocated to the target without moving to the mask first. Since attentional momentum shifts are minimized, asymmetric substitution may be reduced. Second, color pop out can effectively attract attention to the target and thus facilitate target identification. This would reduce substitution masking (Di Lollo et al., in press; Treisman & Gelade, 1980; Wolfe, 1994; Yantis, 1996).

Method

The design was identical to that of Experiment 8 except that the pop out factor replaced the pre-cue factor. In the pop out condition, the target had a unique color different from the distractor color (black target among white distractors in one block and white target among black distractors in another block). In the no pop out condition, the target and distractors had the same color (black in one block and white in another block). The mask always had the same color as the distractors and thus was always quite different from the target. The background of the display was middle gray. The pop out factor was orthogonal to the mask location and the mask offset factors. Eight observers (7 naïve) were tested in 16 practice trials and 64 trials in each of the four blocks (two pop out blocks and two no pop out blocks).

Results and Discussion

Insert Figure 15 here

Mean accuracy is shown in Figure 15. Just like Experiment 8, the pop out factor did not modulate asymmetric substitution masking, because the three-way interaction was not significant, F < 1. The main effect of pop out was significant, with better performance under the pop out condition, F(1, 7) = 54.63, p < .001. The main effect of mask location was significant, with better performance for central masks, F(1, 7) = 104.18, p < .001. The main effect of mask offset was also significant, showing robust substitution masking, F(1, 7) = 143.38, p < .001. In addition, the interaction between mask offset and pop out was significant, showing smaller substitution masking under the pop out condition, F(1, 7) = 44.76, p < .001. The interaction between mask location and mask offset was also highly significant, showing asymmetric substitution, F(1, 7) = 31.04, $p < .001$. The interaction between pop out and mask location was not significant, $F < 1$.

Thus, target feature pop out improved accuracy in general and also reduced substitution masking. However, the asymmetric pattern of substitution masking was not affected by pop out. This provides strong evidence against the attentional momentum hypothesis, assuming that attention and eye movement pre-motor command programming were effectively directed to the feature pop-out cue.

In sum, results from Experiments 7 to 9 converged onto the same conclusion: substitution masking is affected by attentional manipulations, but the asymmetric pattern is not. This is true when attention is manipulated by (1) display set size; (2) pre-cueing; and (3) feature pop-out. Different mechanisms may underlie substitution masking and the asymmetric pattern.

Experiment 10. Asymmetric substitution masking and an asymmetric inhibition mechanism: converging evidence from a probe detection task

We started out with two possible explanations of asymmetric substitution masking. Neither appeared to be valid after the long journey of experimentation. Experiment 6 disconfirmed explanations based on retina acuity gradients (Banks et al., 1979). Experiments 7-9 ruled out two types of attention hypotheses, one based on perceptual closure, the other based on attentional momentum.

In this final section, we propose a hypothesis of asymmetric inhibition to explain asymmetric substitution. This is an inhibition hypothesis that complements Di Lollo et al.'s (in press) reentrant processing theory. Specifically, we propose that there is an inhibitory projection from the higher visual levels to the lower levels during interactive processing of the target. When the lower levels send information to the higher levels, they also receive inhibitory projections from the higher levels at the area surrounding the target. An important property of such inhibition is that it is centered on the target, and we propose that the inhibition is stronger to the central side of the target than the peripheral side.

The function of this inhibition is to filter out the distracting effects of items flanking the target (Luck, et al., 1997; Moran & Desimone, 1985; Motter, 1993). Inhibitory surrounds have been observed in other target report paradigms. For example, when reporting two letters from a circular array, performance is poorer for proximal targets than for distal targets (Bahcall and Kowler, 1998). Thus, when distracting items are present, attentional selection of a target appears to be accompanied by an inhibitory process that suppresses interference from neighboring items. This inhibition may be exerted by reentrant processes from higher level visual areas.

Figure 16 illustrates a schematic model of the asymmetric inhibition mechanism. The model is very simple: higher visual areas send inhibitory projections to lower levels. What's surprising is that our data suggest that the inhibitory projection is asymmetric around the target. It is stronger towards the central side of the target than the peripheral side. A central mask is thus inhibited more than a peripheral mask. This leads to less substitution masking from central masks than from peripheral masks.

Insert Figure 16 here

The asymmetric inhibitory mechanism was conjectured based on the results from Experiments 1 to 9. It is more or less a re-description of these results. Hence, it is important to provide converging evidence for this mechanism outside the substitution masking paradigm.

Our final experiment was adopted from a probe detection task (Cave & Zimmerman, 1997; Kim & Cave, 1995, 1999; Klein, 1988). In these studies, observers were engaged in two tasks in each trial. The primary task was usually a visual search task. The secondary task was to detect a small probe stimulus that sometimes appeared immediately after the primary stimulus. The probe was presented at different locations. RTs to the probe was an indicator of the deployment of attention in the primary task. This logic was used in Experiment 10.

This final experiment serves two functions. First, it provides an independent test of the asymmetric inhibition hypothesis in a modified visual search paradigm. In this experiment, observers were simply instructed to search for a uniquely colored target among distractors. On a small proportion of trials, a tiny probe dot was presented close to the target. Observers were to press the space bar as fast as possible upon detection of the probe dot. Notice that in this paradigm, masks were not presented. It was a plain visual search task. If the asymmetric inhibition hypothesis applies here, we should find stronger inhibition for detecting a central probe. In other words, probe detection should be impaired for a central probe compared with a peripheral probe.

The second function of this experiment is to clarify what triggers the asymmetric inhibition mechanism. From the substitution masking experiments, it is not clear whether the inhibition mechanism is triggered by target identification per se, or by interfering distractors and masks. If letter identification processes per se trigger such feedback inhibition, we should find asymmetric probe detection for all target identification tasks. However, if competing distractors trigger the inhibition, we should only observe asymmetric probe detection when the target is embedded among distractors.

Two groups of naive observers were tested in this experiment. One group was tested in Experiment 10-A. The other in Experiment 10-B. In both versions of the experiment, the observer's task was to identify a target letter in an unspeeded task. On a small proportion of trials (25%), however, a tiny white dot was presented either towards the central or the peripheral side of the target letter. Observers were instructed to abort the letter identification task upon probe detection and press the space bar as quickly as possible. The only difference in the two versions of the task was the distractors. In Experiment 10-A, seven distractor letters were presented. These distractors had a different color (e.g. black) than the target (e.g. white). In Experiment 10-B, there were no distractors; the target appeared alone.

Four factors were manipulated in a mixed design. The first factor was distractor (presence or. absence) and it was tested between subjects. The second factor, target color (black or white), was also tested on different observers. Half of the observers searched for a white letter among black letters, the other half searched for a black letter among white letters. The third factor was probe location (central or peripheral). It was tested within subjects. The final within-subject factor was the time course of the probe dot. The probe was either presented simultaneously with the search array (Inter-stimulus-interval = 0 ms), or was presented 40 ms after the search array was erased (ISI = 53 ms). The ISI factor was to make sure that the asymmetric inhibition effect would apply to more than one specific ISI tested in our experiment. The main factors of interest are the probe location factor and the distractor factor.

Method

Eight naïve observers were tested in Experiment 10-A. On each trial, a search array of letters was presented for 13 ms and erased. The search array was identical to that used in Experiment 9, except that the masks were not presented. The observers were to identify the uniquely colored letter as accurately as possible. On 25% of the trials, a small white dot (0.1 cm X 0.1 cm) was presented either to the central or the peripheral side of the target for 13 ms. The distance between the dot and the closest contour of the target was 0.3 °, the same as the distance between the target and the mask used in Experiment 1. Observers were to press the space bar as quickly as possible upon detection of the probe dot. The ISI between the search array and the probe dot was either 0 ms or 53 ms.

For half of the observers, the target was a white letter presented among black letters. For the other half of the observers, the target was a black letter among white letters. Experiment 10-B used a different group of 8 naïve subjects. It had the same design as Experiment 10-A except that the distractors were not presented. Each observer performed 16 practice trials and 480 trials. Among the 480 experimental trials, the probe was presented on 120 trials: 120 = 2 probe location (central or peripheral) X 2 ISI (0 or 53 ms) X 30 cases. We recorded the accuracy of the letter search task, and both the accuracy and RT of the probe detection task.

Results

Experiment 10-A.

Observers had very high accuracy in the letter search task on trials where the probe was not presented (M = 95.4%, s.e. = 0.9). The probe detection task was also performed at high accuracy. Previous studies that used the probe detection paradigm have focused mostly on the RT measure of probe detection (e.g., Cave & Zimmerman, 1997). In these tasks accuracy was usually too high to permit a separate analysis. In our experiment, we examined both RT and accuracy. Both RT and accuracy showed very similar pattern of results. The accuracy and RT data for the probe trials are presented in Figure 17.

Insert Figure 17 here

We entered target color (black vs. white), probe location (central vs. peripheral) and target-probe ISI (0 vs. 53 ms) into the ANOVA test for accuracy and RT separately. None of the effects involving target color was significant in either accuracy or RT, all Fs < 1.68, ps > .20. So we will only report the effects of probe location and ISI.

The RT measure. RT for peripheral probes was significantly faster than RT to central probes, F(1, 6) = 14.12, p < .009. RT was also faster when the ISI was 53 ms than when it was zero, reflecting lateral masking interference when the ISI = 0. This difference approached significance, F(1, 6) = 4.51, p < .078. The interaction between ISI and probe location was not significant, F < 1. This indicates that the asymmetric RT pattern was observed under both ISIs.

The accuracy measure. The main effect of probe location approached significance, showing higher accuracy when the probe was peripheral, F(1, 6) = 5.88, p < .052. The main effect of ISI was not significant, F < 1. The interaction between probe location and ISI approached significance, F(1, 6) = 4.11, p < .089. This can be explained by the fact that the asymmetric pattern was more obvious in the zero ISI condition than the 53 ms ISI condition. We have no obvious explanation for this.

Thus, probe detection was worse when the probe was to the central side of the target compared when it was to the peripheral side. This is consistent with the asymmetric inhibition hypothesis.

Experiment 10-B.

The asymmetric probe detection observed in Experiment 10-A could be produced by several factors: (1) a peripheral probe may be intrinsically easier to detect than a central probe, perhaps due to attentional momentum; (2) the asymmetric inhibition may be triggered by target identification processes per se; (3) the asymmetric inhibition may be triggered by distractor interference. To test these possibilities, Experiment 10-B used the same design as Experiment 10-A except that distractor interference was minimal – distractors were absent. It is important to find out whether the same asymmetric pattern was observed in this version. If peripheral probes are intrinsically easier to detect or if asymmetric inhibition is triggered by target identification per se, then we should replicate Experiment 10-A. If the asymmetric pattern reflects asymmetric inhibition of distractor events, then the absence of distractors here should result in weaker inhibition and hence, weaker asymmetric masking.

On probe absent trials observers were very accurate to identify the letter (M = 96%, s.e. = 1%). Their performance on probe present trials is shown in Figure 18.

Insert Figure 18 here

We entered target letter color (black vs. white), probe location (central vs. peripheral) and target-probe ISI (0 vs. 53 ms) into an ANOVA test for RT and accuracy separately. In the accuracy measure, none of the factors nor their interactions reached significance, all Fs < 3.0, ps > .13. In the RT measure, the only significant results came from the main effect of ISI, with slower RTs in the zero ISI condition than the 53 ms ISI condition, F(1, 6) = 9.46, p < .022. Again, this is probably a result of lateral masking in the 0 ISI condition. The probe location factor produced no significant behavioral changes. These results stand in sharp contrast to those obtained in Experiment 10-A.

Comparison: 10-A and 10-B

To further test the difference between 10-A and 10-B, we combined the data from these two versions of experiment and performed an ANOVA test on four factors: (1) version of the Experiment; (2) target color; (3) probe location and (4) target-probe ISI. Here we will only report the significant effects associated with the Version factor.

In the accuracy measure, we found a significant interaction between the version of the experiment and probe location, $F(1, 14) = 6.18$, $p < .029$. The asymmetric pattern was only found in version 10-A, not in 10-B. In addition, we found a significant three-way interaction between version, location and ISI, $F(1, 14) = 4.81$, $p < .049$. As pointed out earlier, the asymmetric pattern was more salient when ISI was zero than when it was 53 ms in version 10-A. In version 10-B, however, ISI did not influence the location effect. All other effects associated with the Version factor were not significant, all Fs < 3.08, ps > .10.

In the RT measure, we found a significant interaction between version and probe location, $F(1, 14) = 14.57$, $p < .002$. RT was longer for a central probe than a peripheral probe, but only in version 10-A. None of the other effects of Version were significant, all Fs < 1.83, ps > .20.

Discussion

In a modified visual search task, observers were less accurate and slower to detect a probe dot presented to the central side of the target letter than the same dot presented to the peripheral side. This was observed only when the target letter was embedded among distractors. The asymmetric pattern was eliminated when the target was presented alone. The results provide converging evidence that the asymmetric pattern observed in substitution masking can also be found in a plain visual search task.

The asymmetric probe detection performance found in Experiment 10-A cannot be explained by factors intrinsic to peripheral probe detection. A peripheral probe was not detected more quickly than a central probe in general. In fact, RT was actually slightly, though not significantly, slower to detect a peripheral probe in 10-B when distractor letters were absent.

In addition, the contrast between version 10-A and 10-B indicates that target identification per se was not sufficient to trigger asymmetric inhibition. Asymmetric probe detection was found only when distractors were presented, suggesting that distractor interference is a necessary condition to induce the asymmetric inhibition mechanism. In other words, reentrant processes serve to suppress distraction from neighboring distractors, when present. Results from the substitution masking experiments (Experiments 1 – 9) were consistent with this conclusion. Distractor interference was present in all these experiments. The required level of interference seems to be rather low. For example, even a single mask letter was sufficient to trigger the asymmetric inhibition process, as shown in Experiment 7. Once the threshold of the asymmetric inhibition mechanism is reached, a maximal effect is observed. Further attentional manipulations produced no reduction in the strength of the asymmetry.

Although this experiment clearly reveals an asymmetry that is consistent with the asymmetric inhibition hypothesis, we note that it does not prove the asymmetric inhibition hypothesis. For example, this experiment lacks a baseline to completely justify the notion of "inhibition". The slower RT for a central probe can be interpreted as stronger inhibition on the central side of the target, or it may logically be interpreted as more facilitation on the peripheral side. The inhibition notion is better justified by the substitution masking experiments. Inhibition is implied in those experiments because the mask and the target are in competition. Mask processing would potentially interfere with target identification, to the extent of even substituting the target. So it is difficult to imagine that the mask processing was facilitated, with larger facilitation on the peripheral side of the target. Rather, the target processing triggers an inhibitory surround (Bahcall & Kowler, 1998; Luck et al., 1997; Moran & Desimone, 1985), and we propose that inhibition is stronger towards the central side than the peripheral side. The present results support a working hypothesis of asymmetric inhibition that should generate interesting predictions for future work.

General Discussion

When a mask persists beyond the brief presentation of a target, target identification is impaired (see Figure 3). This is the object substitution masking effect (Di Lollo et al., in press). It is as if the representation of the target is replaced, or substituted, by the persisting presence of the mask. Di Lollo et al. (in press) proposed that substitution masking is produced by a reentrant process across different levels of visual processing. Target information ascends from lower to higher visual levels. While the higher levels are processing the target information, they also reiteratively check back with lower levels to confirm whether the early visual representations are consistent with the target representation. When a mask persists beyond the presence of the target, the mask's representation at lower levels become inconsistent with the target's representation at higher levels. This mismatch between lower and higher levels produces substitution masking.

We presented new evidence showing that the reentrant process is not restricted to the exact location of the target. Inconsistent input from a neighboring location also produces profound disruption, showing substitution masking when the target and the mask are presented at different locations. This may reflect the fact that the receptive fields of cells in higher visual areas are too large to localize items precisely (Desimone & Duncan, 1995). Imprecise reentrance from higher levels to lower levels leads to substitution masking from locations around the target. Although not restricted to the target location, substitution masking is larger when the target and the mask appeared in the same location. Thus, substitution masking is somewhat, but not completely, location specific.

The different location masking allows us to use various types of masks that could not be tested in the standard same-location masking paradigm. In section I, we compared masking effects produced by letters versus rotated/reflected letters, “+” versus random dots, and random dots with different densities. A surprising finding is that substitution masking was not sensitive to the categorical status of the mask or the feature similarity between the target and the mask. It was modulated by the density of the mask, but only at the lower range of mask density tested (e.g., less than 15-dots). This finding suggests that the substitution mechanisms are insensitive to what the mask is. The temporal parameters of mask presentation were more critical, and delayed offset appears to be a necessary and largely sufficient factor for substitution masking. It is the mask as a "token" rather than as a "type" that matters (Chun, 1997; Kanwisher & Driver, 1992). It is important to note that although the identity of the mask does not matter in the substitution masking paradigm, the identity of the target matters. Unpublished data from our lab showed that identifying a more complex target such as the shape of a geometric figure leads to larger substitution than identifying a simpler target such as the color of a patch. As predicted by the reentrant theory of Di Lollo et al. (in press), the complexity of the target matters because it affects the number of reiterations needed for reentrant processing. The longer it takes to identify the target, the more likely that an inconsistency will occur in the reentrant processing. However, the reentrant process is more or less blind to the identity of the mask. It is the spatio-temporal property of the mask rather than its identity that determines whether it will be treated as an "inconsistent" input.

Using the different mask-target location masking paradigm, we discovered that the magnitude of substitution masking is not uniform around the target. Specifically, substitution masking is stronger when the mask appears on the peripheral side of the target than on the central side. The asymmetric substitution masking is very robust and was repeatedly demonstrated in various experiments using different types of masks.

The asymmetric substitution pattern was not anticipated by Di Lollo et al.'s (in press) original reentrant theory because the theory was based on studies where the target and the mask share the same location. The asymmetric pattern is a new and robust finding. Our experiments have delineated several important properties of asymmetric substitution. First, asymmetric substitution is a general phenomenon that is not specific to a particular type of mask or a particular region in the visual field[1] . Second, asymmetric substitution masking is centered on the target, not on retina coordinates. Lastly, the asymmetric pattern is not affected by factors such as attentional cueing or set size manipulations, which strongly influence substitution masking. Thus, the mechanisms that drive asymmetric substitution masking can be considered separately from substitution masking.

First, asymmetric substitution masking cannot be explained by the retina acuity gradient hypothesis proposed by Banks et al. (1979). The asymmetry pattern was not determined by the absolute eccentricity of the mask or the target. A peripheral mask produced stronger substitution even when the combined “target + mask” configuration was at a higher acuity gradient. The asymmetry does not seem to originate from the retina because it could be obtained when the target and the mask were viewed by separate eyes. Thus, asymmetric substitution masking is produced in higher visual areas. The asymmetric masking pattern is determined by the relative peripheral-central relation between the target and the mask, not by the absolute eccentricity of the mask or the target.

Second, the asymmetry pattern was not attenuated by attention. First, the asymmetry could not be explained by perceptual closure of the search array that may lead to asymmetric salience of the mask. Peripheral masks may have been more salient than central masks because the central mask was inside an enclosed perceptual Gestalt, but removal of perceptual closure cues did not reduce asymmetric substitution masking. Second, the asymmetry was not produced by attentional momentum carried over from directing attention from fixation to the mask. Neither target location pre-cue nor target feature pop out reduced asymmetric substitution, although both factors attenuated substitution in general. In other words, there are two components of the substitution masking task. One component is attenuated by focused attention. Another component is the asymmetry, which is insensitive to attentional cueing. Di Lollo et al.'s (in press) reentrant theory explains the first component, substitution masking. An independent mechanism is required to explain the asymmetry component.

We propose that the asymmetric pattern may be explained by postulating asymmetric inhibitory projections from higher levels to lower levels during reentrant processing. Such inhibition is stronger to the central side of the target, resulting in less disruption from central masks than peripheral masks because central masks are inhibited more strongly. Converging evidence for the existence of the asymmetric inhibition mechanism was observed in a modified visual search task. When observers searched for a uniquely colored target, they were less accurate and slower to detect a probe dot appearing on the central side of the target than the peripheral side. Importantly, this asymmetry was eliminated when distractor interference was eliminated, suggesting that the asymmetric inhibition mechanism is triggered by distractor interference, not target identification per se.

We propose that a complete account of reentrant processing should incorporate a mechanism for asymmetric inhibition. During reentrant processing, the higher levels not only go back to the lower levels for an information consistency check, but they may also send inhibitory projections down to the lower levels upon detection of interference. Disrupting the first process produces the basic substitution masking effect. The second process underlies the asymmetric substitution pattern. These two processes operate in very different ways. The consistency check is a reiterative process that flows between different visual levels. Any factors that affect the number of reiterations necessary for identification will modify the magnitude of substitution. For example, increasing set size requires more reiterations and hence, produced larger substitution masking (Di Lollo et al., in press). Attentional pre-cues or target singletons reduce the number of reiterations necessary and led to smaller substitution (Di Lollo et al., in press; also see current Experiments 8 and 9).

The asymmetric inhibition process is an inhibitory projection from the higher to the lower levels, it is stronger on the central side of the target than the peripheral side and it is triggered by distractor interference. The threshold for this system is low, as any small amount of interference (e.g., that from the single mask letter) is sufficient to trigger the asymmetric inhibition. Once triggered, maximal asymmetric effects are produced. In addition, the region of inhibition appears to surround the target in all directions, even when interference is present from only a few adjacent locations. Hence, distractors located to the side of the targets triggered inhibition for all locations around the target, with inhibition weighted more heavily towards the central side of the target than towards the peripheral side, using the center of fixation/display as the reference point.

The postulation of inhibitory mechanisms is intuitive, but our explanation of the asymmetric substitution findings is not complete. First, we cannot explain why there is an asymmetry to begin with. Although we narrowed down possible explanations of the asymmetric mechanism, our data do not allow us to make specific claims about the exact implementation of asymmetric inhibition. One reason why it is hard to make conclusive statements about it is because the asymmetric substitution masking seems to be too robust. It is not affected by our manipulation of preparatory states in the observer (e.g., attentional pre-cue). It is not affected by manipulation of low-level features (e.g., mask feature and mask density), and it strongly manifests even when the retina acuity factor goes against it. From our behavioral tests, the asymmetric substitution seems to be highly insulated and may have a strong physiological basis. Future studies based on physiological as well as psychophysical methods may help clarify why an asymmetry exists in the first place. Second, as we pointed out earlier, the asymmetric inhibition mechanism is conjectured not because it was proved correct by our data, but because it generates predictions consistent with our results. The validity of the hypothesis should be qualified by future studies.

Further work is also necessary to specify the specific architecture of asymmetric inhibition. For example, the model does not specify where the "higher" and the "lower" visual levels are located in the visual processing stream (Felleman & Van Essen, 1991). One strategy to approach this question is to perform parametric psychophysical studies that vary the distance between the target and the mask. By mapping out the asymmetry as a function of the mask-target distance, the eccentricity of the target, and the receptive field properties of cells at different cortical areas in the visual system hierarchy, we may be able to infer the level at which the asymmetric substitution is operating. At present there are some limitations to this approach, however. First, because space can be represented by distributed activity across many cells, the resolution of a population of cells may be smaller than the size of the receptive field of a particular cell. So this approach may under-estimate the lateness of the critical stage. Second, we do not understand the properties of cells in different visual areas well enough for such mapping to be accurate.

Another basic question about the architecture of asymmetric inhibition concerns whether inhibition is occurring within cortical levels or between cortical levels. It may be possible that the asymmetric inhibition effect is driven by asymmetric inhibitory connections between cells within a cortical area. We currently favor the reentrant (between-level inhibition) account because it appears to more readily handle the fact that asymmetric masking is much stronger in the delayed offset condition than in the simultaneous offset condition. Within-level inhibitory interactions should predict a strong asymmetry in both offset conditions, even if the inhibition is modulated by mask duration. However, we acknowledge that computational models may be developed to account for the asymmetric masking effect using an architecture based on within-level inhibitory interactions.

Despite these ambiguities on the architecture of asymmetric inhibition, we may speculate on the causes of the asymmetry. It is interesting to note that at a given target location, any item that appears in a more central location with respect to the target will always compete more effectively for visual processing than a peripheral item would. Central distractors would generally benefit from higher acuity and attentional salience afforded by their closer proximity to fixation. Thus, asymmetric inhibition may have developed to suppress the larger interference arising from more visible centrally located items than from less visible peripherally located items, relative to the selected target. This is not to say that the asymmetric masking can be explained in terms of retina gradients alone; Experiment 6 speaks clearly against such an explanation. In other words, asymmetric masking cannot be explained by the target and mask's proximity to fixation per se. However, when considered with respect to the locus of target selection, one may speculate that relatively central locations should be suppressed more strongly than relatively peripheral locations.

In conclusion, we report new evidence of robust object substitution masking when the target and the mask were at different locations. This can be explained by the reentrant hypothesis with the added assumption that reentrant localization is inaccurate.   In addition, we discovered that the strength of substitution masking was asymmetric around the target: stronger for peripheral masks than for central masks. We propose that this may be explained by asymmetric inhibition from higher levels to lower levels, with stronger inhibition towards the central side of the target than the peripheral side. One functional benefit of this asymmetry is reduced masking from central masks. The asymmetric inhibition hypothesis may be best justified by the future discovery of neurophysiological mechanisms that produce such asymmetric inhibition around selected targets. Future studies that may elucidate the asymmetric inhibition mechanism in more detail are clearly needed.

Reference

Banks, W. P., Bachrach, K. M., & Larson, D. W. (1977). The asymmetry of lateral interference in visual letter identification. Perception and Psychophysics, 22, 232-240.

Banks, W. P., Larson, D. W., & Prinzmetal, W. (1979). Asymmetry of visual interference. Perception and Psychophysics, 25, 447-456.

Banks, W. P., & White, H. (1984). Lateral interference and perceptual grouping in visual detection. Perception and Psychophysics, 36, 285-295.

Bahcall, D. O., & Kowler, E. (1998). Attentional interference at small spatial separations. Vision Research, 39, 71-86.

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

Bouma, H. (1973). Visual interference in the parafoveal recognition of initial and final letters of words. Vision Research, 13, 767-782.

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

Broadbent, D. E. (1958). Perception and communication. New York: Pergamon Press.

Cave, K. R., & Zimmerman, J. M. (1997). Flexibility in spatial attention before and after practice. Psychological Science, 8, 399-403.

Chastain, G., & Lawson, L. (1979). Identification asymmetry of parafoveal stimulus pairs. Perception and Psychophysics, 26, 363-368.

Chambers, L., & Wolford, G. (1983). Lateral masking vertically and horizontally. Bulletin of the Psychonomic Society, 21, 459-461.

Chun, M. M. (1997). Types and tokens in visual processing: A double dissociation between the attentional blink and repetition blindness, Journal of Experimental Psychology: Human Perception and Performance, 23, 738-755.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. Annual Review of Neuroscience, 18, 193-222.

Di Lollo, V., & Enns, J. T. (1998). Perceiving with and without attention: Competition for consciousness among visual events. Poster presented in the 39th annual meeting of the Psychonomic Society. Dallas, TX.

Di Lollo, V., Enns, J. T., Rensink, R. A. (in press). Psychophysics of reentrant visual pathways: A computational model of object substitution (CMOS).

Enns, J. T., Di Lollo, V. (1997). Object substitution: A new form of masking in unattended visual locations. Psychological Science, 8, 135-139.

Felleman, D. J., & van Essen, D. C. (1991). Distributed hierarchical processing in the primate cerebral cortex. Cerebral Cortex, 1, 1-47.

Hebb, D. O. (1949). Organization of behavior. New York: Wiley.

Hommel, B. (1995). Attentional scanning in the selection of central targets from multi-symbol strings. Visual Cognition, 2, 119-144.

Hunt, S. M. J. (1994). MacProbe: A macintosh-based experimenter’s workstation for the cognitive sciences. Behavior Research Methods, Instruments, & Computers, 26, 345-351.

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

Kahneman, D. (1968). Method, findings, and theory in studies of visual masking, Psychological Bulletin, 70, 404-425.

Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: Object-specific integration of information, Cognitive Psychology, 24, 175-219.

Kanwisher, N., & Driver, J. (1992). Objects, attributes, and visual attention: Which, what, and where. Current Directions in Psychological Science, 1, 26-31.

Kanizsa, G. (1979). Organization in vision: Essays on Gestalt Perception. New York: Praeger.

Kim, M.–S., & Cave, K. R. (1995). Spatial attention in visual search for features and feature conjunctions. Psychological Science, 6, 376-380.

Kim, M.-S., & Cave, K. R. (1999). Top-down and bottom-up attentional control: On the nature of interference from a salient distractor. Perception & Psychophysics, 61, 1009-1023.

Klein, R. (1988). Inhibitory tagging system facilitates visual search. Nature, 334, 430-431.

Luck, S. J., Chelazzi, L., Hillyard, S. A., & Desimone, R. (1997). Neural mechanisms of spatial selective attention in areas V1, V2, and V4 of macaque visual cortex, Journal of Neurophysiology, 77, 24-42.

Luck, S. J., Girelli, M., McDermott, M. T., & Ford, M. A. (1998). Bridging the gap between monkey neurophysiology and human perception: An ambiguity resolution theory of visual selective attention. Cognitive Psychology, 33, 64-87.

Maunsell, J. H. (1995). The brain's visual world: Representation of visual targets in cerebral cortex, Science, 270, 764-768.

Maxwell, S. E., & Delaney, H. D. (1990). Designing experiments and analyzing data: A model comparison perspective. Belmont, CA: Wadsworth Publication Cooperation.

Moran, J., & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. Science, 229, 782-784.

Motter, B. C. (1993). Focal attention produces spatially selective processing in the visual cortical areas V1, V2 and V4 in the presence of competing stimuli. Journal of Neurophysiology, 70, 909-919.

Palmer, S. E. (1992). Common region: A new principle of perceptual grouping. Cognitive Psychology, 24, 436-447.

Palmer, S. E. (1999). Vision science: Photons to phenomenology. Cambridge: MIT press.

Pratt, J., Spalek, T. M., & Bradshaw, F. (1999). The time to detect targets at inhibited and noninhibited locations: Preliminary evidence for attentional momentum. Journal of Experimental Psychology: Human Perception and Performance, 25, 730-746.

Rizzolatti, G., Riggio, L., Dascola, I., & Umilta, C. (1987). Reorieting attention across the horizontal and vertical meridians: Evidence in favor of a premotor theory of attention. Neuropsychologia, 25, 31-40.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. Cognitive Psychology, 12, 97-136.

Turvey, M. T. (1973). On peripheral and central processes in vision: Inferences from an information-processing analysis of masking with patterned stimuli. Psychological Review, 81, 1-52.

Van Essen, D. C., & Maunsell, J. H. (1983). Hierarchical organization and functional streams in the visual cortex. Trends in Neuroscience, 6, 370-375.

Wang, Q., Cavanagh, P., & Green, M. (1994). Familiarity and pop-out in visual search. Perception & Psychophysics, 56, 495-500.

Wolfe, J. M. (1994). Guided search 2.0: A revised model of visual search. Psychonomic Bulletin & Review, 1, 202-238.

Wolford, G. (1975). Perturbation model for letter identification. Psychological Review, 82, 184-199.

Wolford, G., & Chambers, L. (1983). Lateral masking as a function of spacing. Perception and Psychophysics, 33, 129-138.

Wolford, G., & Hollingsworth, S. (1974). Lateral masking in visual information processing. Perception and Psychophysics, 16, 315-320.

Yantis, S. (1996). Attentional capture in vision. In A. F. Kramer, G. H. Coles & G. D. Logan (Eds.), Converging operations in the study of visual selective attention. (pp. 45-76). Washington, DC: American Psychological Association.

Author Note

Yuhong Jiang, Department of Psychology, Yale University; Marvin M. Chun, Department of Psychology and Vanderbilt Vision Research Center, Vanderbilt University.

We thank Bernhard Hommel for useful discussions on alternative accounts of substitution masking, and Karen Arnell for pointing out potential display configuration confounds, which we subsequently ruled out. In addition to Hommel and Arnell, Paul Downing, Nancy Kanwisher, Zoe Kourzi, Lawrence E. Marks, Gail Martino, Kevin O'Connor, Jane Raymond, Brian Scholl, and Yaoda Xu provided many useful comments and suggestions. We thank Jennifer N. Lee for comments and for assistance in running Experiment 5B. This study was supported in part by National Science Foundation grant (BCS-9817349).

Correspondence concerning this article should be addressed to Yuhong Jiang, The John B. Pierce Laboratory, 290 Congress Avenue, New Haven, CT 06519, USA. Electronic mail may be sent via Internet to yuhong.jiang@yale.edu or marvin.chun@vanderbilt.edu.

Footnote

[1] The generality of substitution masking and the asymmetric masking pattern can also be confirmed in terms of where the target letter (and the mask) are presented across the visual field. An analysis of data pooled across several experiments suggests that these effects are consistently obtained at all the eight visual positions tested (e.g., up-right location, left-most location, etc.).

Tables

Table 1. Mean accuracy as a function of mask location (peripheral or central), mask offset time and pre-cue validity in Experiment 1(%; standard error in parenthesis)

Mask offset	Valid cue Peripheral mask	Valid cue Central mask	Neutral cue Peripheral mask	Neutral cue Central mask
Simultaneous offset	94 (4)	96 (2)	87 (3)	91 (4)
Delayed offset	73 (6)	87 (4)	47 (9)	47 (7)
Substitution masking	21 (4)	9 (4)	40 (7)	44 (6)

Table 2. Mean accuracy as a function of mask location and mask offset in Experiment 7 (%; standard error in parenthesis)

Mask offset	Peripheral mask	Central mask
Simultaneous	96.7 (2)	97.5 (2)
delayed	56.7 (7)	84.2 (5)
Substitution masking	40.0 (7)	13.3 (6)

Figure Captions

Figure 1. An example of the four-dot mask and the target similar to that used by Di Lollo and Enns (1998).

Figure 2. Sample displays used in Experiment 1. 2A: same target-mask location; 2B: different target-mask location with central mask; 2C: different target-mask location with peripheral mask.

Figure 3. Presentation sequence used in Experiment 1. Slightly different sequence was used in later experiments (Experiments 2~9). There, the fixation display was followed immediately by the search display without the intermediate pre-cue or the blank interval.

Figure 4. Results from Experiment 1: Accuracy as a function of mask location (target-mask locations same vs. different), pre-cue validity (valid vs. neural) and mask offset (delayed vs. simultaneous offset).

Figure 5. Results from Experiment 2: Accuracy as a function of mask type (four-dot vs. letter ‘N’), mask location (peripheral vs. central mask) and mask offset (delayed vs. simultaneous).

Figure 6. Types of masks used in Experiments 3, 4, and 5.

Figure 7. Results from Experiment 3: Substitution masking as a function of mask category (letter vs. rotated letter).

Figure 8. Results from Experiment 4: Effect of feature similarity between the target and the mask.

Figure 9. Results from Experiment 5-A: Effect of the density of the mask (85-dot, 50-dot, and 15-dot).

Figure 10. Results from Experiment 5-B: Effect of mask density (15-dot and 4-dot).

Figure 11. Sample displays used in Experiment 6. 11A shows a sample of central mask (i.e., peripheral target). 11B shows a sample of peripheral mask (i.e., central target). The mask was presented at the same eccentricity in 11A and 11B.

Figure 12. Results from Experiment 6: substitution masking as a function of target location given that the mask is presented at a fixed eccentricity.

Figure 13. Illustration of the attentional momentum hypothesis.

Figure 14. Results from Experiment 8: Effect of attentional pre-cue on substitution masking and asymmetric substitution.

Figure 15. Results from Experiment 9: Effect of target singleton on substitution masking and asymmetric substitution.

Figure 16. A coarse model of the asymmetric inhibition hypothesis. Darker shading on the central side depicts stronger inhibition.

Figure 17. Results from Experiment 10-A: Effects of target location and ISI on probe detection accuracy and RT.

Figure 18. Results from Experiment 10-B: Effects of target location and ISI on probe detection accuracy and RT.

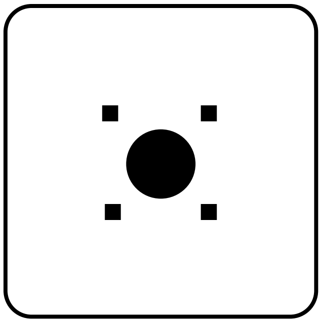


Figure 1.

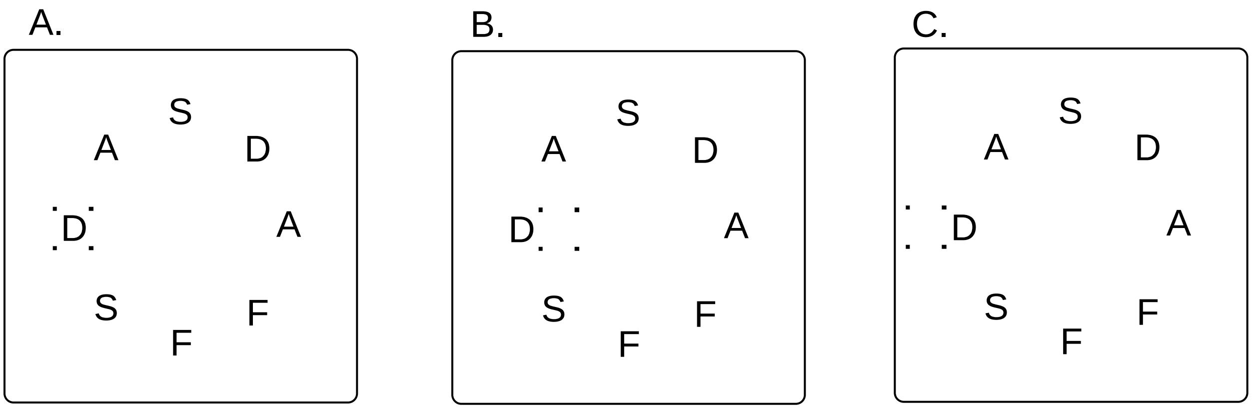
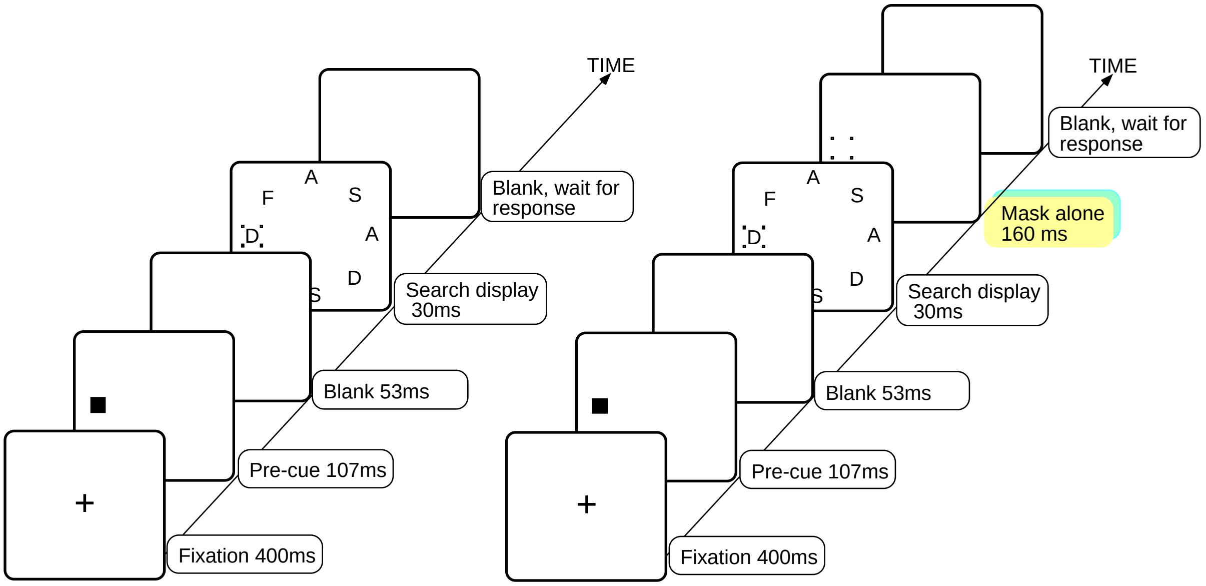


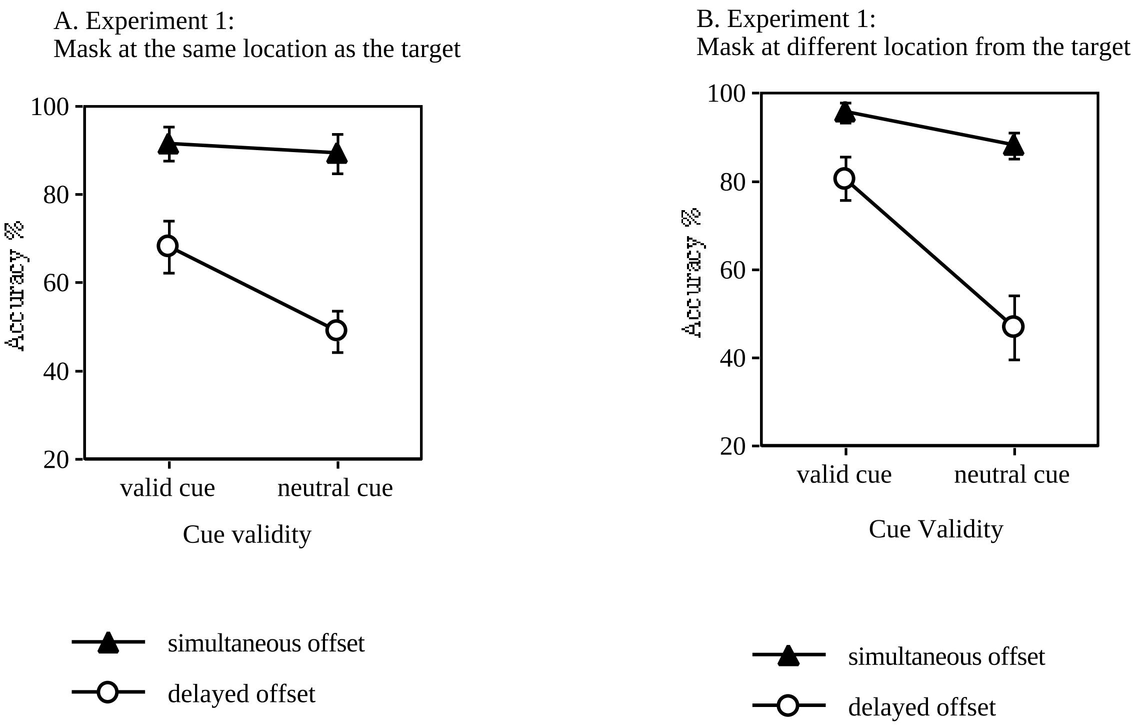
Figure 2.



A. Presentation sequence for the simultaneous offset condition

B. Presentation sequence for the delayed offset condition

Figure 3.


A. Experiment 1:
Mask at the same location as the target

B. Experiment 1:
Mask at different location from the target

Figure 4.

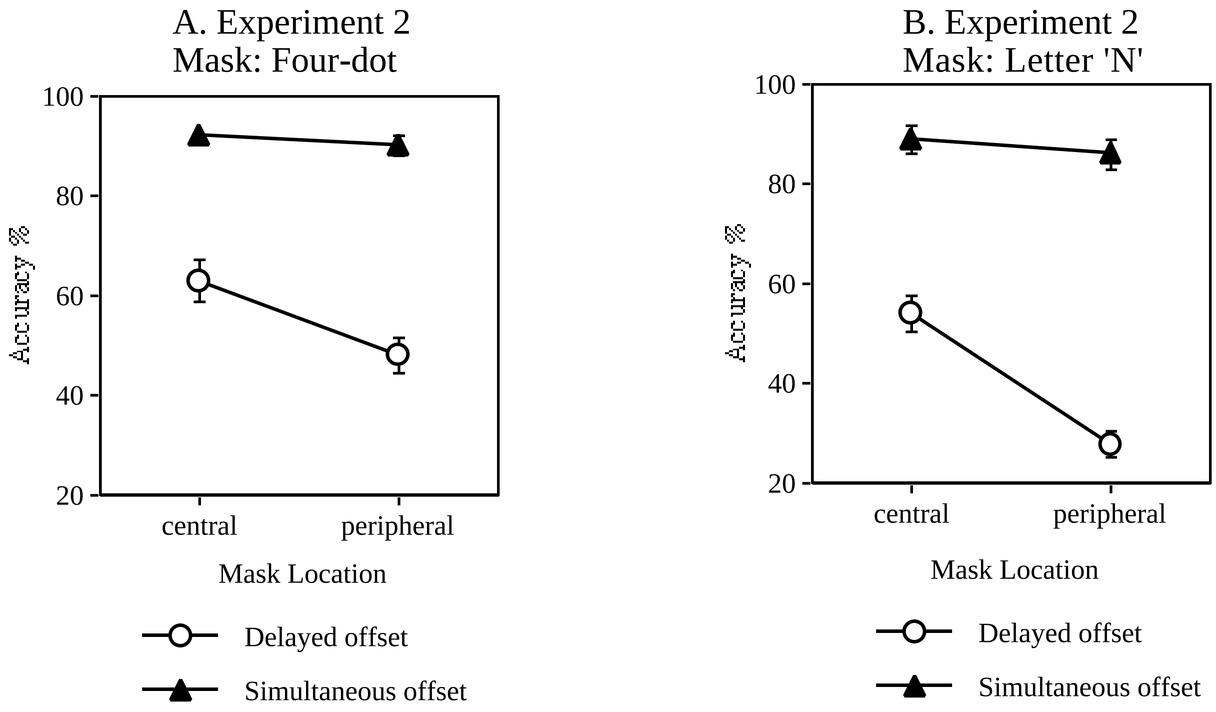

A. Experiment 2
Mask: Four-dot
B. Experiment 2
Mask: Letter 'N'
Accuracy %
100
80
60
40
20
central
peripheral
Mask Location
Delayed offset
Simultaneous offset

Figure 5.

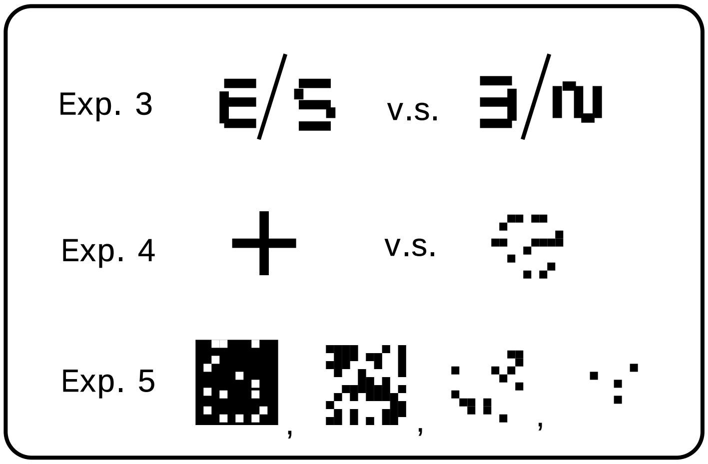


Figure 6.

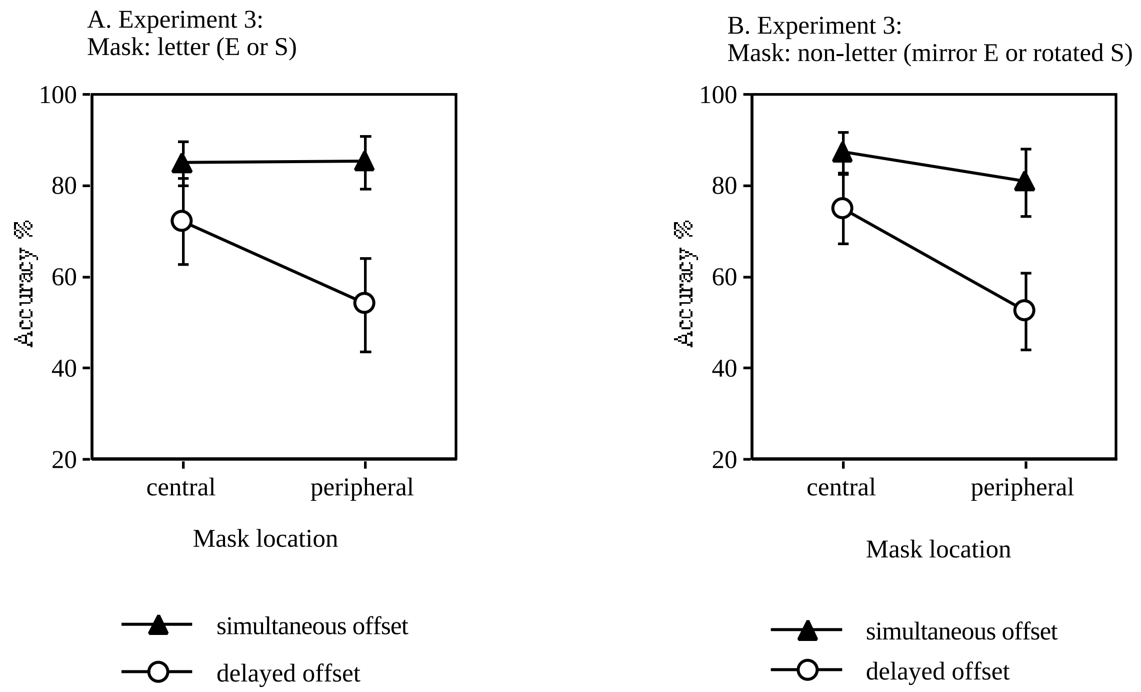

A. Experiment 3:
Mask: letter (E or S)
100
80
60
40
20
Accuracy %
central
peripheral
Mask location
simultaneous offset
delayed offset
B. Experiment 3:
Mask: non-letter (mirror E or rotated S)
100
80
60
40
20
Accuracy %
central
peripheral
Mask location
simultaneous offset
delayed offset

Figure 7.

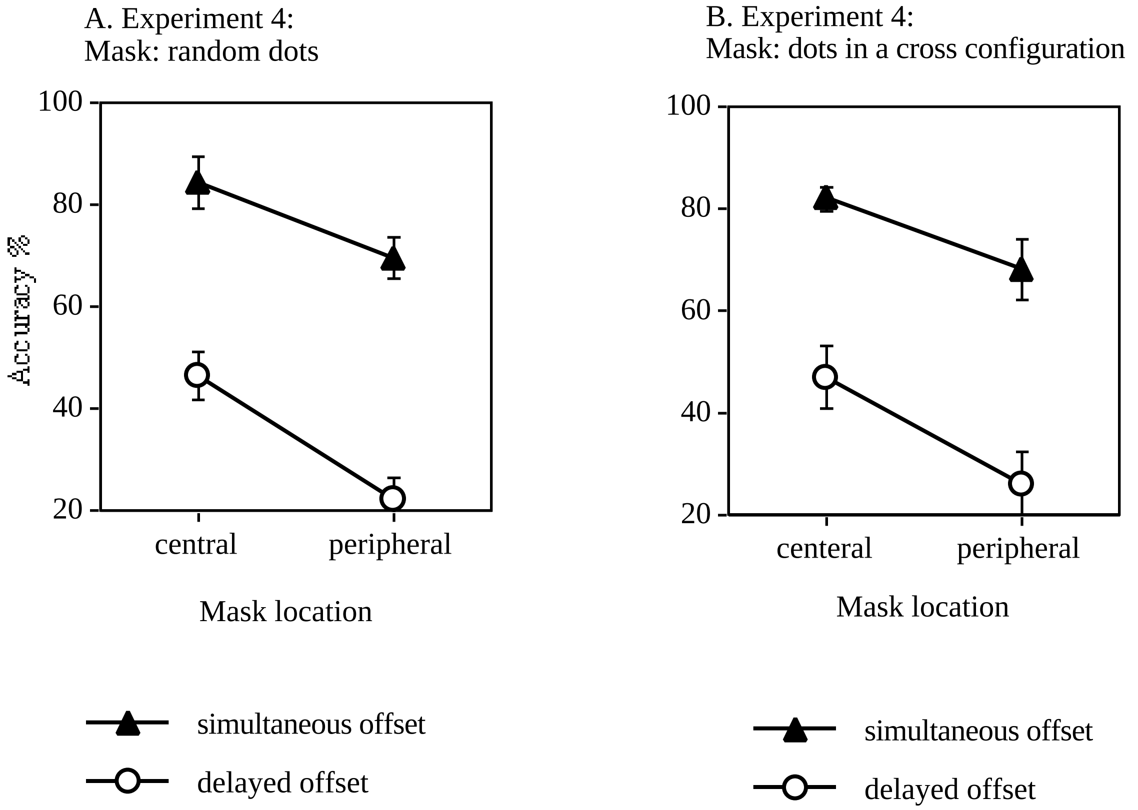

A. Experiment 4:
Mask: random dots
B. Experiment 4:
Mask: dots in a cross configuration
Accuracy %
100
80
60
40
20
central
peripheral
centeral
peripheral
Mask location
Mask location
simultaneous offset
delayed offset
simultaneous offset
delayed offset

Figure 8.

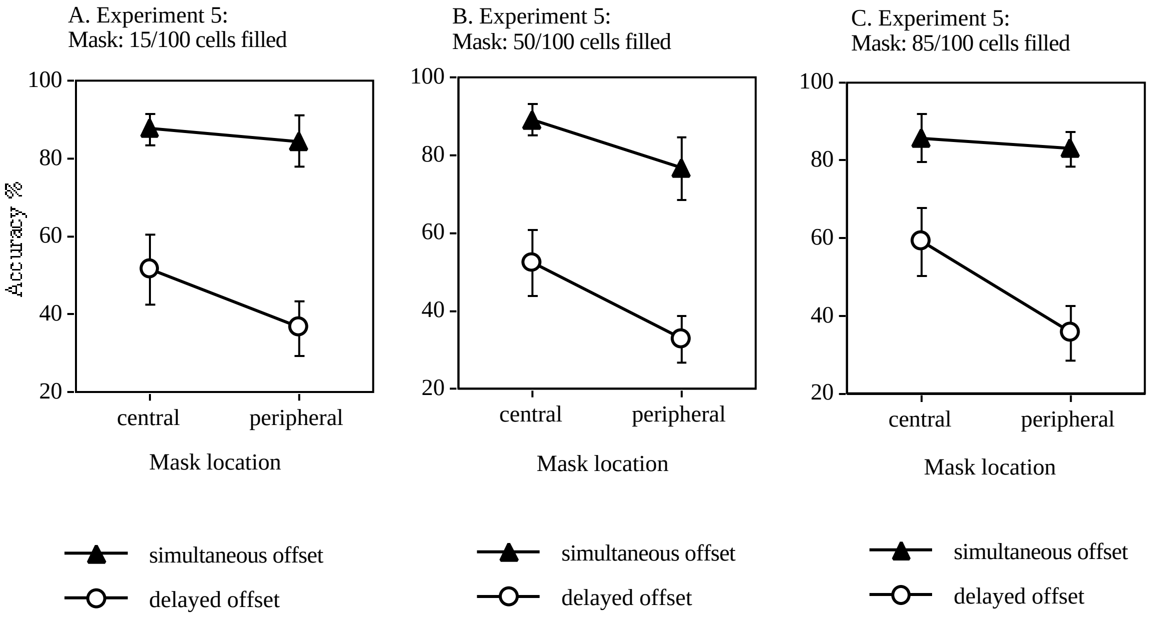

A. Experiment 5:
Mask: 15/100 cells filled
B. Experiment 5:
Mask: 50/100 cells filled
C. Experiment 5:
Mask: 85/100 cells filled
Accuracy %
100
80
60
40
20
central
peripheral
Mask location
simultaneous offset
delayed offset

Figure 9.

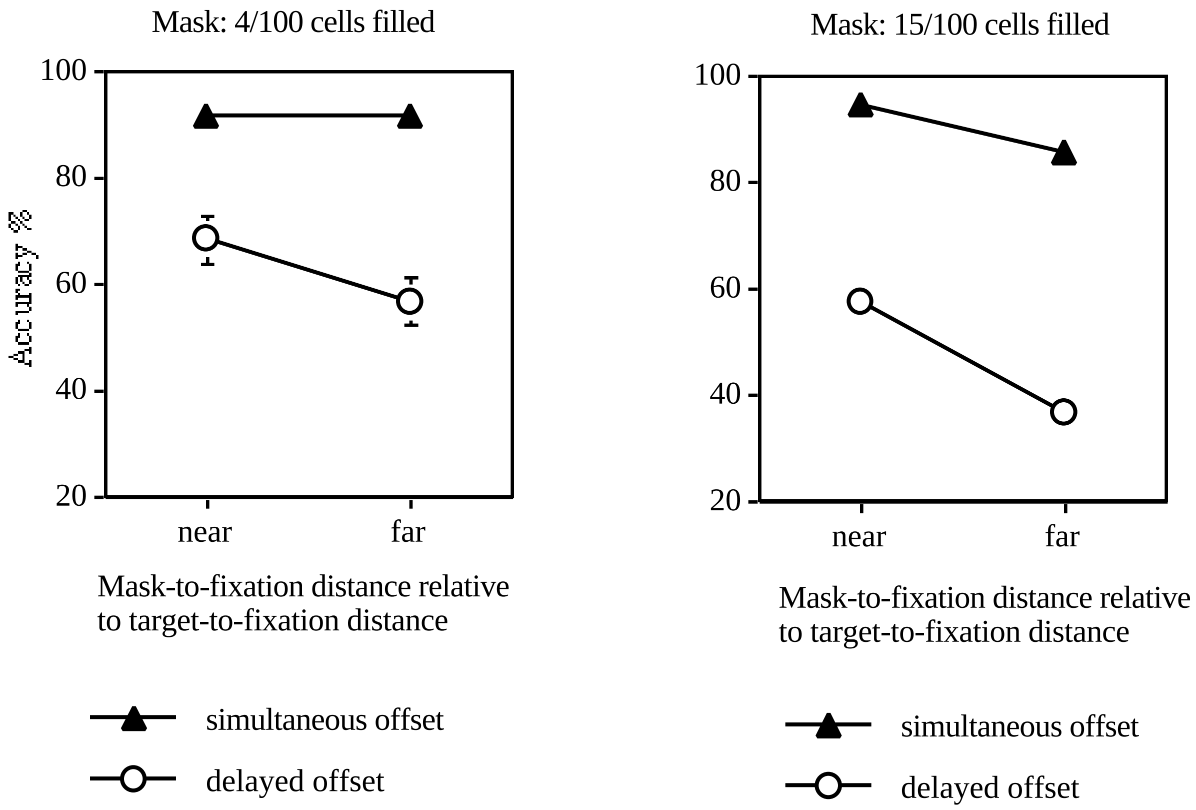

Mask: 4/100 cells filled
Accuracy %
100
80
60
40
20
near
far
Mask-to-fixation distance relative to target-to-fixation distance
simultaneous offset
delayed offset
Mask: 15/100 cells filled
100
80
60
40
20
near
far
Mask-to-fixation distance relative to target-to-fixation distance
simultaneous offset
delayed offset

Figure 10.

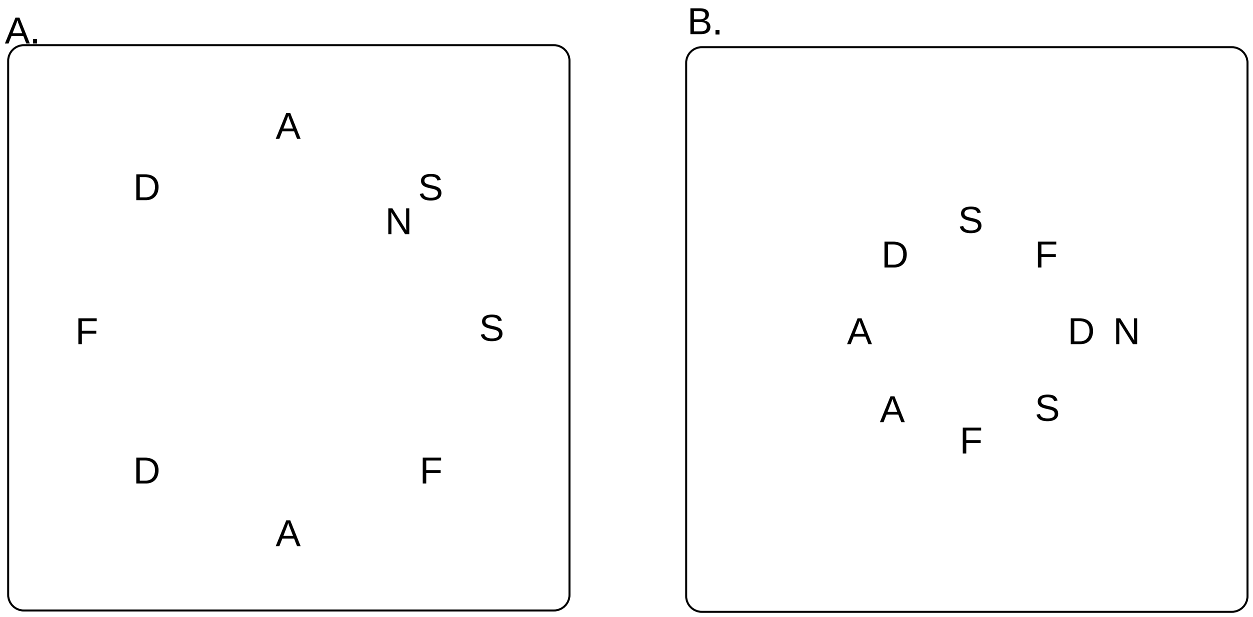


Figure 11.

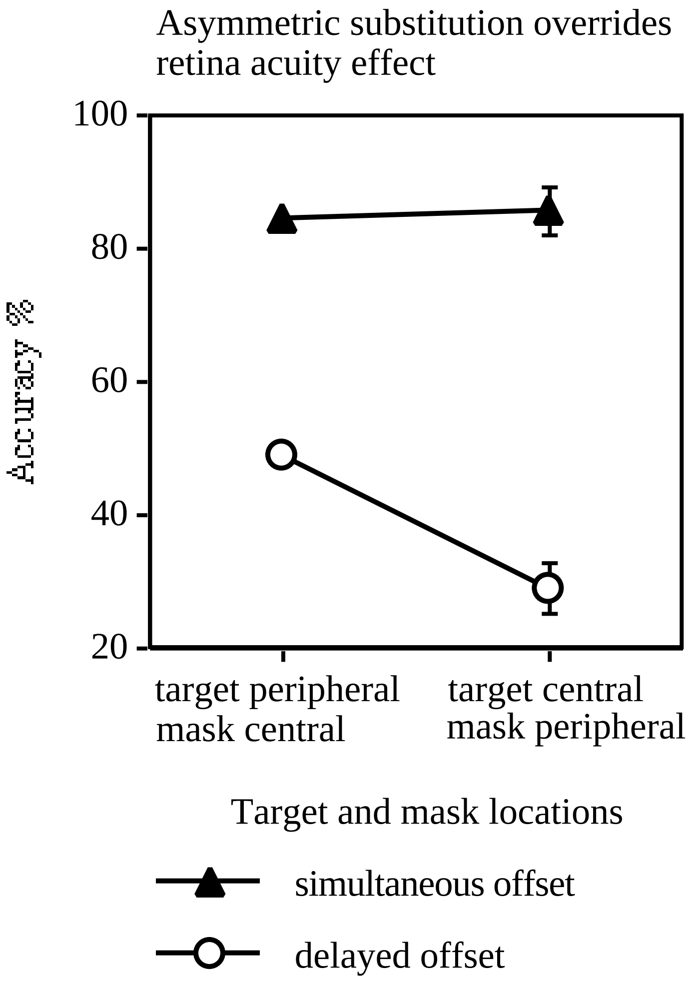
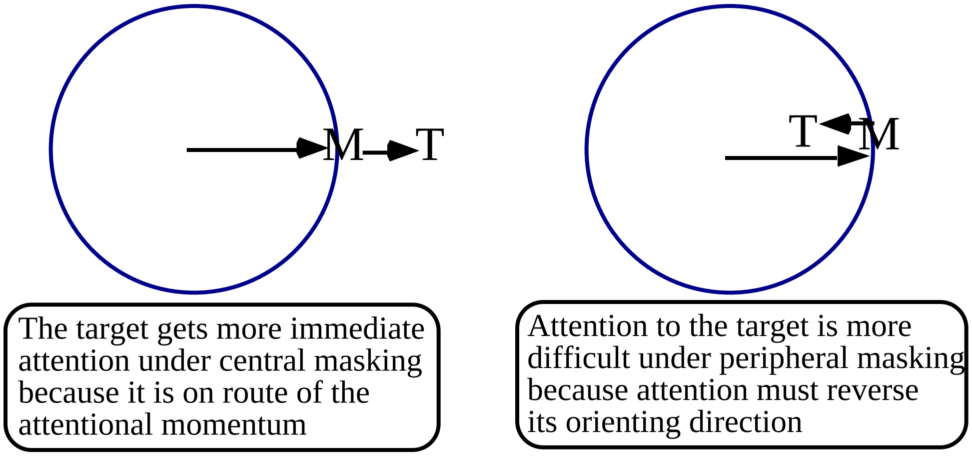

Asymmetric substitution overrides retina acuity effect

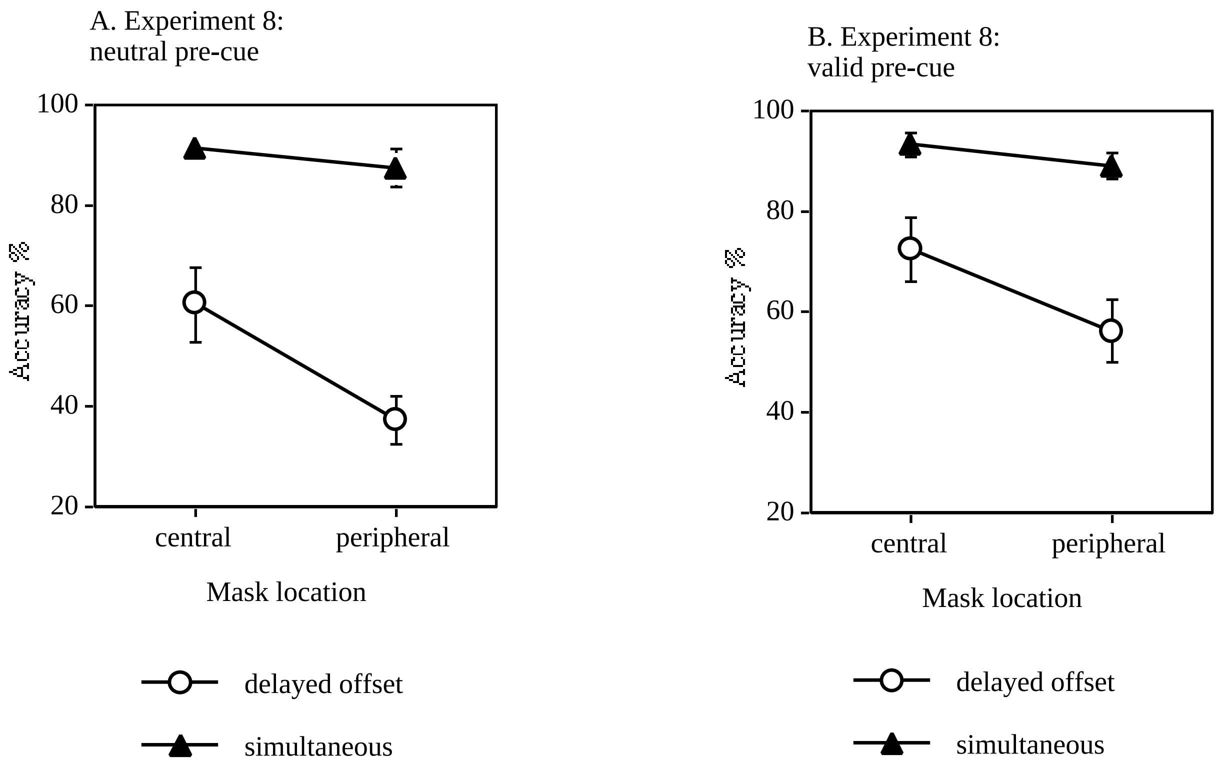
Figure 12.



The target gets more immediate attention under central masking because it is on route of the attentional momentum

Attention to the target is more difficult under peripheral masking because attention must reverse its orienting direction

Figure 13.



A. Experiment 8:
neutral pre-cue

B. Experiment 8:
valid pre-cue

Figure 14.

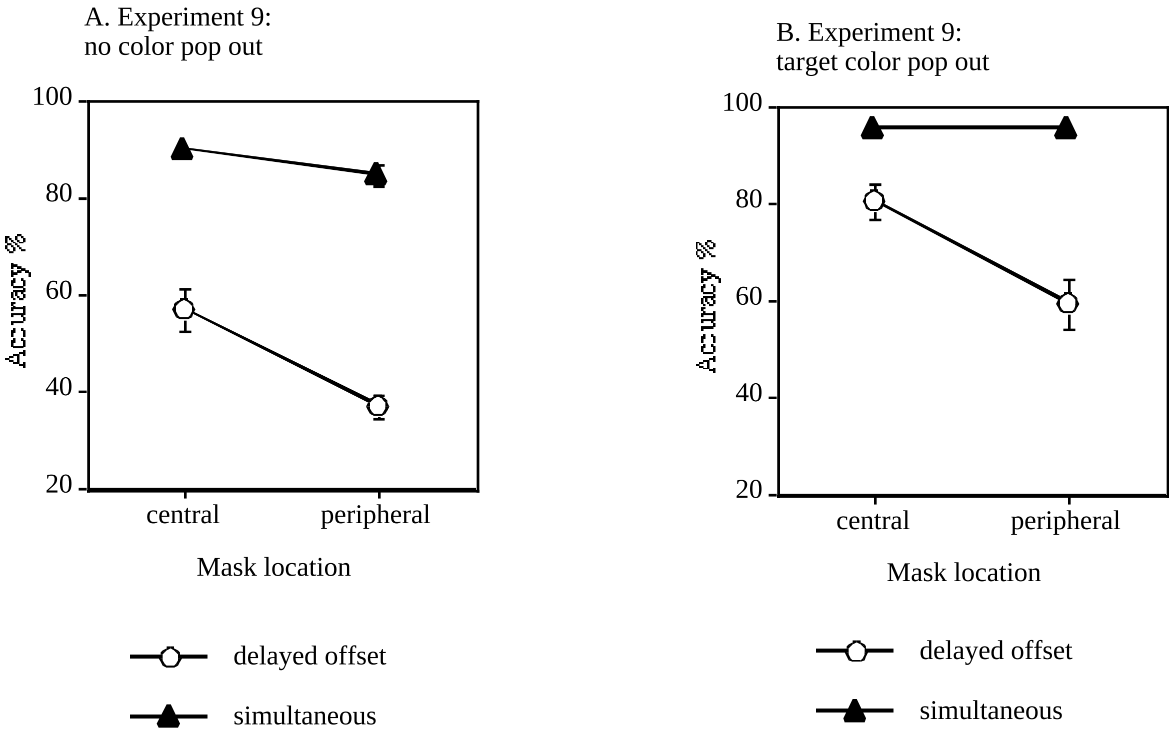

A. Experiment 9:
no color pop out
100
80
60
40
20
Accuracy %
central
peripheral
Mask location
delayed offset
simultaneous
B. Experiment 9:
target color pop out
100
80
60
40
20
Accuracy %
central
peripheral
Mask location
delayed offset
simultaneous

Figure 15.

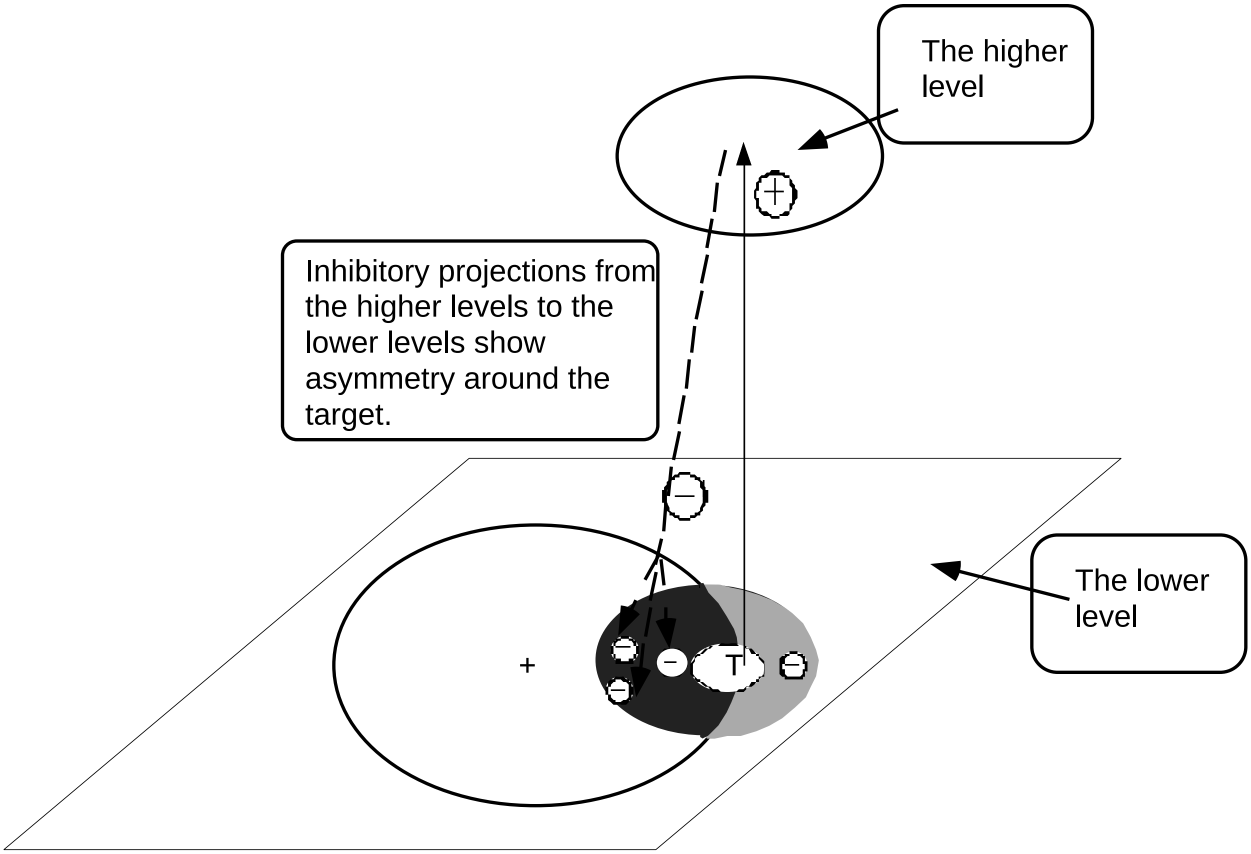
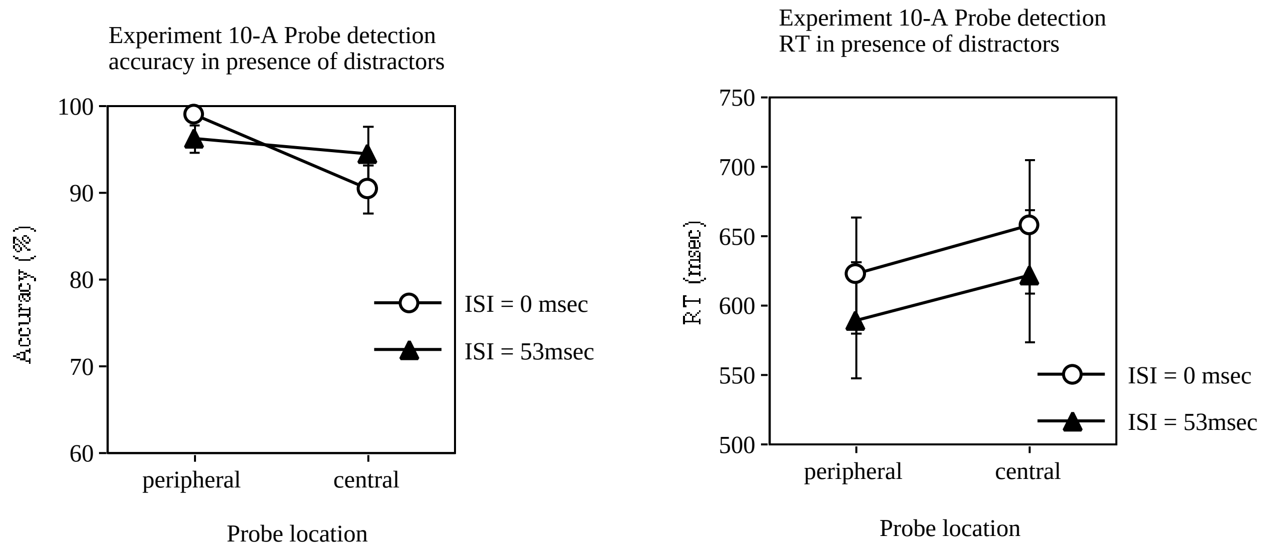

The higher level
Inhibitory projections from the higher levels to the lower levels show asymmetry around the target.
The lower level
+
−
T

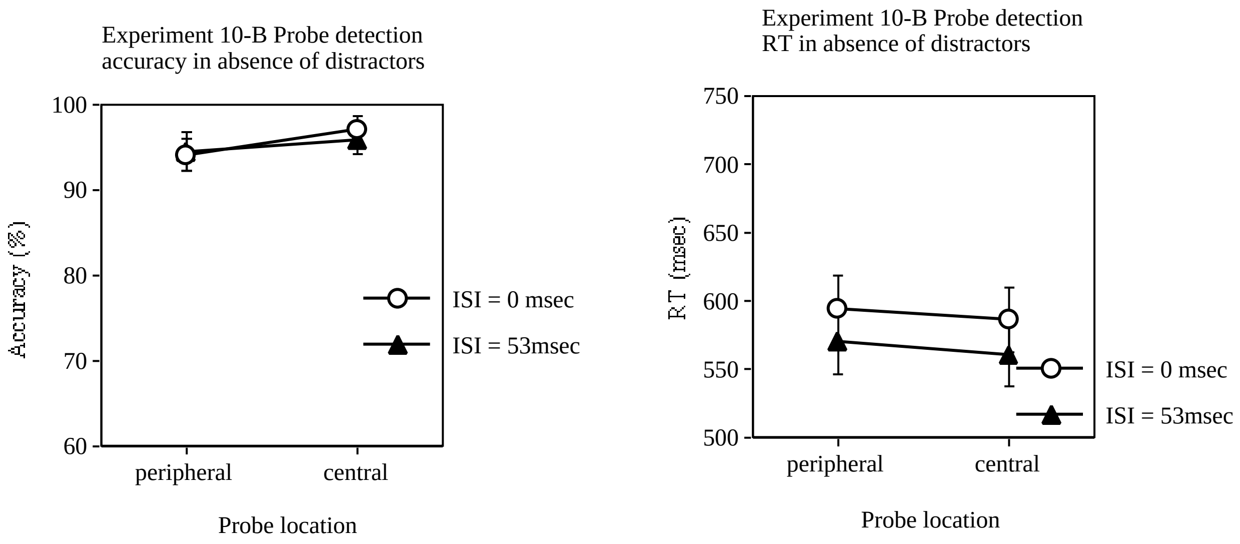
Figure 16.



Experiment 10-A Probe detection accuracy in presence of distractors

Experiment 10-A Probe detection RT in presence of distractors

Figure 17.


Experiment 10-B Probe detection accuracy in absence of distractors

Experiment 10-B Probe detection RT in absence of distractors

Figure 18.