Temporal parameters and time course of perceptual latency priming

Ingrid Scharlau *, Odmar Neumann

Department of Psychology, Bielefeld University, P.O. Box 10 01 31, D-33501 Bielefeld, Germany

Received 7 June 2002; received in revised form 18 November 2002; accepted 9 December 2002

Abstract

Visual stimuli (primes) reduce the perceptual latency of a target appearing at the same location (perceptual latency priming, PLP). Three experiments assessed the time course of PLP by masked and, in Experiment 3, unmasked primes. Experiments 1 and 2 investigated the temporal parameters that determine the size of priming. Stimulus onset asynchrony was found to exert the main influence accompanied by a small effect of prime duration. Experiment 3 used a large range of priming onset asynchronies. We suggest to explain PLP by the Asynchronous Updating Model which relates it to the asynchrony of 2 central coding processes, preattentive coding of basic visual features and attentional orienting as a prerequisite for perceptual judgments and conscious perception.
© 2003 Elsevier Science B.V. All rights reserved.

1. Introduction

Allocating attention to the location of a visual target enhances further processing of this stimulus, resulting in more elaborate, faster or more accurate processing at the expense of other, non-attended stimuli. Research within the peripheral cueing paradigm (Posner, 1980) has established that valid location cues improve accuracy of target identification (Eriksen & Collins, 1969), shorten simple and choice reactions towards the targets (Eriksen & Hoffman, 1972; Posner, 1980; Posner & Cohen,

---

* Corresponding author.
E-mail address: ingrid.scharlau@uni-bielefeld.de (I. Scharlau).

1984), and decrease perceptual latency of the cued targets (Aschersleben, 1999; Hikosaka, Miyauchi, & Shimojo, 1993a,b; Scharlau, 2002; Scharlau & Neumann, in press; Steglich & Neumann, 2000).

Facilitation by a spatial location cue reaches its peak at about 100–200 ms after cue onset (see, e.g., Eriksen & Collins, 1969; Müller & Findlay, 1988; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Posner & Cohen, 1984; Suzuki & Cavanagh, 1997). With longer cueing intervals, this facilitation component declines and may turn into inhibition of the previously attended location (Inhibition of Return, see Gibson & Egeth, 1994; Posner & Cohen, 1984). This temporal course with a fast rise and a slow decay of facilitation has been interpreted as arising from two components of attentional orienting. First, the cue rapidly and automatically causes a transient attentional response. Additionally, a second, sustained component with a slower rise and no decay with time is elicited. This double dynamic was found in the illusory line-motion effect (Hikosaka et al., 1993a,b), discrimination tasks (Müller & Findlay, 1988; Müller & Rabbitt, 1989), visual search and Vernier tasks (Nakayama & Mackeben, 1989), and in the attentional repulsion effect (Suzuki & Cavanagh, 1997).

Most of these studies have used response latency as the dependent variable. By contrast, the time course of cueing effects on perceived latency has rarely been in the focus of research. One exception are studies by Hikosaka and coworkers on the illusory line-motion effect (Hikosaka et al., 1993a,b). In illusory line-motion, the abrupt presentation of a line is preceded by a visible cue at one of its ends. The line is typically perceived as being drawn, or building up, from the cued side, resulting in apparent motion within the line. This effect has been interpreted as reflecting an attentional gradient across the visual field, which is centered at the cue's location. The temporal dynamics of facilitation as measured by the line-motion effect closely resemble those found in cueing studies. However, the line-motion paradigm suffers from a response-bias problem. Observers have the task of judging the motion of a stationary stimulus. In this situation, any salient feature of the stimulus array, such as the presence of a visible cue, or the direction of attention as determined by the instruction, may affect their judgment (Jaskowski, 1993; Pashler, 1998). Further, judgment criteria (leftward or rightward movement) and attentional orientation (left or right) coincide in line-motion studies.

An alternative method of measuring perceptual latency is temporal order judgment. In temporal order judgment studies with attentional manipulation, response bias can be minimized by an orthogonal variation of attended location and judgment criteria: Attention is directed to the left or the right, and judgments are given with respect to the shape of the stimuli, and not their location (Scharlau & Neumann, in press; Shore, Spence, & Klein, 2001). With this method, cueing effects are assessed by comparing the relative perceptual latency of a cued stimulus with that of an uncued stimulus. Studies with this method (Neumann, Esselmann, & Klotz, 1993; Scharlau, 2002; Scharlau & Neumann, in press; Steglich & Neumann, 2000) have revealed a reliable latency effect, termed perceptual latency priming (PLP). A target that is preceded by a masked cue (prime) will be perceived as earlier than a simultaneously presented target at an unprimed location.

Previous studies on PLP have used a masking paradigm in which the prime is visually backward-masked by a target (metacontrast masking). In metacontrast masking, a visual stimulus is masked by a trailing stimulus that is laterally adjacent to it, for example a ring surrounding a disk, or a bar adjacent to a second bar. Metacontrast is strongest with onset intervals of about 40–80 ms (for overviews, see Bachmann, 1994; Breitmeyer, 1984). Though invisible, metacontrast-masked stimuli have been found to exert a strong influence on simple responses (Fehrer & Raab, 1962), choice responses (Eimer, 1999; Klotz & Neumann, 1999; Neumann & Klotz, 1994), and response preparation as measured by the lateralized readiness potential (Eimer & Schlaghecken, 1998). PLP does not critically depend on masking (Scharlau, 2002; Scharlau & Neumann, in press; see also Shore et al., 2001; Stelmach & Herdman, 1991). However, masking is useful in investigations with the temporal order judgment paradigm because the conscious perception of the prime may bias temporal judgment due to a confusion of prime and target or to their perceptual amalgamation (e.g., Pashler, 1998; see below for a further discussion).

PLP has been explained by the asynchrony of two central processes, sensory coding and allocation of attention, as in the Asynchronous Updating Model or AUM (Scharlau & Neumann, in press). According to the AUM, visual information is processed at two levels, a preattentive spatial map containing local descriptions of independent visual features such as colour, orientation or curvature, and an internal model of the environment. The output from the spatial map feeds into processes such as motor activation. If attended, it may also be integrated into the internal model. This internal model comprises a description of the visual environment in terms of objects, scenes and events. Updating of the internal model is slower than updating of the spatial map, and it occurs selectively, as a result of directing attention to a location in the spatial map. The attention shift can be initiated by an abrupt onset or offset within the spatial map that serves as an attention signal.

This asynchrony between the updating of the spatial map and of the internal model can be used to explain PLP. Via its onset signal, the prime causes a shift of attention towards its position in the spatial map. The initiation, execution, and completion of attentional orienting require time. According to the AUM, these processes are a prerequisite for transferring stimulus information into the internal model which serves as basis for conscious perception and perceptual judgments. Since attentional allocation is initiated by the prime, this transfer will be accomplished faster for a primed target than for an unprimed target. Thus, the perceived onset of the primed target is predated relative to its unprimed counterpart. This model also predicts other visual effects such as metacontrast masking (Bachmann, 1994, 1999; Breitmeyer, 1984), the Fröhlich effect (Aschersleben & Müsseler, 1999), and the tandem effect (Müsseler & Neumann, 1992).

According to the AUM, the amount of PLP depends on the time between the attentional signal elicited by the prime's onset and the onset of the target, that is, on stimulus onset asynchrony (SOA). The effect should increase as long as the priming SOA is smaller than the time needed for attentional orienting. In this range of SOAs, the effect size should not be much smaller than the priming SOA available for the

attentional shift provided that the prime is able to attract attention in every trial. With longer SOAs, PLP should remain constant.

The time course of PLP has so far not been systematically explored. In previous studies in which only a few SOAs were employed (Scharlau, 2002; Scharlau & Neumann, in press; see also Hikosaka et al., 1993a), PLP amounted to approximately half the priming SOA. For example, Scharlau (2002) and Scharlau and Neumann (in press) found PLP in the range of 33–40 ms with priming intervals of 64 ms. A similar relationship between priming interval and PLP was found with other priming intervals (Neumann et al., 1993; Steglich & Neumann, 2000), and in other experimental tasks such as tapping synchronization (Aschersleben, 1999). However, the range of priming SOAs tested has rarely exceeded 100 ms.

The present experiments examine the time course of PLP and test the AUM's explanation of this priming effect as an attentional allocation response caused by the prime's onset. Experiments 1 and 2 were concerned with the question which temporal parameters of the prime–target sequence best predict PLP. Previous studies have only assessed the influence of SOA and thus may have failed to notice other temporal relationships that affect perceived latency in a prime–target sequence. Experiment 1 looked into a possible effect of target offset that has been found to influence temporal order judgment in an earlier study (Jaskowski, 1992). An influence of target offset could explain why PLP is typically smaller than the priming SOA. Experiment 2 assessed in more detail differential effects of several interrelated temporal parameters (SOA, prime duration, target duration, interstimulus interval and stimulus termination asynchrony). According to the AUM, PLP is exclusively determined by the SOA between prime and target, since this parameter determines the start of the attention shift. Alternatively, PLP could be explained as an effect of an amalgamation of prime and target into a compound stimulus. This explanation predicts an influence of target duration on PLP. A further possibility is that the interstimulus interval which was perfectly correlated with the priming SOA in most previous studies, is the relevant variable. Finally, it has been suggested that backward masking may best be predicted by stimulus termination asynchrony (Macknick & Livingstone, 1998). Thus, this parameter is also a possible candidate for an effect on PLP. Experiment 2 compared the influence of these parameters with the influence of priming SOA. In Experiment 3, the impact of priming SOA was investigated over a broad range of intervals covering the transient as well as the sustained component of attentional effects that have been found in previous studies (Müller & Findlay, 1988).

2. Experiment 1

Several studies have demonstrated PLP in the temporal order judgment paradigm (Neumann et al., 1993; Scharlau, 2002; Scharlau & Neumann, in press; Steglich & Neumann, 2000; for studies with unmasked primes see also Shore et al., 2001; Stelmach & Herdman, 1991). The latency effect revealed in these studies was consistently smaller than the priming SOA. Experiment 1 addressed the question why the effect did not reach the size of the whole priming SOA. The hypothesis that we examined

was that the effect itself is equal to the priming SOA, but that it was reduced by factors specific to the experimental conditions in these earlier experiments.

According to the AUM, the processing of the target is accelerated in primed trials because the prime induces an attentional shift towards the location of the prime. Irrespective of whether the priming SOA suffices to complete the attentional allocation or not, target processing should thus profit from the whole priming SOA. A factor which may reduce the size of this effect is target offset. Because the targets were typically presented for a short, invariant duration, it was in principle possible to judge the temporal order of offsets instead of onsets. Since, according to the AUM, the offsets are not influenced by a prime, this will reduce the priming effect if participants occasionally base their judgment on offsets rather than onsets. Jaskowski (1991) has indeed reported that—unlike reaction time—temporal order judgment depended not only on stimulus onset, but also on stimulus offset. In order to asses this influence, target pairs with offsets were compared with pairs without offsets. If offsets influence PLP in the described manner, then target duration should interact with PLP, with larger amounts of PLP for no-offset targets.

2.1. Method

Participants. Eleven volunteer participants (five female; mean age: 26.9 years) took part in the experiment and received € 6 or course credits. All participants had normal, or corrected-to-normal vision.

Apparatus. The experiment was controlled by a computer. Stimuli were presented in dark grey (14 cd/m^2) on a light grey background (103 cd/m^2) on a 17 in. colour monitor (60 Hz vertical frequency, 640 × 480 pixels). Participants sat upright in front of the monitor in a dimly lit room with the center of the monitor at eye level. They responded by means of a serial mouse which was operated with two fingers of the dominant hand. A chin rest fixed viewing distance at 60 cm.

Stimuli. The target pair consisted of a square and a diamond (see Fig. 1). These stimuli allow good metacontrast masking. Side length of the targets was 2.3 deg, and the distance between the stimuli was 12.5 deg. The target pair was presented horizontally either above or below the center of the screen. One of the targets was
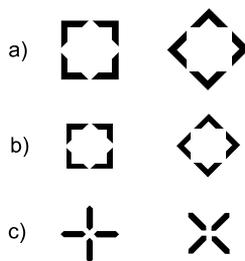

Fig. 1. Stimuli employed in the experiments. Row (a) depicts the targets, and (b) the respective metacontrast-maskable primes of Experiments 1 and 2. Row (c) illustrates the unmasked primes used in Experiment 3. Each prime is depicted below the associated target.

preceded by a prime. The prime was a smaller replica of the primed target. It was presented for 32 ms. The interval between the prime and the target was 64 ms (priming SOA). The temporal intervals between the onsets of targets were −128 to +128 ms in steps of 32 ms (target SOA). Negative numbers indicate that the primed comparison stimulus preceded the standard stimulus. Target duration was either 32 ms, or targets were presented without offsets until the judgment was made (for a sample trial, see Fig. 2). With 32 repetitions of each of the 36 conditions (nine target SOAs × two priming conditions × two target duration conditions), the experiment consisted of 1152 trials. All non-experimental variables (presentation above/below fixation, right/left location of first target, right/left location of prime, primed shape square/ diamond, target SOA) and experimental variables (target with/without offsets, with/ without prime) were presented in a random order with the method of constant stimuli.

Procedure. Participants were instructed to fixate on the center of the screen which was marked by a fixation point throughout each trial. They judged the temporal order of two visual stimuli presented at short temporal intervals. Half of the participants responded with the right mouse button when they saw the square first, and with the left one if the diamond was perceived first. This assignment was reversed for the other half of the participants. The instruction emphasized accuracy. Before
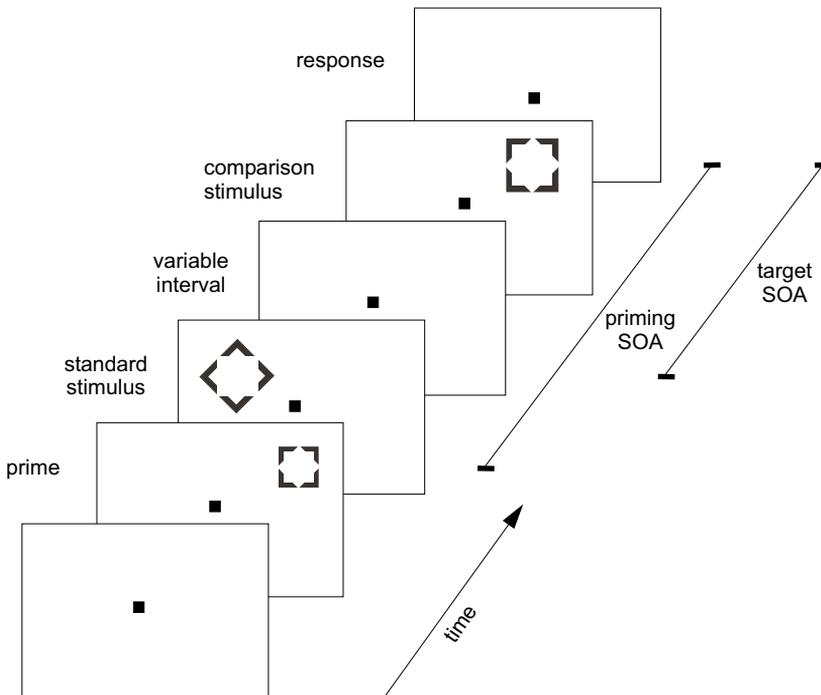

Fig. 2. Succession of events in a sample trial of Experiment 1. Stimuli are not drawn to scale.

the experimental part, participants had the opportunity to practice the task. In these practice trials, no primes were presented. In the experimental part, participants could have breaks whenever they needed. The session lasted about 60 min.

2.2. Results

The primed stimulus was defined as the comparison stimulus and the unprimed stimulus as the standard stimulus. To construct psychometric functions, the frequency of the judgment ''standard stimulus first'' was determined for each combination of SOA, priming (primed/unprimed) and target duration (offset/no offset). Logit analysis, a parametric procedure for estimating the parameters of the psychometric function (Finney, 1971), was used to estimate the point of subjective simultaneity (PSS) and the difference limen (DL) for each participant. PSS is the threshold value at which the two judgments are equally likely, and DL is defined as the mean slope in the inner quartiles of the psychometric function. If necessary, degrees of freedom in the ANOVAs were corrected by the Greenhouse–Geisser-coefficient ε, and alpha was adjusted accordingly (Hays, 1988).

As can be seen from Fig. 3, psychometric functions differed largely as a function of priming, but only marginally with target duration. Priming caused a horizontal shift of the psychometric distributions, indicating that when the comparison stimulus was primed it was perceived as the first one even in trials in which it trailed the unprimed standard stimulus. The ANOVA revealed that priming strongly influenced PSS ($F[1, 10] = 33.96$, $p < 0.001$). There was no influence of offset condition on PSS ($F < 1$). The interaction of priming and offset just reached significance ($F[1, 10] = 5.53$, $p < 0.05$), pointing to a somewhat larger priming effect in the offset condition. Cohen's (1977) d for the priming effect was 2.78 which indicates a strong effect. PSS were 8 ms (no offset) and 3 ms (offset) in the unprimed conditions and 39 and 46 (offset) in the primed conditions. PLP thus was 31 ms without offsets and 43 ms with offsets.
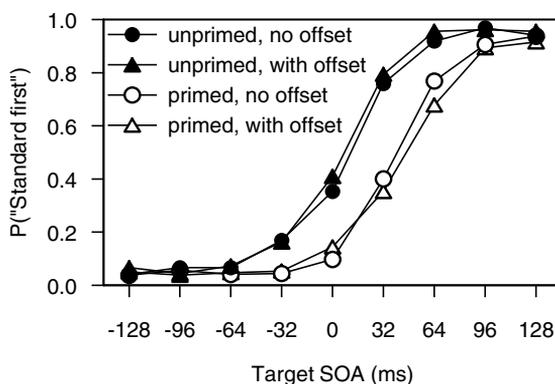

Fig. 3. Results of Experiment 1.

No main effects on DL were found (offset: $F[1, 10] = 1.32$, $p = 0.27$; priming: $F[1, 10] = 1.25$, $p = 0.29$). However, there was a significant interaction of offset and priming ($F[1, 10] = 10.17$, $p < 0.01$). Again, this was due to an increased DL in the primed/offset condition (43 ms), whereas in all other experimental conditions, DLs were virtually identical (34 and 35 ms).

2.3. Discussion

Offsets did not exert a strong influence on PLP. There was a small interaction, but it is not in line with the considerations mentioned in the introduction. There, it was reasoned that target offsets might reduce PLP, since, according to the AUM, they are unaffected by priming. Stimuli without offsets should therefore induce a larger priming effect. However, the small interaction of offset condition and priming found in Experiment 1 was in the opposite direction. Thus, an effect of offsets on order judgment can be ruled out as the reason why PLP has been found to amount to less than the full prime–target SOA.

3. Experiment 2

The sequence of the onsets and offsets of prime and target may be alternatively characterized by two sets of three parameters each: either SOA, prime duration and target duration, or SOA, interstimulus interval and stimulus termination asynchrony. According to the AUM, SOA is the critical parameter for the PLP effect since it is the transient signal of the prime which elicits the attention shift. However, in the previous studies that have employed this paradigm, this prediction has not yet been explicitly tested (Neumann et al., 1993; Scharlau, 2002; Scharlau & Neumann, in press; Steglich & Neumann, 2000).

Alternative explanations of PLP predict that other variables should influence the effect. PLP may be explained by an amalgamation of prime and target into a compound stimulus (see, e.g., Pashler, 1998) with a perceptual center (see Scott, 1998) in between the prime's onset and the target's offset. If observers indeed judged the perceptual center or functional onset, perceived order should depend on target duration since this parameter will influence the perceptual center. Experiment 1 did not test this alternative explanation, since there was only one offset condition, and the no-offset condition rendered the use of offsets for defining a perceptual center impossible. Experiment 2 used two different target durations to examine the amalgamation hypothesis. A second alternative explanation of the PLP effect is based on the finding that the size of the effect amounted to approximately half the priming SOA. This was equivalent to the interstimulus interval between prime and target in previous studies (e.g., Scharlau & Neumann, in press). Experiment 2 employed two different prime durations to control for an interstimulus interval effect. Third, Macknick and Livingstone (1998) reported that backward masking is best predicted by stimulus termination asynchrony of prime and target, that is, by the relationship between their offsets. This psychophysical finding was related to physiological recordings from the pri-

mary visual cortex of rhesus monkeys. Backward masking was found to inhibit the after-discharge of neurons. Macknick and Livingstone (1998) concluded that the after-discharge was particularly relevant for stimulus visibility. Experiment 2 was designed to control for a stimulus termination asynchrony effect on PLP by varying both prime duration and mask duration.

3.1. Method

Participants. Twelve volunteer participants (ten female; mean age: 25.6 years) took part in the experiment and received € 8 or course credits. All participants had normal, or corrected-to-normal vision. One participant showed no discrimination of order (flat psychometric distribution). His data were eliminated from the analysis.

Apparatus did not differ from Experiment 1.

Stimuli. Stimuli were the same as in Experiment 1 with the following exceptions. Each target appeared in one randomly chosen quarter of the screen 8.5 deg from the center. The temporal intervals between the targets were −96 to +96 ms in steps of 64 ms (target SOA). In two-thirds of the trials, a prime preceded one of the targets. The SOA between the prime and the target was either 48 or 80 ms (priming SOA). In half of the primed trials, the prime was presented for 16 ms, in the other half it was presented for 48 ms (prime duration) so that the interstimulus interval was 32 or 0 ms in the conditions with short priming SOA and 64 or 32 ms in the conditions with long priming SOA. Targets were presented for 64 or 128 ms (target duration). Thus, the experiment had, apart from target SOAs (four conditions), 12 experimental conditions (three priming conditions (without prime, short vs. long priming SOA) × two prime duration conditions × two target duration conditions). With 36 repetitions of each of the 12 conditions and four target SOAs, the experiment consisted of 1728 trials which were divided into two sessions. Target pairs were again presented with the method of constant stimuli.

Procedure did not differ from Experiment 1, except that there were two sessions of about 40 min each.

3.2. Results

Thresholds and performance parameters were computed as in Experiment 1. As can be seen from Fig. 4, the psychometric distributions differ between experimental conditions. The distribution for the longer priming SOA is shifted towards the right relative to the function for the smaller priming SOA, and both functions are displaced with respect to the unprimed trials.

A three-way ANOVA of individual PSS revealed a highly significant effect of priming SOA ($F[2, 20] = 137.39$, $p < 0.0001$; $\varepsilon = 0.67$). No other main effect or interaction reached significance (prime duration: $F[1, 10] = 2.85$, $p = 0.12$; target duration: $F[1, 10] = 1.87$, $p = 0.20$; all two-way interactions $F < 1$; three-way interaction $F[2, 20] = 1.39$, $p = 0.27$; $\varepsilon = 0.92$). Cohen's *d* for the priming effect was 1.24 for the
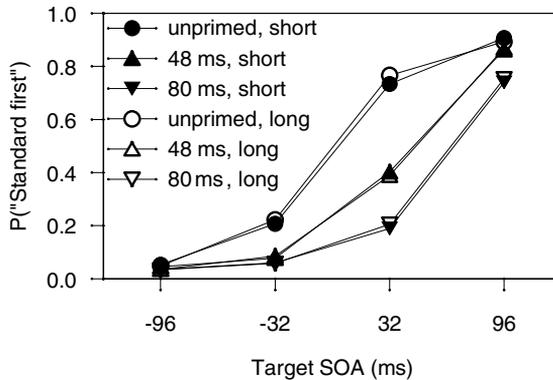
Fig. 4. Results of Experiment 2.

smaller priming SOA and 2.61 for the larger priming SOA. Mean PSS were 7 ms in the unprimed condition, 42 ms with priming SOA 48 ms and 68 ms with priming SOA 80 ms, which results in priming effects of 35 and 61 ms, corresponding to 73% and 85% of the respective priming SOA.

However, this analysis may not be an appropriate test of the alternative explanations, because unprimed conditions were included. Therefore, the three-way ANOVA was repeated with only the primed conditions. Again, there was a highly significant effect of priming SOA ($F[1, 10] = 131.67$, $p < 0.001$). Prime duration just reached significance ($F[1, 10] = 5.06$, $p < 0.05$), whereas mask duration did not ($F[1, 10] = 1.75$, $p = 0.22$). No interaction reached significance (all $F < 1$). PSS were 54 ms for the short prime duration and 56 ms for the long prime duration.

For DL, all main effects and interactions failed to reach significance (all $F < 1$) with the exception of prime duration which was marginally significant ($F[1, 10] = 6.5$, $p < 0.05$). DL was smaller, that is, performance better, with the short than with the long prime duration (35 vs. 38 ms).

3.3. Discussion

The results of Experiment 2 are clear: Priming SOA exerted the strongest influence on perceptual latency. Prime duration had a small effect of 2 ms, with a larger impact of the longer prime duration. One possible explanation for this latter influence is that attention can be more easily focussed on a location if it contains a stimulus rather than being blank. Another possibility is that longer primes had a stronger effect because of energy summation. No other variable affected perceived temporal order. This is evident for target duration which did not yield significant main effects. However, it can also be concluded with respect to the two other variables mentioned in the introduction, interstimulus interval and stimulus termination asynchrony. Effects of interstimulus interval would have shown up in a prime duration × priming SOA

interaction. The interstimulus interval was 32 ms in two of the experimental conditions (prime duration 16 ms and priming SOA 48 ms; prime duration 48 ms and priming SOA 80 ms), zero with prime duration and priming SOA 48 ms, and 64 ms with prime duration 16 ms and priming SOA 80 ms. Effects of stimulus termination asynchrony should have likewise yielded an interaction of prime duration and target duration. Neither of these interactions was found.

Experiments 1 and 2 thus warrant the conclusion that PLP depends on the priming SOA and is slightly modified by prime duration. Except for this latter influence which is numerically small these results are in line with the AUM according to which PLP is due to an attention shift elicited by the masked prime. Experiments 1 and 2 did not yield evidence on why the size of PLP is smaller than the priming SOA. However, the PSS shift found here was larger in relative size than that found in previous experiments. In the studies by Scharlau (2002) and Scharlau and Neumann (in press), it amounted to half the priming SOA which was 64 ms. By contrast, Experiment 2 yielded an effect that was not much smaller than the priming SOA. The reasons for this discrepancy remain to be explored.

It should be noted, though, that the standard stimulus may be a critical factor for the size of PLP compared with priming SOA. Consider, for example, the case in which the standard stimulus precedes the comparison stimulus by 64 ms and the priming SOA is also 64 ms (Experiment 1). In this case, the prime and the standard stimulus are presented simultaneously and compete for attentional allocation. In some trials the prime will ''win'' this competition, and in some cases the standard stimulus will win. PLP will be diminished in the latter trials. If the standard stimulus leads the prime, the latter has an even smaller chance of capturing attention. A related argument holds for trials in which the prime precedes the standard stimulus which in turn leads the comparison stimulus (e.g., target SOA 32 ms with priming SOA 64 ms or target SOA 64 ms with priming SOA 96 ms in Experiment 1). In short, the impact of the prime on the processing of the target may be reduced to the degree to which it competes with the standard stimulus for the allocation of attention.

4. Experiment 3

Experiments 1 and 2 have supported the AUM's prediction that the prime's onset is mainly responsible for PLP and that therefore the priming SOA is the critical parameter. Experiment 3 looked more closely into the time course of PLP. The priming SOA was varied over a range of intervals ranging from 7 to 224 ms, including the transient as well as the sustained components of attentional orienting as suggested by experiments with the cueing paradigm (e.g., Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989). According to the AUM, the absolute amount of PLP should first rise with priming SOA since the larger the priming SOA, the more the time for initiation, execution and completion of the attentional shift. However, when the priming SOA has become large enough so that attentional allocation can be completed within the SOA (e.g., Müller & Findlay, 1988; Müller & Rabbitt, 1989;

Nakayama & Mackeben, 1989), there should be no additional gain when it is further increased. PLP should therefore remain constant with larger SOAs.

4.1. Method

Participants. Nineteen volunteer participants (nine female; mean age: 27.7 years) took part in the experiment and received € 9 or participated in fulfilment of course requirements. All participants had normal, or corrected-to-normal, vision. The data of one participant had to be discarded because of insufficient instruction; two participants did not show up for the second session and their data from the first session were not analysed.

Apparatus did not differ from Experiments 1 and 2 with the exception that the vertical frequency of the monitor was 145 Hz.

Stimuli. Targets were the same as in the previous experiments. Primes were replaced by crosses (see Fig. 1, row c). With the largest priming SOAs, the primes were easily visible even if laterally adjacent to the targets which posed the problem of preventing participants from confusing primes and targets in their judgment. This might have resulted in artificial differences between the priming SOAs in which the primes were maximally masked (a range of 40–80 ms, see Breitmeyer, 1984) and shorter or larger priming SOAs where masking is impaired. Thus, we abandoned masking and used cross-shaped primes that are essentially unmaskable by our targets and can be easily discriminated from them. In an earlier study, we found that PLP by masked primes and unmasked crosses is of the same size (Scharlau & Neumann, in press, Experiment 3; see Fig. 1). Target SOAs ranged from −126 to +126 ms in steps of 42 ms. Priming SOAs were 7, 14, 28, 56, 112, and 224 ms plus a condition in which no primes were presented. Primes were presented for 7 ms, and targets were presented until the judgment was made. There were 49 experimental conditions (seven target SOAs × seven priming SOAs). Each condition was repeated 16 times in each session, resulting in a total of 784 trials per session.

Procedure was identical to that in Experiments 1 and 2 except that participants were instructed to ignore the prime. This was necessary because the prime was visible.

4.2. Results

Fig. 5 depicts the psychometric functions. As can be seen, there is no horizontal shift of the psychometric functions with priming SOAs smaller than 28 ms. With larger SOAs, the horizontal shift increases up to a maximum at an SOA of 56 ms.

Individual PSS and DL were entered into a one-way ANOVA. There was a significant effect of priming on PSS ($F[6, 90] = 13.02$, $p < 0.001$; $\varepsilon = 0.33$). PLP values were computed by subtracting individual PSS in the unprimed condition from the respective values with priming. For each SOA, a one-tailed t-test of PLP values against zero was computed. For the two smallest priming SOAs, no significant PLP was found (7 ms: $t[15] < 1$; 14 ms: $t[15] = 1.63$, $p = 0.12$). All other PLP effects differed significantly from zero (28 ms: $t[15] = 5.22$, $p < 0.001$, Cohen's $d = 1.79$; 56
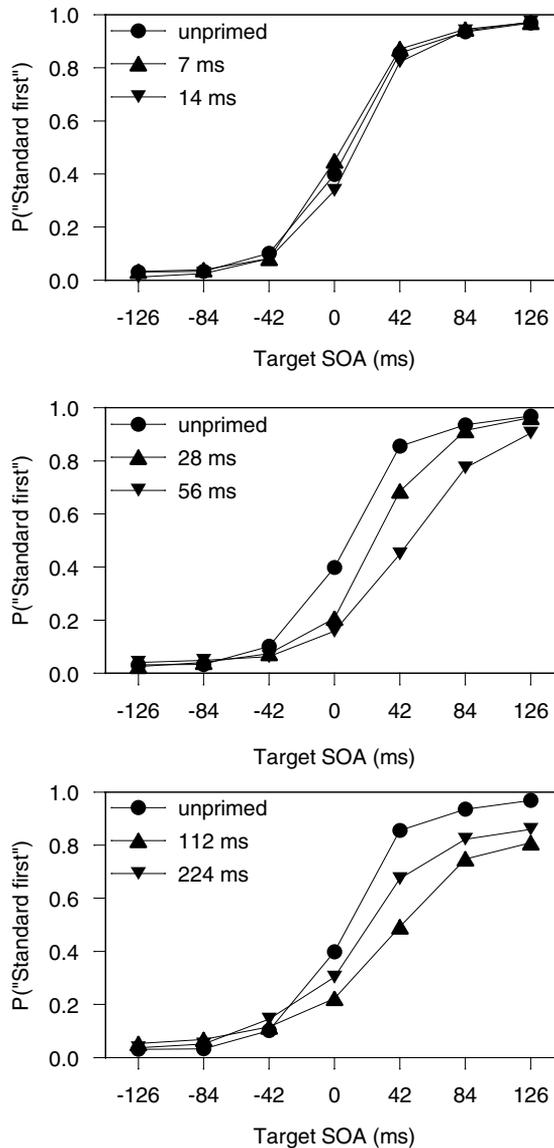
Fig. 5. Results of Experiment 3: psychometric distributions for the different priming SOAs each in comparison with the unprimed condition.

ms: $t[15] = 5.94$, $p < 0.001$, Cohen's $d = 2.39$; 112 ms: $t[15] = 4.27$, $p < 0.001$, Cohen's $d = 1.77$), though with the largest SOA, the test just reached significance (224 ms: $t[15] = 2.05$, $p < 0.05$, Cohen's $d = 0.87$).

A one-way ANOVA of DL values revealed a significant effect of priming ($F[6, 90] = 11.46$, $p < 0.001$, $\varepsilon = 0.32$). DL increased with priming SOA up to a
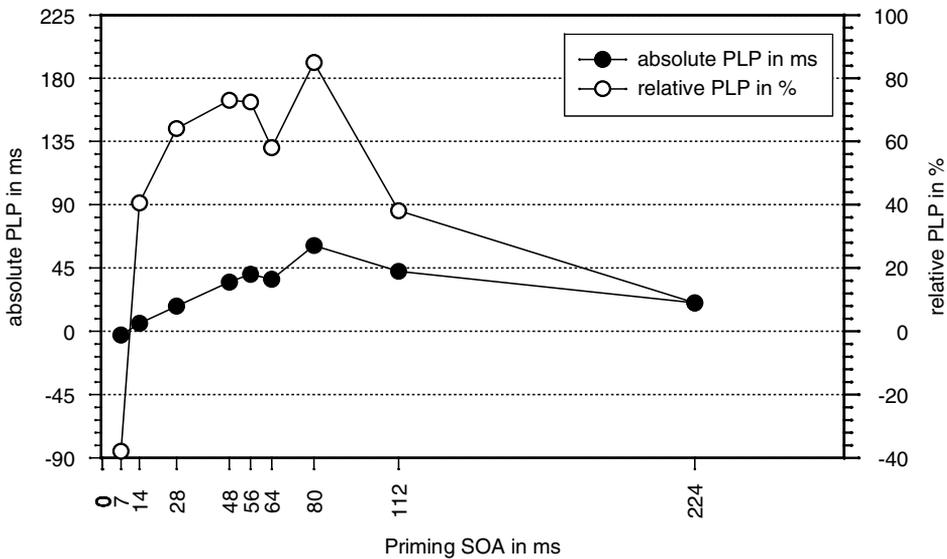
Fig. 6. Absolute and relative perceptual latency priming effects for all reported experiments.

maximum of 50 ms in the 112-ms priming SOA condition. With a priming SOA of 224 ms, it was reduced to 40 ms.

4.3. Discussion

The time course of attentional facilitation revealed in PLP is summarized in Fig. 6 which depicts both the absolute amount of PLP (PSS difference between the unprimed and the respective primed conditions) and its relative amount (facilitation in percent of the priming SOA). Data from Experiments 1 and 2 have been added to the data from the present experiment. With priming SOAs smaller than 100 ms, priming benefits amounted to a large proportion of the priming SOA. This confirms that much of the benefits of location priming are achieved within the first 100 ms after prime onset.

Experiment 3 thus demonstrated that PLP depends on priming SOA in the predicted way. Its size first increased with SOA until it reached an asymptote at about 50–100 ms, and was slightly reduced at priming SOAs larger than 100 ms. This reduction was accompanied by an impairment of discrimination performance (larger DL). Apparently, temporal order judgment becomes increasingly difficult as the prime and the target are separated by larger temporal intervals and become distinctive perceptual events. Apart from this decline beyond 100 ms, the data are as predicted by the AUM. As long as the priming SOA is shorter than the time required to shift attention to the prime's location, this model predicts that any increase of the SOA will increase the benefit from the prime. No further increase in benefit is expected if the attention shift has been completed during the SOA.

5. General discussion

The present experiments assessed the time course of PLP and tested the explanation suggested by the AUM, according to which PLP arises because the prime draws attention towards its location. In Experiments 1 and 2 it was found that PLP is mainly determined by the SOA between prime and target. Apart from a slight effect of prime duration, none of the other investigated temporal variables modulated the priming effect. Additionally, target offsets did not affect PLP. Experiment 3 assessed the time course of PLP. Priming effects increased rapidly with priming SOA up to a value of approximately 50–100 ms. This is in accordance with findings that orienting of attention seems largely completed within the first 100 ms after the onset of the attentional signal (Jonides, 1981; Müller & Findlay, 1988).

These results support the hypotheses derived from the AUM. Experiments 1 and 2 demonstrated that, as predicted by the model, the prime's onset (operationalized by priming SOA) exerts the strongest, if not the only, influence on perceived latency of the masking target. The time course of the attention shift as revealed in Experiment 3 closely resembles the qualitative predictions drawn from the AUM: Priming effects increase with priming SOA and reach an asymptote when the SOA becomes large enough for the attention shift to be completed within the priming SOA. The attentional benefit amounted to about 60% of the priming SOA (apart from smaller effects for very small priming SOAs which probably do not suffice for the initiation of an attention shift, and the largest SOA where prime and target are clearly separate events and impair temporal perception). At least two explanations may account for the reduced effect. First, the prime may not be able to attract attention on every single trial. Averaged across trials, this will lead to an effect of less than priming SOA. Second, the standard target possibly interferes with priming benefits, especially if it is temporally located between the prime and the comparison target.

Both the AUM and the present results seem to be compatible with recent neurophysiological evidence on the control of visual attention. Based on the distinction between the dorsal and the ventral stream (Creem & Proffitt, 2001; Milner & Goodale, 1995; Ungerleider & Mishkin, 1982), and the difference between the magnocellular and the parvocellular pathway (e.g., Livingstone & Hubel, 1988), Vidyasagar (1999), for example, reasoned that processing in the dorsal stream is largely preattentive and serves attentional selection. Information processed in the dorsal stream is used for attentional selection of 'locations of interest'. These locations are used to selectively facilitate processing in striate cortex and in the ventral pathway ("attentional spotlight", e.g., Vidyasagar, 1998). In this feedback, dorsal processing takes advantage of certain properties of the magnocellular pathways which dominates the dorsal stream, especially faster processing (see, e.g., Nowak & Bullier, 1997) and spatial coding. Several other authors also found evidence that the parietal lobe was involved in the control of attention (e.g., Hopf et al., 2000; Lynch, 1980). There is growing evidence that focusing visual attention involves feedback, or "re-entrant" activity from parietal areas into occipito-temporal regions (DiLollo, Enns, & Rensink, 2000; Jaskowski, van der Lubbe, Schlotterbeck, & Verleger, 2002).

The attentional orienting process that seems, according to the findings reported above, responsible for PLP may be attributed to several attentional mechanisms. There is evidence that peripheral cues cause shifts of attention that are functionally different from shifts of attention that are initiated by symbolic cues. The exogenous orienting mechanism has been described as reflexive or automatic (Jonides, 1981) which is supported, for example, by the finding that capture by onsets does not seem to depend on cue validity (Jonides, 1981; Müller & Rabbitt, 1989; Posner & Cohen, 1984). According to the attentional capture account, certain stimulus dimensions, such as abrupt onset (Jonides & Yantis, 1988) or being a new object (Yantis & Hillstrom, 1994) capture attention in a stimulus-driven, bottom-up fashion. However, the latency benefits may also be due to contingent capture, that is, orienting that is contingent on a match between cue properties and the observer's intention to search for certain stimulus properties (Folk, Remington, & Johnston, 1992). A further possibility is offered by an application of the direct parameter specification concept (Klotz & Neumann, 1999) to the specification of the parameters of an attentional shift (Scharlau & Ansorge, 2002; Scharlau & Neumann, in press). According to this model, response parameters can be specified by direct pathways from stimulus to response, bypassing a conscious representation of the stimulus. This theory has been used to explain the effects of masked primes on speeded responses. It assumes that direct parameter specification is possible if an action plan has been completed before motor activation. During a trial, this action plan is executed without further intentional control, which allows for masked primes to initiate motor preparation. PLP may be another case of direct parameter specification, with the parameters directly specified being those of an attention shift.

The present experiments do not distinguish between these attentional models. If the attentional capture account holds, PLP should be independent of whether or not there is a match between stimulus properties of the prime and the observer's search criteria that are associated with the targets. If influences of intentions on PLP could be demonstrated, this would speak in favour of both the direct parameter specification and the contingent capture accounts. However, according to the latter, differential effects are not to be expected within specific stimulus dimensions apart from the coarse difference between dynamic and static features if participants are searching for abrupt onsets. According to the direct parameter specification model, additional stimulus dimensions that the prime shares with the target, such as shape, should entail differential attentional effects (see, e.g., Neumann & Klotz, 1994). Second, the model suggests that direct specification of an attention shift should even be possible if the attentional signal (the prime) is completely masked and cannot be consciously perceived. Further research is needed to test these predictions.

Acknowledgements

References

Aschersleben, G. (1999). Task-dependent timing of perceptual events. In G. Aschersleben, T. Bachmann, & J. Müsseler (Eds.), *Cognitive contributions to the perception of spatial and temporal events. Advances in psychology* (pp. 293–318). Amsterdam, Netherlands: North-Holland/Elsevier Science Publishers.

Aschersleben, G., & Müsseler, J. (1999). Dissociations in the timing of stationary and moving stimuli. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 1–12.

Bachmann, T. (1994). *Psychophysiology of visual masking: The fine structure of conscious experience*. Commack, NY: Nova Science Publishers Inc.

Bachmann, T. (1999). Twelve spatiotemporal phenomena and one explanation. In G. Aschersleben, T. Bachmann, & J. Müsseler (Eds.), *Cognitive contributions to the perception of spatial and temporal events. Advances in psychology* (pp. 173–206). Amsterdam, Netherlands: North-Holland/Elsevier Science Publishers.

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

Cohen, J. (1977). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Lawrence Erlbaum Associates.

Creem, S., & Proffitt, D. R. (2001). Defining the cortical visual systems: "What", "Where", and "How". *Acta Psychologica, 107*, 43–68.

DiLollo, V., Enns, J. T., & Rensink, R. A. (2000). Competition for consciousness among visual events: The psychophysics of reentrant visual processes. *Journal of Experimental Psychology: General, 129*, 482–507.

Eimer, M. (1999). Facilitatory and inhibitory effects of masked prime stimuli on motor activation and behavioural performance. *Acta Psychologica, 101*, 293–313.

Eimer, M., & Schlaghecken, F. (1998). Effects of masked stimuli on motor activation: Behavioral and electrophysiological evidence. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 1737–1747.

Eriksen, C. W., & Collins, J. F. (1969). Temporal course of selective attention. *Journal of Experimental Psychology, 80*, 254–261.

Eriksen, C. W., & Hoffman, J. E. (1972). Temporal and spatial characteristics of selective encoding from visual displays. *Perception & Psychophysics, 12*, 201–204.

Fehrer, E., & Raab, E. (1962). Reaction time to stimuli masked by metacontrast. *Journal of Experimental Psychology, 63*, 143–147.

Finney, D. J. (1971). *Probit analysis* (3rd ed.). Cambridge: University Press.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 1030–1044.

Gibson, B. S., & Egeth, H. (1994). Inhibition and disinhibition of return: Evidence from temporal order judgments. *Perception & Psychophysics, 56*, 669–680.

Hays, W. L. (1988). *Statistics* (4th ed.). Orlando, FL: Holt, Rinehart, and Winston.

Hikosaka, O., Miyauchi, S., & Shimojo, S. (1993a). Focal visual attention produces illusory temporal order and motion sensation. *Vision Research, 33*, 1219–1240.

Hikosaka, O., Miyauchi, S., & Shimojo, S. (1993b). Visual attention revealed by an illusion of motion. *Neuroscience Research, 18*, 11–18.

Hopf, J.-M., Luck, S. J., Girelli, M., Hagner, T., Mangun, G. R., Scheich, H., & Heinze, H.-J. (2000). Neural sources of focused attention in visual search. *Cerebral Cortex, 10*, 1233–1241.

Jaskowski, P. (1991). Perceived onset simultaneity of stimuli with unequal durations. *Perception, 20*, 715–726.

Jaskowski, P. (1992). Temporal order judgment and reaction time for short and long stimuli. *Psychological Research/Psychologische Forschung, 54*, 141–145.

Jaskowski, P. (1993). Selective attention and temporal-order judgment. *Perception & Psychophysics, 22*, 681–689.

Jaskowski, P., van der Lubbe, R. H. J., Schlotterbeck, E., & Verleger, R. (2002). Traces left on visual selective attention by stimuli that are not consciously identified. *Psychological Science, 13*, 48–54.

Jonides, J. (1981). Voluntary vs. automatic control over the mind's eye's movement. In J. B. Long & A. D. Baddeley (Eds.), *Attention and performance IX* (pp. 187–203). Hillsdale, NJ, US: Erlbaum.

Jonides, J., & Yantis, S. (1988). Uniqueness of abrupt visual onset in capturing attention. *Perception & Psychophysics, 43*, 346–354.

Klotz, W., & Neumann, O. (1999). Motor activation without conscious discrimination in metacontrast masking. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 976–992.

Livingstone, M., & Hubel, D. H. (1988). Segregation of form, color, movement and depth: Anatomy, physiology and perception. *Science, 240*, 740–749.

Lynch, J. C. (1980). The functional organization of the posterior parietal association cortex. *Behavioral and Brain Sciences, 3*, 485–499.

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

Milner, D., & Goodale, M. (1995). *The visual brain in action*. Oxford, UK: Oxford University Press.

Müller, H. J., & Findlay, J. M. (1988). The effect of visual attention on peripheral discrimination thresholds in single and multiple element displays. *Acta Psychologica, 69*, 129–155.

Müller, H. J., & Rabbitt, P. M. A. (1989). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception and Performance, 15*, 315–330.

Müsseler, J., & Neumann, O. (1992). Apparent distance reduction with moving stimuli (Tandem Effect): Evidence for an attentional-shifting model. *Psychological Research, 54*, 246–266.

Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research, 29*, 1631–1647.

Neumann, O., Esselmann, U., & Klotz, W. (1993). Differential effects of visual-spatial attention on response latency and temporal order judgment. *Psychological Research, 56*, 26–34.

Neumann, O., & Klotz, W. (1994). Motor responses to nonreportable, masked stimuli: Where is the limit of direct parameter specification? In H. Moscovitch & C. Umiltà (Eds.), *Attention and performance XV: Conscious and nonconscious information processing* (pp. 124–154). Cambridge, MA: MIT Press.

Nowak, L. G., & Bullier, J. (1997). The timing of information transfer in the visual system. *Cerebral Cortex, 12*, 205–241.

Pashler, H. (1998). *The psychology of attention*. Cambridge, MA: MIT Press.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*, 3–25.

Posner, M. I., & Cohen, Y. (1984). Components of visual orienting. In H. Bouma & D. G. Bouwhuis (Eds.), *Attention and performance X: Control of language processes* (pp. 531–556). Hillsdale, NJ, US: Erlbaum.

Scharlau, I. (2002). Leading, but not trailing, primes influence temporal order perception: Further evidence for an attentional account of perceptual latency priming. *Perception & Psychophysics, 64*, 1346–1360.

Scharlau, I., & Ansorge, U. (2002). Exogenous and intention-dependent control of attention shifts in dynamic displays. In R. P. Wuertz & M. Lappe (Eds.), *Dynamic perception* (pp. 89–94). St. Augustin: Infix.

Scharlau, I., & Neumann, O. (in press). Perceptual latency priming by metacontrast-masked stimuli: Evidence for an attentional interpretation. Psychological Research.

Scott, S. K. (1998). The point of P-centres. *Psychological Research, 61*, 4–11.

Shore, D. I., Spence, C., & Klein, R. M. (2001). Visual prior entry. *Psychological Science, 12*, 205–212.

Steglich, C., & Neumann, O. (2000). Temporal, but not spatial, context modulates a masked prime's effect on temporal order judgment, but not on response latency. *Psychological Research/Psychologische Forschung, 63*, 36–47.

Stelmach, L. B., & Herdman, C. M. (1991). Directed attention and perception of temporal order. *Journal of Experimental Psychology: Human Perception and Performance, 17*, 539–550.

Suzuki, S., & Cavanagh, P. (1997). Focused attention distorts visual space. An attentional repulsion effect. *Journal of Experimental Psychology: Human Perception and Performance, 23*, 443–463.

Ungerleider, L. G., & Mishkin, M. (1982). Two cortical visual systems. In D. J. Ingle, M. A. Goodale, & R. J. W. Mansfield (Eds.), *Analysis of visual behavior* (pp. 549–587). Cambridge, MA, US: MIT Press.

Vidyasagar, T. R. (1998). Gating of neural responses in macaque primary visual cortex by an attentional spotlight. *NeuroReport, 9*, 1947–1952.

Vidyasagar, T. R. (1999). A neuronal model of attentional spotlight: Parietal guiding the temporal. *Brain Research Reviews, 30*, 66–76.

Yantis, S., & Hillstrom, A. P. (1994). Stimulus-driven attentional capture: Evidence from equiluminant visual objects. *Journal of Experimental Psychology: Human Perception and Performance, 20*, 95–107.