The spatial distribution of attention in perceptual latency priming

Ingrid Scharlau
Bielefeld University, Bielefeld, Germany

The spatial distribution of visual attention is a yet unresolved question. One of the main topics is whether attention is distributed in a graded fashion around an attended location (e.g., Downing, 1988; Zimba & Hughes, 1987). The present experiments explore whether, and on which conditions, gradients of attention arise and contribute to perceptual facilitation. A masked or unmasked prime precedes one of two targets whose temporal order has to be judged. The prime captures attention, which shortens the perceptual latency of the primed target (perceptual latency priming; Scharlau & Neumann, 2003a; Shore, Spence, & Klein, 2001). No strong evidence for an attentional gradient was found. (1) Accuracy of temporal order judgements was independent of the distance between the two targets that were judged. That is, facilitation of the second target by the first target was spatially invariant. (2) With targets of short duration, facilitation was independent of prime–target distance. (3) With targets of long duration, gradients were found: Facilitation declined continuously with distance. Thus, long duration of stimuli may be a sufficient precondition for an attentional gradient. A control experiment showed that object-based attention contributes only marginally to perceptual latency priming.

In the early 90s, Hikosaka, Miyauchi, and Shimojo (e.g., 1993a, 1993b, 1993c) discovered a phenomenon termed the line motion effect or *illusory line motion*. Observers watch a stationary line that covers several degrees of visual angle. Preceding the line, a visual cue is presented at one of its ends. Observers typically perceive motion within the line, which seems to develop from the cued end. Voluntarily attending to one of the ends of the line produces a similar effect. Illusory motion begins at the attended end and proceeds towards the unattended end of the line.

Correspondence should be addressed to Ingrid Scharlau, Department of Psychology, Bielefeld University, P.O. Box 10 01 31, D-33501 Bielefeld, Germany. Email: ingrid.scharlau@uni-bielefeld.de

The research reported in this paper was supported by the Deutsche Forschungsgemeinschaft (DFG), Grant NE 366/5-2 to Odmar Neumann. Thanks to Ellen Brinkmeier and Kirsten Labudda for their assistance with the experiments and the manuscript, and to Ulrich Ansorge, Elena Carbone, Manfred Heumann, Werner Klotz, and Odmar Neumann for discussing the topics involved and the data. Also, I would like to thank Mark Auckland, Kyle Cave, Nelson Cowan, and an anonymous reviewer for their valuable suggestions on an earlier version of this manuscript.

Parts of the experimental data were presented at the Regionalkolloquium 2002, July 6th 2002, Bielefeld, Germany.

http://www.tandf.co.uk/journals/pp/02724987.html DOI:10.1080/02724980343000828

The phenomenon of illusory line motion is in accordance with models about *visuo-spatial attention*, which claim that attention facilitates the processing of visual information at attended locations (Neumann & Müsseler, 1990; Posner, 1980; Shore, Spence, & Klein, 2001; Stelmach & Herdman, 1991): The abruptly presented cue is assumed to capture attention (Jonides & Yantis, 1988; Posner, 1980; Yantis & Jonides, 1984). Allocating attention towards a location in visual space leads to better, more effective, or faster processing of stimuli appearing there (e.g., Bashinski & Bacharach, 1980; Downing, 1988; Eriksen & Hoffman, 1972; Hawkins, Hillyard, & Luck, 1990; Müller & Findlay, 1987; Posner, 1980). Differential speed of processing may provide an explanation of illusory line motion: Attending to the cue speeds up transmission of signals from this location and thus shortens perceptual latency. Hikosaka and coworkers (1993a, 1993b, 1993c) further assumed that a gradient of attention arises around the cue. Thus, the closer a signal appears to the cue, the larger the benefits it achieves (see also Schmidt & Klein, 1997). Signals from the cued and nearby locations reach central processing mechanisms earlier than signals from the uncued end. These latency differences are detected by motion detectors, resulting in the perception of apparent motion.

Several other researchers also reported graded distributions of visual attention. For example, LaBerge (1983) demonstrated that latencies of discrimination responses increased with distance from the attentional focus within 1° of visual angle. Further evidence was revealed in the flanker paradigm (e.g., Eriksen & Eriksen, 1974; Eriksen & Hoffman, 1972): A response-incongruent flanker stimulus adjacent to an imperative stimulus increased response times as compared with a neutral flanker that was not associated with a response. This interference decreased with target–flanker distance and vanished if target and flanker were separated by more than 2° of visual angle. Other researchers found distance effects also with arrays indicating gradients of 3° or even larger (Downing, 1988; Downing & Pinker, 1985; Handy, Kingstone, & Mangun, 1996; Henderson & Macquistan, 1993; Klein & McCormick, 1989; Mangun & Hillyard, 1988; McCormick & Klein, 1990; Sagi & Julesz, 1986; Shulman, Wilson, & Sheehy, 1985; Steinman, Steinman, & Lehmkuhle, 1995). Whether such gradients can explain illusory line motion, however, is yet unclear. Critically, most of these gradients encompass smaller fields than the extent of line motion in which the line measured 5° to 13.5° of visual angle (Hikosaka et al., 1993a, 1993b; Hikosaka, Miyauchi, Takeichi, & Shimojo, 1996; Shimojo, Miyauchi, & Hikosaka, 1997).

Moreover, the attentional explanation for illusory line motion is controversial. Downing and Treisman (1997), for example, argued that illusory line motion may be caused by an *impletion* process by which intermediate states of moving and changing objects (the cue changing into the line) are inferred. Apparent motion is largely independent of feature discontinuities between the stimuli: If their features differ, the apparently moving stimulus seems to change its features while under way (e.g., Kolers, 1972; Kolers & von Grünau, 1976; Orlansky, 1940; Wertheimer, 1912). Provided there are adequate temporal and spatial distances, a red stimulus, for example, presented alternately with a green stimulus at some distance appears as a jumping stimulus changing colour during the jumps. Impletion is an inference that the visual system draws about ambiguous stimuli in order to provide coherent and continuous environmental objects (see, e.g., Farrell & Shepard, 1981; Shepard, 1984). According to Downing and Treisman, illusory line motion is the consequence of impletion between a cue and a line—that is, a jumping stimulus that changes its shape during each jump. In accordance with their hypothesis, Downing and Treisman observed that a trailing cue led to a “shrinking line illusion". This is predicted by the impletion hypothesis as the result of the trajectory and change of a moving object, whereas an attentional account of it is unlikely.

Apart from these unresolved problems, the original research on the phenomenon of illusory line motion suffers from at least three problems. First, the paradigm does not allow assessment of the spatial features of the attentional gradient (size and slope): The observers only report the direction of line motion. It is unclear whether they perceive motion in the whole line or only in parts of it. Second, latency facilitation is indirectly inferred from apparent motion, and its size is presented as the proportion of trials in which motion is perceived across different cue–line intervals. Third, the illusory line motion experiments are not sufficiently safeguarded against response bias: In the studies of Hikosaka and coworkers (1993a, 1993b, 1993c), skilled observers indicated with a two-alternative forced-choice judgement the direction of motion in a line that did not move or change. In such a situation, a response bias according to the location of the cue is likely (see, e.g., Frey, 1990; Pashler, 1998; Shore et al., 2001; Spence, Shore, & Klein, 2001). In sum, the evidence for attentional gradients in illusory line motion is only weak. Note also that other researchers failed to find clear evidence for a graded distribution of attention (e.g., Cave & Zimmerman, 1997; Hughes & Zimba, 1985, 1987; Kim & Cave, 1995).

The present study attempts to overcome the methodological problems of the illusory line motion paradigm and assess the contribution of attentional gradients to latency facilitation. It uses an experimental paradigm that is closely related to the phenomenon of illusory line motion and its explanation—namely, *perceptual latency priming* (PLP; Scharlau, 2002; Scharlau & Neumann, 2003a). PLP is similar in origin to illusory line motion (attention-mediated facilitation of perceptual latency), but compared with illusory line motion, it has several advantages: The size of gradients can be measured, the latency effects can be quantified, and PLP has been demonstrated to be free of response bias.

PLP is defined as the facilitation of the latency of a visual stimulus by a preceding visual cue (a "prime") as compared to the latency of an unprimed stimulus. As illusory line motion it has been attributed to a decrease of perceptual latency. The main difference between these two phenomena is the way in which perceptual latency is assessed. In illusory line motion, the decrease of latency is assessed indirectly via apparent motion phenomena. PLP is measured in a more straightforward way by comparing the perceived latency of an attended and an unattended stimulus (e.g., Neumann, Esselmann, & Klotz, 1993; Scharlau, 2002; Scharlau & Neumann, 2003a, 2003b; Shore et al., 2001; Spence et al., 2001; Steglich & Neumann, 2000; Stelmach & Herdman, 1991). Compared to illusory line motion, this paradigm has the advantage that the spatial distribution of attention can be assessed directly by varying the distance between the focus of attention (the prime's location) and the targets. Second, the amount of facilitation can be quantified by estimating subjective simultaneity between an attended and an unattended target. Third, the contribution of response bias (Pashler, 1998) or criterion effects to PLP is very weak, if present at all (Scharlau, in press, 2003; Scharlau & Neumann, 2003a; Shore et al., 2001; Stelmach & Herdman, 1991).

There is a second reason for the investigation of the spatial distribution of attention. PLP has been explained by the asynchronous updating model (Neumann & Müsseler, 1990; Scharlau, 2002; Scharlau & Neumann, 2003a). This model was originally developed to explain metacontrast masking, a type of visual backward masking in which the mask laterally adjoins the masked stimulus (Bachmann, 1994; Breitmeyer, 1984). According to the model, metacontrast masking is due to an asynchrony between the updating of two stimulus representations: the spatial map and the internal model. In the spatial map, simple features are quickly encoded and updated. Updating of similar features at the same location results in overwriting (later codes overwrite earlier ones). The contents of the spatial map are preattentive and not consciously perceived. They can feed directly into specification of motor responses (Neumann, 1990), and they can cause shifts of attention (Scharlau & Ansorge, 2003). Conscious perception requires a representation in the internal model, which is in turn mediated by spatial attention. Due to the selectivity of attentional allocation, the internal model is updated selectively, and because of the slowness of attention shifts, it is updated less quickly than the spatial map. According to the asynchronous updating model, PLP results from the following processes: (1) The prime elicits a shift of attention; (2) feature coding in the spatial map proceeds from prime coding to target coding while attention is shifted; (3) after attentional allocation is completed, the target, and not the prime, is transferred into the internal model; (4) compared to an unprimed target, the internal model code of the primed target is predated because it profits from the attention shift that was originally caused by the prime; and (5) the amount to which the prime is represented in the internal model depends on the priming SOA and the amount to which prime features are overwritten by similar features of the target.[1]

Metacontrast masking depends critically on the contour distance between prime and mask (Breitmeyer, 1984; Werner, 1935; though see Enns & Di Lollo, 1997). The asynchronous updating model refers to this phenomenon in terms of the spatial map. Although the spatial coordinates of this map are not specified, the model presupposes that attention is allocated towards a certain *location*. However, it has so far not been tested whether attentional allocation that is involved in PLP is indeed organized spatially. The present study seeks to address this question, too.

Overview

The experiments presented below test the attentional gradient hypothesis that underlies the explanation of illusory line motion. They employ a PLP paradigm with temporal order judgements. This paradigm allows to vary the spatial distance between the prime's location—that is, the focus of attention—and the targets. Three main predictions can be derived from the gradient account: First, the accuracy of temporal order judgements will be reduced by short distances between the targets. The first target triggers an attentional gradient, and the second target achieves facilitation, too, provided that it is presented within the gradient. This facilitation results in reduced discrimination accuracy for short target–target distance compared to large target–target distance. Second, PLP itself will be reduced by short target–target distance. The prime elicits PLP. Since it is the first event in the display, it causes an attentional gradient. The target presented at the prime's location is facilitated. Following the same logic as above, the second target is also facilitated if it falls into the attentional gradient. The closer the second target is presented to the centre of the gradient, the larger the facilitation it will achieve. Since PLP is defined as relative facilitation of the primed compared with the

[1]A related, nonattentional dual-process account of PLP has been given by Bachmann (1994, 1999).

unprimed target, PLP will be smaller for short than for large target–target distance. These two predictions are tested in Experiments 1a and 1b.

Third, PLP will be reduced if the prime does not share the exact location of the primed target. The larger the distance between prime and primed target (the target–target distance being constant), the smaller the PLP. Experiments 2a and 2b study the influence of prime–target distance with short targets. In Experiment 3a and 3b, targets are of long duration. Both congruent and neutral primes were employed to control for object priming effects. As a control, the contribution of object-based attentional mechanisms to PLP is investigated in Experiment 4.

EXPERIMENT 1A

Experiment 1a assesses the influence of target–target distance on the accuracy of temporal order judgements and PLP. Two predictions can be derived from the attentional gradient hypothesis. First, the accuracy of temporal order judgement is related to target–target distance. The attentional gradient elicited by the first target facilitates perception of the second target, shortens its latency, and thus impairs discrimination of temporal order. This reduction in accuracy should be proportional to the distance between the two targets. Second, PLP should be smaller with short than with long target–target distance. If a prime is presented, the prime elicits an attentional gradient. The target that is presented at the prime's location is facilitated. The second target's latency is facilitated only if it falls into the attentional gradient. Facilitation for the second target is expected to be the larger the closer it is to the centre of the attentional gradient. Since PLP measures relative facilitation of the primed compared with the unprimed target, it will be reduced by short target distance.

Method

Participants

A total of 10 voluntary participants whose informed consent was obtained took part in the experiment (6 female; mean age 27.7 years). They received €3.50. In this as in the following experiments, all participants had normal or corrected-to-normal visual acuity.

Apparatus, stimuli, and procedure

Stimuli were presented in dark grey (14 cd/m²) on a light-grey background (103 cd/m²) on a 17-in. colour monitor with a refresh rate of 62 Hz. Participants sat in a dimly lit room. Their head rested on a chin rest, which fixed viewing distance at 60 cm. They responded by pressing either the left or the right mouse button.

In each trial, two visible targets were presented: a square and a diamond with star-shaped inner contours. These stimuli allow for good metacontrast masking (see Figure 1; Klotz & Neumann, 1999; Neumann & Klotz, 1994; for masking strength in the temporal order judgement see Scharlau & Neumann, 2003a). Edge length of the targets was 2.3°. In half of the trials, a prime was shown that was a small replica of the target and fitted into its inner contours (edge length 1.7°). In order to control for stimulus eccentricity, all targets had the same distance from fixation. They were presented on an imaginary circle centred around fixation (radius 6.5°). There were eight possible equidistant target positions. Target distance was varied in four steps. Targets were presented either in adjacent positions, with one or

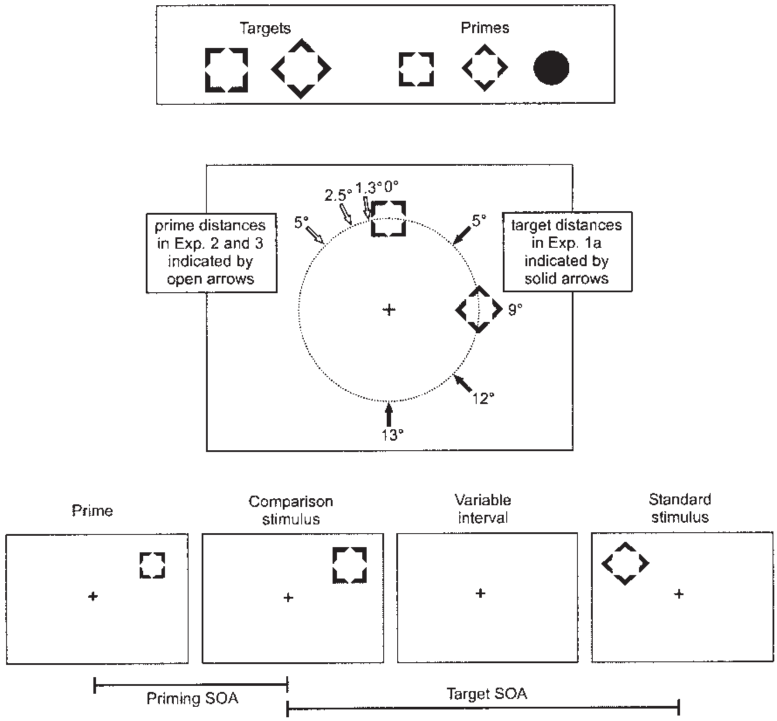

Figure 1. Upper part: Stimulus shapes used in the experiments. Middle: Possible spatial locations in a sample array. The comparison stimulus is presented in the upper centre (for illustration: a square). The possible distances of the standard stimulus are given in the right part (distances as in Experiment 1a). Note that the standard stimulus was equally often presented in clockwise and counterclockwise direction from the comparison stimulus. Possible prime distances are depicted in the upper left (distances as in Experiments 2 and 3). Again, the prime could be displaced counterclockwise (as in Figure 1) and clockwise. Distances are given in degrees of visual angle from the comparison stimulus. The circle was not visible on the screen; it illustrates that all stimuli had the same eccentricity. Below: Succession of events in a sample trial with the comparison preceding the standard stimulus (negative target SOA). Stimuli are not drawn to scale.

two empty positions between them, or at maximal distance—that is, on opposite locations of the imaginary circle. These conditions corresponded to 5°, 9°, 12°, and 13° of visual angle. Each location was equally likely to contain one of the targets in each trial (see Figure 1 for possible spatial positions). A fixation point consisting of a small black cross was visible on the screen throughout the experiment.

Primes were shown at the position of one of the targets 64 ms prior to its presentation. Prime and target duration was 32 ms. Target SOAs (stimulus onset asynchronies between the two targets) ranged between –80 and +80 ms in steps of 32 ms. Negative numbers for target SOAs indicate that the primed target (the comparison stimulus) led the unprimed target (the standard stimulus); positive SOAs indicate that the standard stimulus appeared first in the target sequence. In unprimed trials, the assignment of positive and negative values was made randomly. There were 48 conditions (6 target SOAs × 4 target distance conditions × 2 priming conditions). Each condition was presented 16 times in a random order resulting in a total of 768 trials. Trials were presented with the method of constant stimuli.

Participants judged the temporal order of the targets. Half of the participants responded with the left mouse button if they saw the square first and with the right button if they perceived the diamond first; for the other half the assignment was reversed. The instruction emphasized accuracy. Every 96 trials, a break was initiated automatically.

Results

The primed target was defined as comparison stimulus, and the unprimed target as standard stimulus. To construct psychometric functions, the frequency of the judgement "standard stimulus first" was determined for each priming and target distance condition and target SOA. Logit analysis (Finney, 1971) was used to estimate the point of subjective simultaneity (PSS) and the difference limen (DL, interquartile range) for each participant. If appropriate, degrees of freedom were corrected by the Greenhouse–Geisser coefficient ε, and adjusted α values are reported (Hays, 1988). Individual data were not analysed if they met one of the following criteria: (a) In unprimed trials, less than a quarter of the psychometric function was assessed, and (b) the slope of any psychometric distribution was negative. Both criteria indicate that observers were not able to sufficiently discriminate temporal order. All data were analysed in Experiment 1.

As can be seen in Figure 2 (upper part), priming shifted the psychometric distributions horizontally. This indicates changed perception of temporal order. Further, target distance

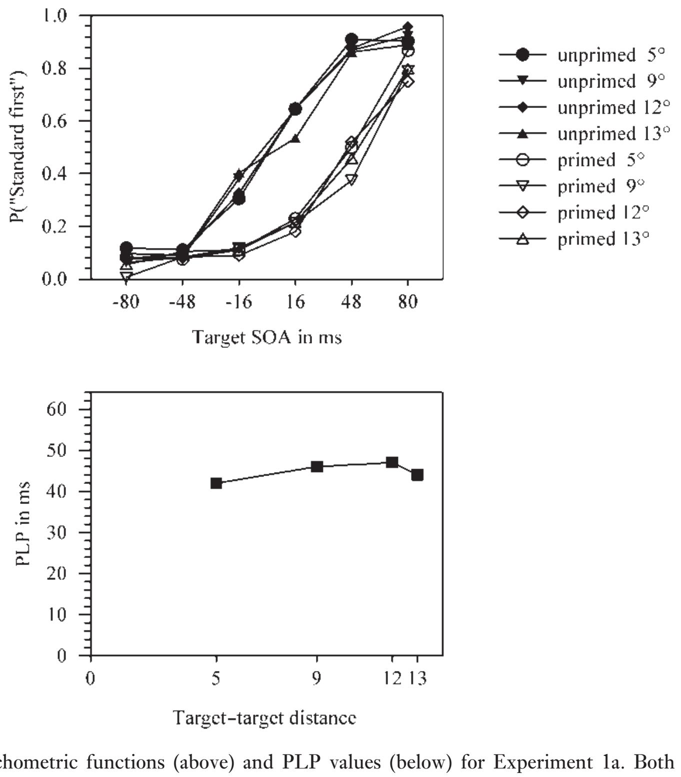

Figure 2. Psychometric functions (above) and PLP values (below) for Experiment 1a. Both the shift of the psychometric functions (PLP) and their slope (DL) are independent of target distance. Average PLP is given without the participant with the large PSS in the 9° condition.

influenced neither the slope of the psychometric distribution (discrimination accuracy) nor the amount of the horizontal shift. The psychometric distribution indicates perceived simultaneity when the unprimed stimulus led the primed one by about 48 ms.

A two-way analysis of variance (ANOVA) of PSS revealed a highly significant main effect of priming, $F(1, 9) = 40.47, p < .001$. Neither a main effect of target distance, $F(3, 27) = 1.05, p = .34$, nor an interaction of priming and target distance, $F(3, 27) = 1.17, p = .31$, was found. PSS was 0, +2, +2, and +3 ms in the unprimed and +42, +77, +49, and +47 ms in the primed conditions. The large PSS value with 9° distance was due to a single participant with a PSS of +329 ms in this condition. Reduced by the data of this participant, the average PSS was +48 ms. PLP was estimated as the difference of the PSS in primed and unprimed conditions (see Figure 2, lower part). Reduced by the participant's data mentioned above, it was on average + 45 ms, which is about two thirds of the priming SOA and thus of the same size as that found in earlier studies (Scharlau, 2002; Scharlau & Neumann, 2003a, 2003b).

A two-way ANOVA of DL revealed a significant main effect of priming condition, $F(1, 9) = 10.27, p < .05$. Neither a main effect of target distance, $F < 1$, nor an interaction of priming and target distance, $F(3, 27) = 1.11, p = .33$, was found. DL was slightly larger—that is, performance was poorer—in primed conditions (unprimed, 36 ms; primed, 42 ms).

Discussion

Experiment 1a revealed a reliable effect of priming on perceptual latency, which amounted to 45 ms. Priming also slightly impaired discrimination accuracy. Such an influence of priming is rarely found. However, there was no influence of target distance in Experiment 1a. Neither PSS nor DL varied with target distance.

Experiment 1a thus did not confirm the attentional gradient hypothesis. In line with this hypothesis, decreasing target distance was expected to reduce judgement accuracy as well as PLP. However, the smallest target distance was about 5° of visual angle. Though a line motion effect has been reported with a line length of 5° and larger, from the published data it is not clear whether the perceived motion (and thus the attentional gradient) encompassed the whole line. Gradient effects measured with response latencies typically arise in much smaller regions (for example, 1° in LaBerge, 1983). Thus, Experiment 1a was replicated with smaller target distances.

EXPERIMENT 1B

Experiment 1b replicated Experiment 1a with the single exception that target distances were reduced and covered 1.3° to 9° of visual angle.

Method

Participants

A total of 10 voluntary participants whose informed consent was obtained took part in the experiment and received €5 (7 female; mean age 29.0 years).

Apparatus, stimuli, and procedure

Apparatus, stimuli, and procedure were identical with those of Experiment 1a except for the following differences. There were 32 possible equidistant target positions on the imaginary circle. Target distance was varied in four steps corresponding to 1.3°, 2.5°, 5°, and 9° of visual angle. With the smallest distance, targets overlapped. Each location was equally likely to contain one of the targets in each trial. There were five target SOAs ranging between –64 and +64 ms in steps of 32 ms. There were 40 conditions (5 target SOAs × 4 target distance conditions × 2 priming conditions). Each condition was presented 20 times in a random order resulting in a total of 800 trials.

Results

The data of two participants had to be discarded due to a negative slope in one of the unprimed conditions. Figure 3 (upper part) indicates that priming again horizontally shifted the psychometric distributions. A two-way ANOVA of PSS revealed a highly significant main effect of priming, $F(1, 7) = 119.92$, $p < .0001$. Neither a main effect of target distance nor an interaction of priming and target distance was found, both $F < 1$. PSS was –1, +8, +2, and +6 ms in the unprimed and +48, +44, +58, and +58 ms in the primed conditions, resulting in PLP values of +49, +36, +56, and +52 ms (see Figure 3, lower part). PLP was on average +48 ms, closely resembling the results of Experiment 1a.

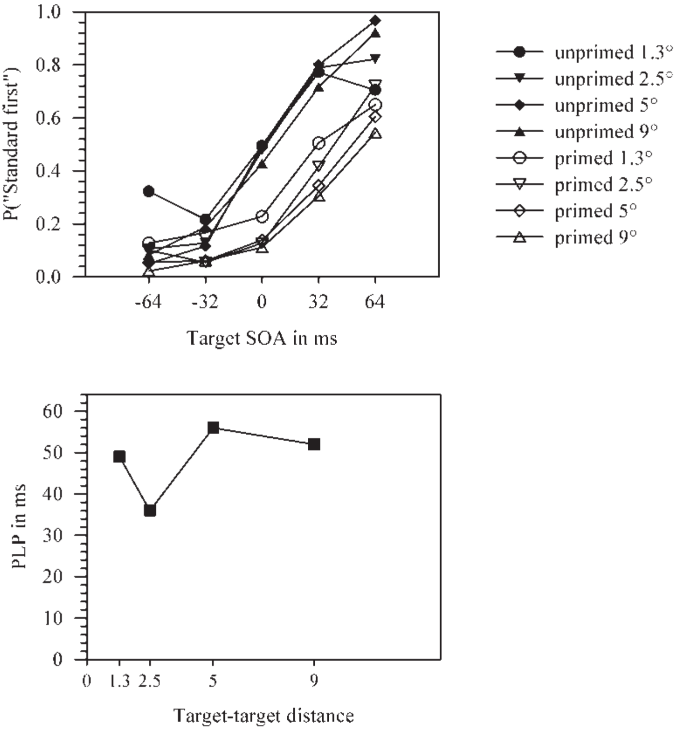

Figure 3. Psychometric functions (above) and PLP values (below) for Experiment 1b. Both the shift of the psychometric functions (PLP) and their slope (DL) are independent of target distance.

A two-way ANOVA of DL revealed no significant main effects: priming, $F < 1$; distance, $F(3, 21) = 4.22$, $p = .07$. The interaction did not reach significance either, $F < 1$. DL was larger with the smallest distance (69 ms averaged over primed and unprimed trials) than with the larger distances (32, 30, and 32 ms for the 2.5°, 5°, and 9° conditions, respectively).

Discussion

Experiment 1b replicated Experiment 1a. No influence of target distance on PLP was found. Decreasing target distance to overlapping presentation (1.3°) slightly reduced the accuracy of temporal order perception. This is in accordance with two explanations: either an attentional gradient of less than 2.5°, or the difficulty of establishing separate percepts if stimuli overlap.

In sum, the main finding of Experiment 1 was that target distance in a temporal order judgement task exerted only a marginal influence on judgement accuracy (i.e., with overlapping stimuli) and did not influence PLP. The distance effect corresponding to the attentional gradient predicted by the attentional gradient hypothesis was not found. Also, the results are not in accordance with models in which an analogue movement of attention across the visual field is proposed (Shulman, Remington, & McLean, 1979; Tsal, 1983). Such models predict distance effects.

EXPERIMENT 2A

Target distance is one way to operationalize an attentional gradient in the PLP paradigm. A second possibility is the spatial separation of prime and primed target. According to the attentional gradient account, the prime elicits an attention shift towards its location, resulting in an attentional gradient centred around the prime's location. Facilitation will be the larger the closer a stimulus is presented to the prime's location. Experiment 2a explores effects of prime–target distance. According to the attentional gradient account, priming effects will be largest if prime and target share the same location and fall off with increasing prime–target distance.

Presenting prime and target at different locations affects masking strength. Metacontrast masking is strongest with the target centred around the prime (e.g., Breitmeyer, 1984). Though there may be some masking with the target laterally adjacent to only one of the prime's sides (and even with larger distances, see Enns & Di Lollo, 1997), larger distances separating prime and target impair masking strength. However, as demonstrated in an earlier study (Scharlau & Neumann, 2003a), PLP is independent of masking strength.

Method

Participants

A total of 10 voluntary participants whose informed consent was obtained took part in the experiment (6 female; mean age 25.4 years). They received €5.

Apparatus, stimuli, and procedure

Apparatus, stimuli, and procedure were identical with those of Experiment 1b except for the following differences. Target distance was either 9° or 13° of visual angle. This variation of target distance was not related to the experimental hypothesis; it served to ensure spatial uncertainty about the relative target locations. Similar to the targets, the primes appeared on an imaginary circle centred around fixation with a radius of 6.5°. Prime–target distance was varied in four steps, 0°, 1.3°, 2.5°, and 5° of visual angle. With 1.3° distance, prime and comparison stimulus overlapped. An unprimed condition served as a baseline. Target SOAs were varied in five steps ranging between –96 and +96 ms in steps of 48 ms. There were 25 conditions (5 target SOAs × 5 prime distance conditions, the latter including the unprimed condition). Each condition was presented 24 times in a random order, resulting in a total of 600 trials. In order to simplify prime–target distinction, target duration was increased to 64 ms. In addition to the instruction mentioned above, participants were told to ignore the prime in their judgements if they detected it.[2]

Results

Data of all participants were analysed. Figure 4 (upper part) indicates that priming again shifted the psychometric distributions horizontally. A one-way ANOVA of PSS revealed a highly significant main effect of priming, $F(4, 36) = 19.71$, $p < .0001$. Bonferroni comparisons on the .05 level indicated that this effect was due to the difference between the unprimed and

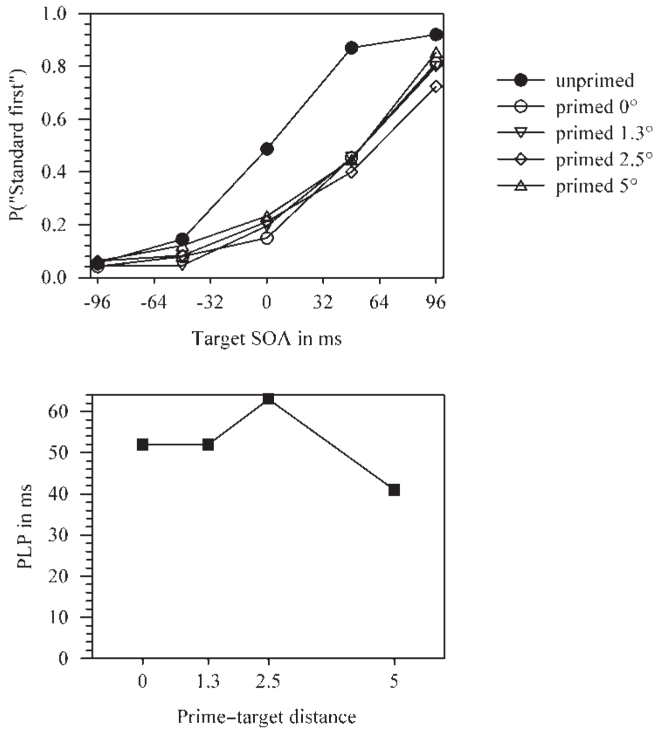

Figure 4. Psychometric functions (above) and PLP values (below) for Experiment 2a employing a congruent prime and short targets. Attentional facilitation is equal for the different prime–target distances.

[2]The original design contained a second block in which participants indicated the target's location with the mouse. Because these data are not related to the question discussed in this paper, they are not referred to.

each of the primed conditions, whereas the primed conditions did not differ among themselves. For each primed condition, the amount of PLP was calculated by subtracting the individual PSS of each primed from that of the unprimed condition. PLP values were each tested against zero (one-tailed *t* tests). In every condition, PLP significantly differed from zero. Mean PLP was +52 ms in the 0° condition, $t(9) = 5.57$, $p < .0001$, again +52 ms in the 1.3° condition, $t(9) = 10.84$, $p < .0001$, +63 ms in the 2.5° condition, $t(9) = 6.93$, $p < .0001$, and +41 ms in the 5° condition, $t(9) = 4.93$, $p < .0001$.

Discussion

No influence of prime distance on perceived temporal order was found in Experiment 2a. Varying the distance of prime and comparison stimulus between 0° and 5° of visual angle did not influence the amount of PLP. Reliable attentional facilitation by a prime was found in each of the conditions.

In sum, a target trailing exactly at the prime's location received the same benefits as a target that was displaced up to 5°. This finding indicates a broad and ungraded distribution of attention (see Shepherd & Müller, 1989). However, there is an alternative explanation for the results: The prime's shape was similar to the primed target, and it may have been difficult to ignore the visible prime. Possibly, participants judged the visible prime´s onset instead of the target's onset. Experiment 2b controls for this possibility. Neutral primes are used, which do not resemble a target shape and thus do not carry imperative information. Prime–target confusion should vanish with neutral primes.

EXPERIMENT 2B

Experiment 2b replicated Experiment 2a in using neutral primes. Neutral primes were dissimilar to the targets in contours and orientation, reducing the opportunity for perceptual confusion.

Method

Participants

A total of 10 voluntary participants whose informed consent was obtained took part in the experiment (4 female; mean age 26.4 years). They received €5.

Apparatus, stimuli, and procedure

Apparatus, stimuli, and procedure were identical with those of Experiment 2a except that the prime was a small circle of about the same size as the target-like primes used in the former experiments (see Figure 1). There were 25 conditions (5 target SOAs × 5 prime distance conditions). Each condition was presented 32 times in a random order resulting in a total of 800 trials.

Results

Data of all participants were analysed. Figure 5 (upper part) indicates that priming shifted the psychometric distributions horizontally. A one-way ANOVA of PSS revealed a significant effect of priming, $F(4, 36) = 28.33$, $p < .0001$, which was due to the difference between the

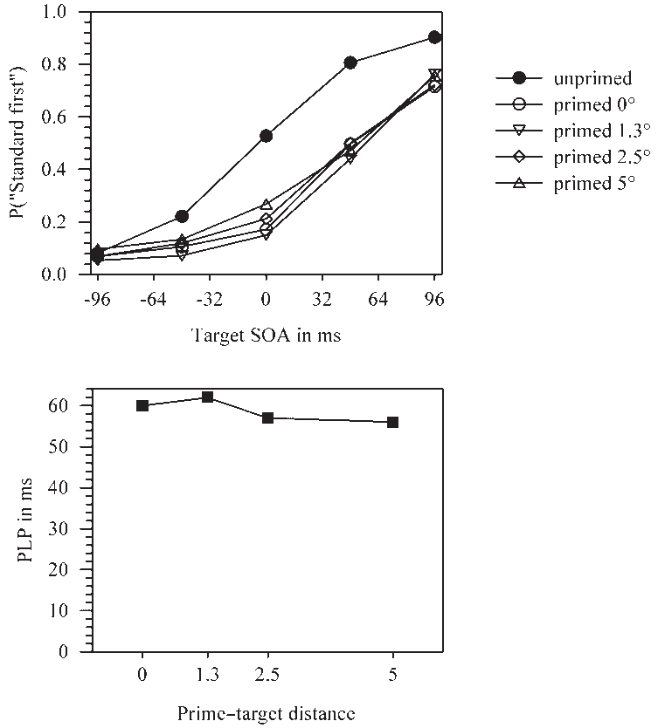

Figure 5. Psychometric functions (above) and PLP values (below) for Experiment 2b employing a neutral prime and short targets. Attentional facilitation is equal for the different prime–target distances.

unprimed and each of the primed conditions (Bonferroni post hoc comparisons on the .05 level). PSS without prime was –3 ms, and +57, +59, +54, and +53 ms for the four primed conditions. PLP was on average +60 ms in the 0° condition, +62 ms in the 1.3° condition, +57 ms in the 2.5° condition, and +56 ms in the 5° condition (see Figure 5, lower part). PLP differed significantly from zero in all conditions: 0°, $t(9) = 8.45$, $p < .0001$; 1.3°, $t(9) = 11.24$, $p < .0001$; 2.5°, $t(9) = 6.67$, $p < .001$; 5°, $t(9) = 4.63$, $p < .001$ (one-tailed t tests).

Discussion

In Experiment 2b, a priming effect of neutral (nonimperative or target-dissimilar) primes was found. Attentional facilitation by a neutral prime cannot be assigned to difficulties in distinguishing between the features of prime and target. Despite this difference, the results were the same as those in Experiment 2a: PLP was found, and the prime's location did not influence PLP. Attentional facilitation was independent of whether the prime was presented at the target´s location or distant from the target.

To summarize, Experiments 2a and 2b found that both a congruent and a neutral prime facilitated perceptual latency, and that this facilitation is present in a large area (5° at least) surrounding the prime's location. Further, the results of Experiment 2a and 2b disfavour the constant time hypothesis of attentional movements (Remington & Pierce, 1984). This may be concluded from the condition in which prime and comparison stimulus shared the same location. According to the constant time hypothesis, the duration of an attention shift is fixed and is thus independent of the distance to be covered. Given that attention is attracted by the prime, a shift of attention towards the primed target's location is unnecessary in this condition. According to the constant time hypothesis, priming benefits must be larger in this case than in conditions in which a movement of attention is required to focus attention on the target. No evidence for such a difference was found. Further, PLP benefits were rather large in Experiments 2a and 2b. They amounted to an average of +55 ms, which is 87% of the priming SOA and thus larger than the effect of 30 to 40 ms typically found with a priming SOA of 64 ms (Scharlau, 2002; Scharlau & Neumann, 2003b).

EXPERIMENT 3A

The previous experiments failed to find evidence for a spatial gradient of attention or location-based mechanisms of attentional selection. Primes presented at different distances from the targets entailed the same amount of PLP. However, the dynamic displays used in the previous experiments were different from illusory line motion displays in that the targets were short, whereas in the studies by Hikosaka and coworkers (1993a, 1993b, 1993c), the line was typically presented until observers indicated their judgement. To my knowledge, there is no theoretical account that would predict attentional gradient effects exclusively for long-duration targets. However, an experimental test of this factor may shed light on the differences between studies that found attentional gradient effects and those that failed to find such effects. Experiment 3a replicated Experiment 2a with larger target duration.

Method

Participants

A total of 10 voluntary participants whose informed consent was obtained took part in the (7 female; mean age 27.6 years) experiment and received €4.50.

Apparatus, stimuli, and procedure

Apparatus, stimuli, and procedure were identical with those of Experiment 2a except for the following difference. Targets were presented on the screen until participants indicated their judgement. Target SOAs were varied in five steps ranging between –64 and +64 ms in steps of 32 ms. There were 25 conditions (5 target SOAs × 5 prime distance conditions). Each condition was presented 24 times in a random order resulting in a total of 600 trials. Participants were told to ignore the prime if they detected it.

Results

Data of all participants were analysed. Figure 6 (upper part) indicates that priming shifted the psychometric distributions horizontally. The shift is larger with small distances than with large distances. A one-way ANOVA of PSS revealed a significant main effect of priming, $F(4, 36) = 12.06$, $p < .01$. Post hoc Bonferroni comparisons ($p < .05$) indicated that the 0° distance condition differed from any other condition except for the 1.3° condition, and the

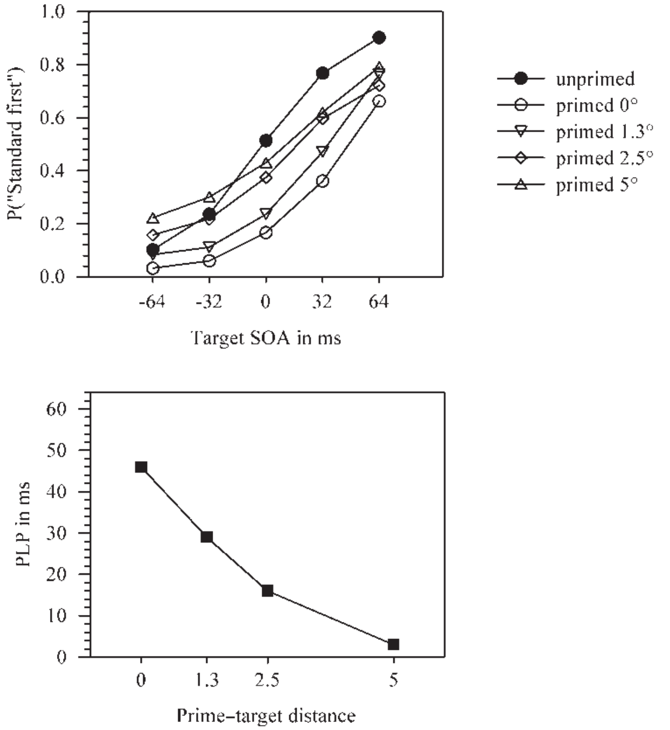

Figure 6. Psychometric functions (above) and PLP values (below) for Experiment 3a employing a congruent prime and long targets. Attentional facilitation is present only with prime–target distance of less than 2.5°.

1.3° condition additionally was different from the 5° condition. All other comparisons were negative. A similar pattern of results was revealed by one-tailed t tests of PLP. In the 2.5° and 5° condition, PLP did not differ from zero; 2.5°, +16 ms, $t(9) = 1.37$, $p = .10$; 5°, +3 ms, $t < 1$. In the 0° condition, PLP was +46 ms and significantly different from zero, $t(9) = 6.18$, $p < .0001$. With overlapping prime and target, PLP amounted to +29 ms, which was again significantly different from zero, $t(9) = 3.69$, $p < .01$ (see Figure 6, lower part, for the PLP results).

Discussion

In contrast to the experiments reported above, Experiment 3a revealed a graded distribution of attention. Facilitation was present if prime and comparison stimulus were centred at the same location or if the prime was displaced by 1.3° of visual angle and thus overlapped the comparison stimulus. With larger prime distance, PLP was smaller. Numerically, the results support an attentional gradient account: PLP decreases with prime–target distance. The gradient possibly covers at most 5° of visual angle. Statistically, the picture is less clear: Facilitation was either present (0° and 1.3°, which did not differ among themselves) or absent (2.5° and 5°, again not differing).

No evidence for object-based attentional facilitation or confusion of prime and target was revealed by the comparison of Experiments 2a and 2b. Experiment 3b was designed to replicate this finding with long-duration targets. Also, by replicating Experiment 3a, it might resolve the ambiguity between the numerical and the statistical results.

EXPERIMENT 3B

Following the same logic as that in Experiment 2b, Experiment 3b replicates Experiment 3a with neutral primes.

Method

Participants

A total of 15 voluntary participants whose informed consent was obtained took part in the experiment (11 female; mean age 29.9 years) and received €4.50.

Apparatus, stimuli, and procedure

Apparatus, stimuli, and procedure were identical with those of Experiment 3a except that neutral primes (discs) were used.

Results

Data of 2 participants were not analysed. Figure 7 (upper part) indicates that only same-location primes shifted the psychometric distributions. A one-way ANOVA of PSS revealed no main effect of priming, $F(4, 48) = 2.04$, $p = .17$. However, a one-tailed t test of PLP revealed a highly significant PLP effect of +22 ms in the 0° condition, $t(12) = 6.25$, $p < .0001$. The other PLP values did not differ from zero; 1.3°, +8 ms, $t(12) = 1.06$, $p = .16$; 2.5°, +12 ms, $t(12) = 1.09$, $p = .15$; 5°, –4 ms, $t < 1$. In general, PLP was smaller than that in the previous experiments.

Discussion

In Experiment 3b, attentional facilitation was closely centred around its focus. Stimuli sharing the location of a visual prime achieved facilitation, whereas displaced stimuli gained only small benefits that statistically did not differ from zero. Also, the absolute amount of facilitation in the nondisplaced condition was small. If attention was attracted by the prime to the target location, a reallocation of attention was unnecessary. However, attention apparently had to be disengaged, shifted, and reengaged (Posner & Cohen, 1984) if prime and target were spatially separated, and more likely so if the prime did not share the target's features. Combined, the results of Experiments 3a and 3b reveal that graded distributions of attention may arise and that they may be of different size, but are at most 5° of visual angle.

It is yet unclear how target duration, the variable changed between Experiments 2 and 3, can affect the allocation of attention. Of course, temporal judgements of visual stimuli may be affected by the duration of stimuli. For example, offsets may influence the judgements with short-duration stimuli. If offsets were less subject than onsets to attentional facilitation, PLP should be smaller with stimuli with offsets. By contrast, PLP was, if anything, larger for stimuli with offsets in the present experiments (see also Experiment 1 in Scharlau &

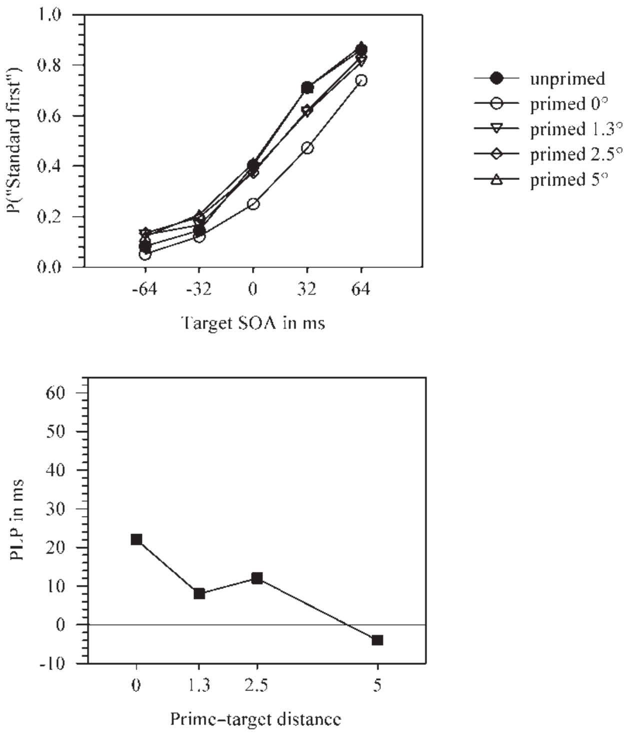

Figure 7. Psychometric functions (above) and PLP values (below) for Experiment 3b employing a neutral prime and long targets. Attentional facilitation is present only with prime and target presented at the same location.

Neumann, 2003b). Also, duration would have to interact with spatial separation to explain the difference between Experiments 2a/b and 3a/b. I return to this question in the General Discussion.

EXPERIMENT 4

In recent years, several authors have claimed that attention selects objects rather than unparsed locations of visual space (for reviews, see Driver & Baylis, 1998; Kanwisher & Driver, 1992; Lamy & Tsal, 2001). For example, a perceptual judgement of two properties is easier if the properties belong to the same object than if they belong to two different objects even if the distance of the features is the same (Duncan, 1984). Further, irrelevant flanker stimuli in an Eriksen task interfere stronger with responding if they are grouped with the target by a common feature (Baylis & Driver, 1992; Driver & Baylis, 1998; Kramer & Jacobson, 1991). The absence of distance effects in Experiments 1 and 2 and the small size of spatial effects in Experiment 3 render object-based selection a possible alternative explanation for PLP: Attention might have been allocated to the prime, which was amalgamated into a single object with the primed target. Contrary to this explanation, no difference between target-like (congruent) and target-dissimilar (neutral) primes was found in Experiment 2. Target-like primes, however, should be more easily integrated with the target than should dissimilar primes. Experiment 3 indicated a small difference: Here, the influence of target-dissimilar primes was smaller and spatially more confined than the influence of target-similar primes. However, this comparison is between experiments. Experiment 4 aims at directly determining to which part PLP is mediated by object-based selection.

In Experiment 4, object-based and space-based mechanisms are studied jointly. A target is primed either by a smaller replica of itself (congruent condition) or by a neutral shape that cannot as easily be amalgamated into a single object. Further, prime–target distance is varied. The prime is either presented at the exact location of the primed target, or shifted from the primed target's location by 9° of visual angle. Targets are presented at a distance of either 9° or 13° of visual angle. In the latter case, the displaced prime is equally close to both targets. This condition is well suited to assess object-based attentional effects because it excludes spatial facilitation. The targets are equally distant from the prime, and thus either they will both not profit from the prime, or they will both be facilitated to the same amount. By contrast, object-based attentional selection allows for facilitation in the congruent priming condition, but not in the neutral one.

Method

Participants

A total of 12 voluntary participants whose informed consent was obtained took part in the experiment (8 female; mean age 29.2 years). They received €5.

Apparatus, stimuli, and procedure

Apparatus, stimuli, and procedure were identical with those of Experiment 1b except for the following differences. There were two separate blocks given in random order to participants, one with a congruent prime (a smaller replica of the comparison stimulus), and the other one with a neutral prime (a circle of approximately the same intensity as that of the congruent prime). Target distance was either 9° or 13°. The prime–target distance was either 0° or 9°, or no prime was shown. There were 60 conditions (5 target SOAs × 2 target distance conditions × 3 prime distance conditions × 2 prime congruency conditions, the latter blocked). Target distance was included as a factor since an interaction of prime distance and target distance was expected: With large target distance and large prime distance, the prime was equally close to both targets, so that spatial facilitation should be absent. Each condition was presented 16 times in a random order resulting in a total of 480 trials per block.

Results

The data of one participant had to be discarded. Figure 8 (upper parts) indicates that priming shifted the psychometric distributions horizontally with both congruent and neutral primes. However, this is reduced to three experimental conditions: both two conditions in which prime and primed target shared a location, and the condition in which the prime was closer to the comparison than to the standard stimulus. By contrast, a prime that was equally distant from the comparison and the standard stimulus had only a marginal effect. Moreover, this effect was independent of its perceptual similarity with one of the targets.

A three-way ANOVA of PLP revealed a highly significant main effect of priming, $F(1, 10) = 88.49$, $p < .0001$. It is qualified by a target distance by priming interaction, $F(1, 10) =$

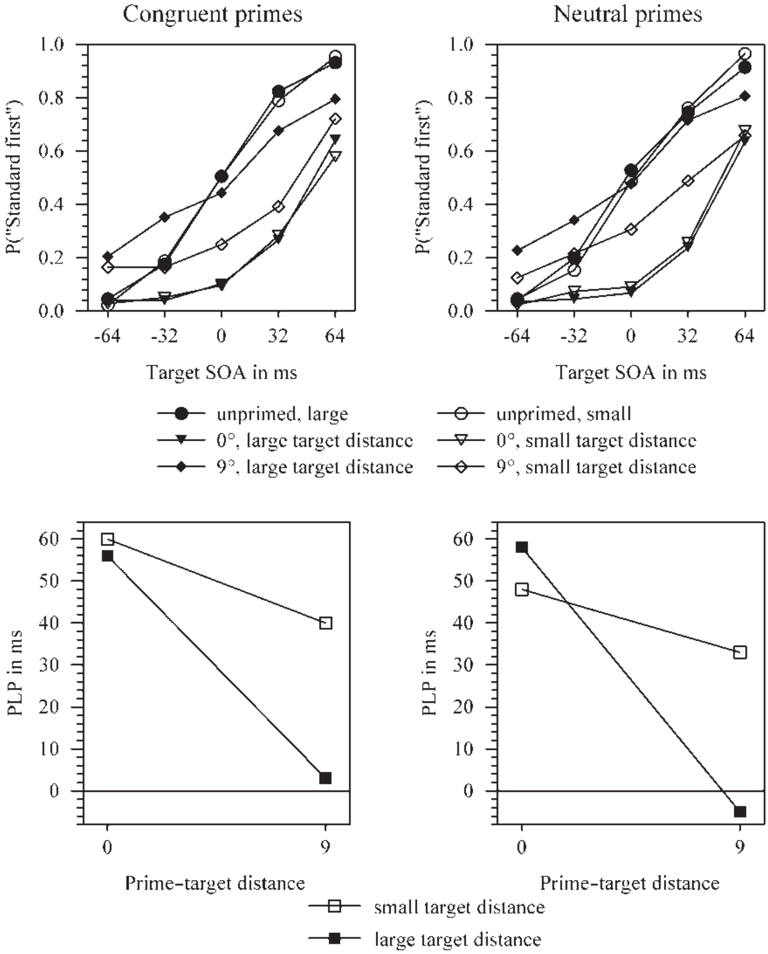

Figure 8. Psychometric functions (above) and PLP (below) in Experiment 4. Left column: congruent primes. Right column: neutral primes. No PLP is found if the prime is equally distant from both targets, and PLP is only slightly larger for congruent than for neutral primes.

49.39, $p < .0001$. Target distance as a main factor was also just significant, $F(1, 10) = 7.77$, $p < .05$, as well as prime congruency, $F(1, 10) = 5.03$, $p < .05$. PLP was slightly smaller with neutral than with congruent primes (34 vs. 40 ms; see Figure 8, lower parts). PLP values were separately tested against zero in one-tailed t tests. In all conditions except for the two spatially nonpredictive conditions, PLP was statistically different from zero: prime distance 0°/target distance 9°/ congruent prime, +60 ms, $t(10) = 12.46$, $p < .0001$; 9°/9°/congruent, +40 ms, $t(10) = 5.55$, $p < .001$; 0°/13°/congruent, +56 ms, $t(10) = 10.35$, $p < .0001$; 9°/13°/congruent, 3 ms, $t < 1$; 0°/9°/neutral, +48 ms, $t(10) = 12.75$, $p < .0001$; 9°/9°/neutral, +33 ms, $t(10) = 3.95$, $p < .01$; 0°/13°/neutral, +58 ms, $t(10) = 6.93$, $p < .0001$; 9°/13°/neutral, –5 ms, $t(10) = –1.01$, $p = .35$.

Discussion

Experiment 4 investigated the possibility of object-based attentional selection in the PLP design. Very small object-based mechanisms in PLP were found, combined with effective spatial mechanisms. (1) The differential attentional effect of congruent and neutral primes was only just significant, and the PLP difference (6 ms) was very small, amounting to less than 20% of PLP averaged across all conditions. (2) The condition in which the prime was spatially nonpredictive (i.e., equally distant from both targets) was regarded as a critical test of object-based selection. Any PLP effect found here would be of object-based origin. However, neither congruent nor neutral primes entailed PLP in this condition. Most importantly, congruent primes did not prime the object representation of the similar target. However, spatial mechanisms of priming were clearly present in Experiment 4: Spatially predictive primes and those that were closer to one than the other target entailed PLP. Further, the amount of PLP was again reduced with larger prime–target distance.

GENERAL DISCUSSION

Illusory line motion, the apparent motion of a line attended at one of its ends, has been ascribed to an attentional gradient centred around the cue. The attentional gradient was supposed to facilitate perceptual latency of the line segments in proportion to the distance from the attentional focus (Hikosaka et al., 1993a, 1993b, 1993c; see also Downing & Pinker, 1985). However, the original experiments were insufficiently safeguarded against a response bias. Also, they did not directly assess the spatial distribution of attention, and the amount of facilitation could not be calculated.

The present experiments employed a closely related experimental paradigm, perceptual latency priming (PLP). In this paradigm, a prime precedes one of two targets whose temporal order is judged. Via attentional allocation, the prime reduces the perceptual latency of the primed target. This method was chosen to settle the question, raised by the explanation of illusory line motion as well as the debate about spatial properties of visual attention—whether the prime elicits an attentional gradient that facilitates target perception in proportion to prime–target distance. With this paradigm, only marginal evidence for an attentional gradient was found. (1) From the attentional gradient account, the prediction was derived that both judgement accuracy and PLP should increase with target–target distance. Neither of these predictions was fulfilled. Judgement accuracy and PLP were independent of spatial distance, apart from a small reduction in accuracy with overlapping targets. This latter finding may be due either to a very small gradient or to perceptual confusion (Experiments 1a and 1b). (2) A second prediction from the gradient account is that PLP should decrease with an increase in prime–target distance. However, with short-duration targets, PLP was independent of prime–target distance, and it was large (Experiments 2a and 2b). Combined, both results support a broad distribution of attention jointly with strong effects. (3) With long-duration targets, PLP was smaller than with short targets. Also, it depended heavily on prime–target distance and was possibly distributed as a gradient. Facilitation was reliable for same-location and, given the prime was target similar, for overlapping prime–target pairs. With larger separation, there was still some priming effect, but it failed to reach significance even with distances as small as 2.5° (Experiments 3a and 3b). Long target duration thus seems to be a sufficient precondition for attentional gradients. The gradient was at utmost 5°, but possibly less than 2.5° of visual angle. This accords well with findings from other paradigms (Eriksen & Eriksen, 1974; LaBerge, 1983). By contrast, the gradient's size is not sufficient to explain illusory line motion. Here, the line is typically longer than 5°. As a control, Experiment 4 compared object-based and space-based attentional selection and found no contribution of object-based selection. This supported the evidence from the comparison of Experiments 2a and 2b, as well as Experiments 3a and 3b: Attention to objects does not provide an explanation of PLP.

In sum, the present experiments did not find evidence for the notion that attention is necessarily distributed in a gradient fashion. How is the pattern of results—broad region of facilitation jointly with strong effects for short-duration targets, but a sharp gradient and smaller effects with long-duration targets—to be explained? In the following, I consider some alternative explanations for the effect of target duration, followed by closing remarks on the spatiotemporal characteristics of attention in PLP.

First, it may have been easy to tell the short-duration prime from the long-duration targets in Experiment 3, whereas in the other experiments the temporal characteristics of prime and targets were more similar, and, consequently, discrimination was more difficult. If there was easy discrimination, the primes might not be attended to, or attention, once focused on the prime, might be quickly disengaged from the prime's location. By itself, this explanation is not fully satisfying because it cannot account for the presence of PLP with nondisplaced primes in Experiment 3. It may, though, account for part of the effects. Future research should address this question by varying prime and target duration independently.

Second, the identification task used in the present experiment was a simple one that required only the detection of simple features (orientation or colour; combined with the respective onsets). Possibly, it can be accomplished without localization of the stimuli. In recent years, there has been considerable debate about whether attending to features is mediated by mandatory attention to the location of this feature in visual space. The strongest evidence for this location dominance hypothesis has been reported by Tsal and Lavie (1993). They found that even if attending to location was useless for a task, attending to colour was accompanied by location-specific facilitation (see also Tsal & Lavie, 1988). The experiments reported above demonstrate that attending to location is not mandatory but mediated by processing the relevant stimuli and, possibly, by the representational level on which attention operates. The short stimuli might have been identified either without localization or with localization errors that cancelled out distance effects. Only with long-target duration might the position of the targets have been processed (see, e.g., White, 1969, for a similar account), and the prime's position was able to influence perceptual latency.

Third, spatial attention may have been involved in the present experiments, but it might be more difficult to hold attention in an empty field than in a field in which stimulation is present. Thus, the long-duration targets may have facilitated attentional focusing as compared to short duration targets. This account converges with the finding of Zimba and Hughes (1987) that gradient distributions were absent in a blank visual field but could be achieved when possible target locations were indicated by landmarks.

Fourth, a mechanism inherent in object-based models may have contributed to the results. Several recent studies have demonstrated that, rather than unparsed regions of the visual field, objects or groups attract attention (for reviews, see Driver & Baylis, 1998; Kanwisher &

Driver, 1992; Lamy & Tsal, 2001). Attention may thus be allocated towards a representation that is independent of location. Alternatively, it may depend on location only in that spatially distinct codes can be recognized as the same object on condition that they can be integrated into a single object by a plausible motion. From studies on apparent motion it is well known that movement may be perceived between two very dissimilar stimuli (e.g., Kolers, 1972; Kolers & Pomerantz, 1971), or that the creation of an object file (Treisman & Gelade, 1980) is not disrupted if there is a reasonable change in some of the object's features (e.g., Kahneman & Henik, 1981). In line with the explanation of illusory line motion by impletion (Downing & Treisman, 1997), PLP may thus be mediated by an impletion process between, or a single object file of (Yantis & Gibson, 1994), the stimuli presented in PLP designs. How impletion and apparent motion work in the PLP designs used in the present study remains to be investigated. Also, the contribution of feature changes to object-based attention is yet unclear.

In recent research, several conditions have been formulated that might be sufficient to create a graded distribution of visual attention. Among these are the presence of landmarks in the visual field (Zimba & Hughes, 1987; see also Hamm & Klein, 2002). Another sufficient precondition may be the necessity to generate a directed movement (a spatially defined movement; Hodgson, Müller, & O'Leary, 1999). Also, the presence and size of gradients may be influenced by the task demands and the respective attentional allocation strategies: Reaction times show broader gradients than do measures of perceptual sensitivity (Handy, Kingstone, & Mangun, 1996). The present research adds a further factor to this list—that is, the duration of target stimuli. How reliable this factor is, and whether it generalizes, for example, to the duration of the prime, remains to be investigated.

It should also be noted that spatial attention is not necessarily distributed in either a graded or an ungraded, broad fashion. Cave and coworkers (e.g., Cave & Zimmerman, 1997; Cepeda, Cave, Bichot, & Kim, 1998; Kim & Cave, 1995) demonstrated that attention might be tightly focused on the target area. They reasoned that the amount to which attention is focused is adjusted to the possible amount of distractor interference. If distractors are highly similar to the target, precise focusing is necessary, but it is unnecessary if the distractors are not easily confused with the target. Cave and Zimmerman (1997) also reported that distractors near to the target were inhibited stronger than far distractors, a finding that is in contrast to attentional gradients. In the present experiments, the two targets were possibly easy to tell apart. Further, it is unclear whether there is a distractor present in the temporal order judgement task. The task requires the observers to attend to both of the targets. It is, however, possible to regard the trailing target as a distractor, if observers attended solely to the first target and reported its shape. Settling this question requires further research.

Let me conclude by summarizing which spatio-temporal characteristics a model of attentional control in PLP should cover. In sum, the results are most easily reconciled with a model in which attentional orienting takes the form of a focusing process (see, e.g., Shepherd & Müller, 1989), which begins with a wide focus that may be subsequently narrowed. The spatial precision of the narrowing processing depends on the stimulation present in the display. (1) Soon after prime onset, attention is distributed over a large field (Experiments 1 and 2). This facilitation is strong (remember the large size of PLP in Experiment 2). This feature contrasts with the zoom lens model in which strength or power of attention and its field size are inversely related (Eriksen & Yeh, 1985). (2) This wide-focus attentional state is sustained if stimulation in the visual field is short lived or if the field is blank (see Zimba &

Hughes, 1987). (3) If there are landmarks present in the visual field, attention may efficiently narrow down to a small focus. (4) Possibly, the sustained presence of information helps to direct attention away from task-irrelevant information (the prime—remember the small size of PLP in Experiment 3a and the yet smaller size in Experiment 3b). (5) However, this top-down control of attention possibly is weak, as revealed by the small effect of prime identity in Experiment 4. (6) In PLP, attention operates on a representational level in which objects play a minor role. Alternatively, if objects are involved, they are insensitive to changes of simple features of the objects.

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Original manuscript received 23 September 2002
Accepted revision received 1 September 2003
PrEview proof published online date/month/year