

# Fixation disengagement enhances peripheral perceptual processing: evidence for a perceptual gap effect

Lynn Huestegge · Iring Koch

Received: 24 February 2009 / Accepted: 30 October 2009 / Published online: 15 November 2009  
© Springer-Verlag 2009

**Abstract** Temporal gaps between the offset of a central fixation stimulus and the onset of an eccentric target typically reduce saccade latencies (saccadic gap effect). Here, we test whether temporal gaps also affect perceptual performance in peripheral vision. In Experiment 1, subjects executed saccades to briefly presented peripheral target letters and reported letter identity afterwards. A central fixation stimulus either remained visible throughout the trial (overlap) or disappeared 200 ms before letter onset (gap). Experiment 2 tested perceptual performance without saccade execution, whereas Experiment 3 tested saccade execution without perceptual demands. Peripheral letter perception performance was enhanced in gap as compared to overlap conditions (perceptual gap effect) irrespective of concurrent oculomotor demands. Furthermore, the saccadic gap effect was modulated by concurrent perceptual demands. Experiment 4 ruled out a general warning explanation of the perceptual gap effect. These findings extend recent theories assuming a strong coupling between the preparation of goal-directed saccades and shifts of visual attention from the spatial to the temporal domain.

**Keywords** Premotor theory of attention · Saccades · Eye movements · Peripheral letter perception · Gap effect

## Introduction

During the daily interaction with our environment, a vast array of perceptual information needs to be processed, and

numerous behavioral options coexist at any given moment in time. A prerequisite for successfully coping with these demands is an efficient selection mechanism that (a) prioritizes processing of both relevant perceptual information and relevant action-related goals and (b) generates meaningful links between the perception and action domains. The concept of attention has traditionally been proposed to encompass these input- and output-related selection processes (e.g., Pashler 1998). Whereas the more traditional view of attention has mainly focused on input-related mechanisms, highlighting the need of selection for subsequent conscious perception, memory, recognition, or visual search (e.g., Broadbent 1958; Sperling 1960; Treisman 1988), the last 2 decades witnessed increasing interest in selection for the purpose of planning goal-directed actions (e.g., Allport 1987; Neumann 1987; Van der Heijden 1992).

The visual system directly incorporates both functional roles of attention. It encodes visual stimuli while at the same time programming motor actions (i.e., saccades) on the basis of these stimuli and can therefore be regarded as a natural integrator of perception and action (Findlay and Gilchrist 2003). The present study aims at further clarifying how the visual system integrates perceptual and action-related demands.

Previous research has established overwhelming evidence for a close link between input- and output-related attentional mechanisms in the visual domain by demonstrating a strong correlation of the spatial location of a saccade target and the location of prioritized perceptual processing on a behavioral and neurophysiological level. Although humans are able to select visual information in peripheral vision without a concurrent shift of gaze (i.e., covert spatial attention, see Posner 1980), many studies have questioned whether it is possible to shift gaze without enhanced

---

L. Huestegge (✉) · I. Koch  
Institute of Psychology, RWTH Aachen University,  
Jägerstrasse 17-19, 52066 Aachen, Germany  
e-mail: Lynn.Huestegge@psych.rwth-aachen.de

perceptual processing at the saccade target location, or to produce shifts of gaze and covert attention to different spatial locations at the same time. To address this issue, in a typical experiment subjects are asked to saccade to a specified location and to detect a target letter that is briefly presented before the initiation of the eye movement at that or a different location. Typically, letter perception accuracy is best at or around the position of the saccade target (Deubel and Schneider 1996; Hoffman and Subramaniam 1995; Kowler et al. 1995). Similar results were obtained by using response times instead of accuracy rates as an indicator for perceptual efficiency (Shepherd et al. 1986). Furthermore, primate single-cell recording studies in which saccade-triggering neurons in the frontal eye field received sub-threshold microstimulation (i.e., without the occurrence of saccades) revealed facilitated perceptual performance at locations within the motor field of these neurons (see Desimone et al. 1989; Moore and Armstrong 2003; Moore and Fallah 2004).

Whereas these studies presented evidence for a modulation of performance in the perceptual task resulting from manipulations of attention by the simultaneous motor task, another line of evidence comes from studies that reversed this reasoning. For example, primates who attend to a specific location while performing a saccade exhibited deviated trajectories of the saccades as a function of the location of covert attention (Kustov and Robinson 1996). Additionally, subjects who are either experimentally or pathologically disabled to move their eyes to specific locations show corresponding deficits in covert attention (Craigheo and Rizzolatti 2005; Sheliga et al. 1995; Smith et al. 2004).

Apart from this behavioral evidence for a tight coupling of saccade targeting and corresponding perceptual processing, many neuroscience studies in humans and primates provided additional evidence. For example, tasks involving covert spatial orienting of attention activate similar neural networks (e.g., Beauchamp et al. 2001; Corbetta et al. 1998; De Haan et al. 2008; Nobre et al. 2000; Rosen et al. 1999; Van der Lubbe et al. 2006), trigger similar ERP components (Eimer et al. 2007), and activate the same distinct type of neurons in the superior colliculus (Ignashchenkova et al. 2004), as do similar tasks that require the execution of saccades. Similar results were also obtained for pursuit movements instead of saccades (Ohlendorf et al. 2007). By comparison, only comparatively minor differences between overt and covert attentional shifts were demonstrated, mainly regarding the overall activation intensity and specific parts of the networks involved (e.g., see De Haan et al. 2008; Juan et al. 2008; Khan et al. 2009).

Based on the empirical findings referred to above, several theoretical frameworks were derived. Whereas some of them merely postulate that overt and covert orienting systems are functionally related (e.g., Posner 1980), others are

more specific about their interplay. For example, Wurtz and Mohler (1976) speculated that shifts of attention might be identical to saccade programs. Similarly, the oculomotor readiness account (Klein 1980) holds that when attention is directed to a specific location, this prepared (but not executed) eye movement enhances information processing at the respective location. Subsequently, the premotor theory of attention (Rizzolatti et al. 1987; see also Rizzolatti et al. 1994) maintains that covert spatial attention derives from an activation of brain maps engaged in sensorimotor transformation processes. More specifically, this activation leads to both an increase in the readiness to execute a motor response to a specific location and a facilitation of perceptual processing at that location. Note that motor responses and spatial attention here are not exclusively linked to the visual system, an assumption that is supported by empirical evidence for a spatial coupling of perception and action in other modalities, such as auditory attention and manual movements (e.g., Castiello 1996; Craigheo et al. 1999; Deubel et al. 1998; Eimer et al. 2006; Tipper et al. 1992; Spence and Driver 1996).

A similar theoretical approach, the Visual Attention Model (VAM; Schneider 1995; Schneider and Deubel 2002), differs from the premotor theory mainly by assuming that the coupling between perception and spatial motor programming is object-specific rather than location-based, and by assuming that motor programming is a consequence of visual attention processes rather than its prerequisite (see also Clark 1999; Henderson 1992; Peterson et al. 2004).

Despite these differences between theoretical accounts, they have in common that spatial attention is directly linked to processes of motor preparation. However, the behavioral evidence for a tight coupling of the two attention systems only refers to the demonstration of a close link between spatial parameters in both tasks, that is, that a coincidence of target locations for both tasks leads to enhanced processing in one or both tasks. In contrast, the present study investigates whether this coupling also holds for temporal parameters. More specifically, we asked whether a temporal modulation of the motor task goes in hand with a modulation of performance in a concurrent perceptual task.

A classic way of experimentally manipulating saccade latencies is the extinction of the foveal stimulus prior to the presentation of a saccade target. In such a gap paradigm (Saslow 1967), subjects are instructed to fixate a foveal stimulus until the onset of a saccade target in the periphery. Crucially, in some trials the foveal stimulus remains present throughout the trial (overlap trial), whereas in other trials, the foveal stimulus disappears prior to the onset of the target. Typically, saccade latencies are reduced in gap trials as compared to overlap trials (i.e., the gap effect). Subsequent research provided evidence for the assumption that the temporal gap might act as a warning signal allowing for

temporal preparation for target onset (e.g., Kingstone and Klein 1993; Reuter-Lorenz et al. 1991; Ross and Ross 1980; Tam and Stelmach 1993). Neurophysiological studies revealed that the extinction of the foveal stimulus releases ocular inhibition in the superior colliculus (Dorris and Munoz 1995). Although other types of warning signals also reduce saccadic RTs (e.g., color/luminance changes of the foveal stimulus, acoustic stimuli, or visual/acoustic compound stimuli), the classic gap paradigm is typically the most effective (e.g., Pratt et al. 2000).

Previous paradigms that combined the gap paradigm with perceptual requirements (e.g., Mackeben and Nakayama 1993; Pratt and Nghiem 2000; Song and Nakayama 2007) are not suited to specifically address the issue whether central fixation offset alone enhances perceptual performance in the periphery. First, most of these studies involved the presentation of an additional spatial cue in the periphery prior to target onset, thus not allowing one to estimate the effect of central fixation offset alone (Mackeben and Nakayama 1993; Pratt and Nghiem 2000). Second, some did not involve the measurement of eye movements to specify the interplay of eye movements and attention (e.g., Mackeben and Nakayama 1993). Third, most of these studies involved a speeded manual RT task as a measure of perceptual performance, so that it cannot be ruled out that gap conditions mainly affected response-related instead of perceptual abilities (Pratt and Nghiem 2000; Song and Nakayama 2007, Experiment 3). Indeed, it was demonstrated that central fixation offset reduces manual RTs in speeded manual tasks (e.g., Bekkering et al. 1996), and thus a more unbiased measure of perceptual (instead of motor-related) performance might be achieved by utilizing a non-speeded perceptual task. Thus, the question of whether a central fixation offset directly affects perceptual performance in the periphery still remains unresolved.

The rationale of the present study was as follows: if the introduction of a gap between central fixation stimulus offset and peripheral saccade target onset leads to faster fixation disengagement, and attentional processes in the perception and action domains are coupled not only spatially, but also temporally, then attentional disengagement should be faster, subsequently leading to more efficient perceptual processing at the peripheral saccade target location. Furthermore, when both types of attention involve similar neural networks, a perceptual attention task might draw on the same resource as the programming of saccades and should thus alter the gap effect on saccade RTs as compared with a situation in which a perceptual attention task is not explicitly instructed.

To investigate these claims, we combined the gap paradigm with a peripheral letter perception task. Perceptual accuracy was tested by a letter recognition requirement at the end of each trial. In Experiment 1, subjects were asked

to saccade to briefly presented letters at various locations in the periphery and to report letter identity. Well before letters can be processed foveally, they were replaced (i.e., masked) by squares. Crucially, in some trials the central fixation stimulus remains constant throughout the trial (overlap trials), whereas in others it was removed 200 ms prior to the onset of the saccade target, an interval which is known to elicit the largest gap effect (e.g., Fischer and Weber 1993). While there are various theoretical accounts assuming different components of the saccadic gap effect (e.g., Kingstone and Klein 1993), the present study only hinges on the use of the gap paradigm as an effective way of manipulating fixation release times, irrespective of the specific components that may be involved to achieve this effect. We predicted that letter discrimination performance should be enhanced in gap trials as compared to overlap trials. In Experiment 2, we used the same setting but instructed subjects to remain fixated on the central fixation cross throughout the experiment to determine whether any performance enhancement in the perceptual task relies on the concurrent overt execution of saccades. In Experiment 3, subjects were only asked to saccade to the peripheral targets, without the need to identify the letters. We reasoned that this allows an assessment to which degree the gap effect on eye movements in Experiment 1 is modulated by the concurrent perceptual task. Finally, Experiment 4 was designed to rule out a general warning explanation of any gap effects on perceptual performance.

## Experiment 1

### Method

#### *Participants*

Sixteen students from RWTH Aachen University with normal or corrected-to-normal vision took part in this study, ten female and six male. Mean age was 25 years ( $SD = 7.18$ ), ranging from 20 to 47. They gave their informed consent and received credits for participation.

#### *Apparatus and stimuli*

Participants were seated 67 cm in front of a 21" cathode ray monitor (temporal resolution: 100 Hz, spatial resolution:  $1,240 \times 1,068$  pixels) with a keyboard in front of them. The spacebar of the keyboard was used during calibration routines. Saccade latencies and amplitudes were registered using a head-mounted Eyelink II infrared reflection system (SR Research, Osgoode, Ontario, Canada). One camera measured the position of the pupil of the right eye with a temporal resolution of 500 Hz and a spatial resolution

$<0.022^\circ$ . A chin rest was used to minimize head movements, which were compensated for online with the help of a second camera recording the position of the head relative to the monitor. On the keyboard, the arrow keys and the space bar were chosen as response keys for the perceptual identification task. Subjects were asked to operate the arrow keys with four fingers of the right hand, whereas their left hand was placed above the space key.

### Procedure

Each trial began with the presentation of a central fixation cross that remained present for 1,500 ms (1,300 ms in gap trials). Then, at one out of four possible horizontal positions ( $3^\circ$  or  $6^\circ$  to the left or right) a letter was presented for 90 ms and afterwards masked by a square. The mask remained present for 800 ms. The size of the fixation cross, the letters (courier font), and the squares was  $1/3^\circ$  each. All stimuli were presented in green on black background. Crucially, in half of the trials the central fixation cross remained present throughout the trial (overlap condition), whereas in the remaining trials, the central fixation cross was extinguished 200 ms prior to the onset of the letter in the periphery (gap condition). Subjects were instructed to saccade to the peripheral target as fast and accurately as possible and to report letter identity at the end of each trial. The letter presentation time was fixed to 90 ms. Preliminary experiments were conducted to ensure that no floor or ceiling effects in perceptual performance occurred. After the presentation of the square, subjects were asked to fixate the central fixation cross for 1,000 ms. Finally, a keyboard was presented visually on the screen, displaying all ten letters that were used as target letters in the experiment (A, C, D, H, I, K, R, S, V, W), in addition to a question mark (“?”). This visually presented keyboard was operated by using the arrow keys of the keyboard, and a selection was confirmed by pressing the space bar, which automatically triggered the next trial. Subjects were encouraged to select one of the letters even when they were not sure about their choice, and to use the question mark only when they were completely unsure of which letter they had seen.

In total, the experiment consisted of 240 trials presented in randomized order, with an additional 30 practice trials at the beginning that were not further analyzed. The duration of the experiment amounted to about 40 min. Prior to the experiment, subjects underwent a calibration routine.

### Design

The variables target eccentricity ( $3^\circ$  vs.  $6^\circ$ ) and task condition (gap vs. overlap) were manipulated intraindividually.

As dependent variables, we measured saccade latencies and saccadic gain, computed as the difference between actual target position and the landing position of the primary saccade, as well as accuracy in the letter perception task.

### Results and discussion

Because of blinks, measurement error, trials without an execution of a saccade with a minimal amplitude of  $1^\circ$ , or trials involving anticipations (saccade RTs  $<70$  ms, see Fischer and Weber 1993), we discarded 2.6% of trials.

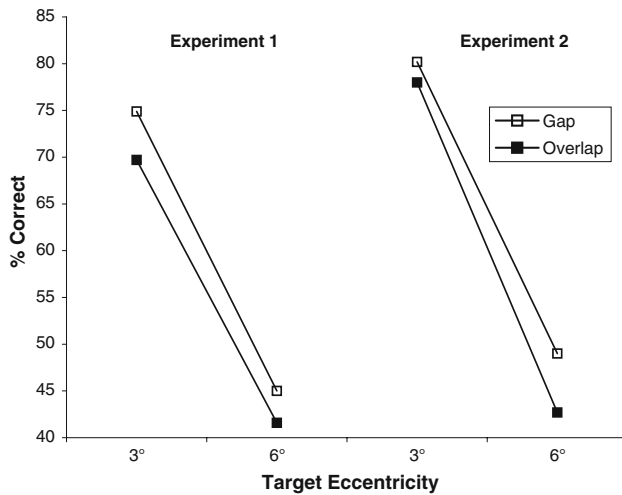
A two-way ANOVA of mean saccade RTs (correct trials only) with task condition (gap vs. overlap) and target eccentricity as independent variables yielded a significant main effect for task condition,  $F(1,15) = 119.60$ ,  $p < .001$ ,  $\eta_p^2 = 0.89$ , indicating longer RTs in the overlap condition (186 ms) than in the gap condition (145 ms). The overall size of this expected gap effect (41 ms) is comparable to classic findings with a 200 ms gap interval (e.g., Saslow 1967; Reuter-Lorenz et al. 1991).

There was no significant main effect of eccentricity,  $F < 1$ . However, there was a significant interaction of task condition and eccentricity,  $F(1,15) = 4.62$ ,  $p = .048$ ,  $\eta_p^2 = 0.24$ , indicating that the difference between gap and overlap trials was greater for targets at  $6^\circ$  eccentricity (44 ms) than for targets at  $3^\circ$  eccentricity (39 ms). This interaction is not quite in line with previous studies, which rather reported no significant modulation of the gap effect as a function of target eccentricity (e.g., Shafiq et al. 1998). However, the effect was comparatively small and was not replicated in Experiment 3 (see below).

An analysis of saccadic gain revealed an overall undershoot of the saccade targets of about  $0.1^\circ$ , but this did neither differ as a function of task condition,  $F(1,15) = 1.19$ ,  $p > 0.10$ , nor of eccentricity,  $F < 1$ . The interaction of eccentricity and task condition was also not significant,  $F < 1$ .

Letter perception performance was significantly above the guessing probability of 10% for each individual subject. Most importantly, accuracy was higher in gap trials (60.0%) as compared to overlap trials (55.6%),  $F(1,15) = 12.30$ ,  $p = .003$ ,  $\eta_p^2 = 0.45$  (see Fig. 1). Therefore, the introduction of a gap led to a significant increase in perceptual performance, despite the fact that subjects were not able to process the letters foveally due to the brief presentation time and the subsequent masking. This perceptual gap effect strongly supports our prediction that faster fixation disengagement also goes in hand with faster attentional disengagement, subsequently leading to an increase in perceptual performance at the saccade target location.

Additionally, accuracy was higher for targets at  $3^\circ$  (72.3%) as compared to targets at  $6^\circ$  eccentricity (43.3%),  $F(1,15) =$



**Fig. 1** Perceptual accuracy (%) as a function of task condition (overlap vs. gap) and target eccentricity (3° vs. 6°) in Experiments 1 and 2. Note that an accuracy of 10% equals guessing rate

193.64,  $p < 0.001$ ,  $\eta_p^2 = 0.93$ . There was no significant interaction of task condition and eccentricity,  $F < 1$ .

## Experiment 2

Experiment 2 was conducted to determine whether the obtained perceptual gap effect depends upon the overt execution of goal-directed saccades. To this end, we utilized the same setting as in Experiment 1, but explicitly instructed subjects not to saccade to the peripheral targets.

### Method

#### Participants

Sixteen new students from RWTH Aachen University with normal or corrected-to-normal vision took part in this study, eleven female and five male. Mean age was 24 years ( $SD = 4.79$ ), ranging from 21 to 35. They gave their informed consent and received credits for participation.

#### Apparatus, stimuli, procedure, and design

The apparatus, stimuli, procedure, and design was identical to Experiment 1, except that subjects were explicitly instructed to remain fixated at the center of the screen throughout the experiment. Besides the computation of accuracy, we measured eye movements only to ensure that subjects followed the central fixation instruction. Trials with erroneously executed saccades towards the peripheral

targets, defined as saccades with a minimal amplitude of 1°, were removed from further analysis.

## Results and discussion

In some trials, subjects were not able to suppress a saccade ( $M = 21.8\%$ ,  $SD = 11.8$ ), suggesting that it was comparatively difficult to follow task instructions. Some subjects reported that they experienced the illusion to perceive target letters more clearly when they fixated them, which may have contributed to this finding. The occurrence of these erroneous saccades did not significantly differ between gap and overlap conditions,  $t(15) = 1.93$ ,  $p = 0.072$ . These trials were discarded from the further analysis.

Figure 1 shows the mean accuracy in the letter perception task as a function of task condition and eccentricity for the remaining trials. Accuracy was higher in gap trials (64.6%) as compared to overlap trials (60.3%),  $F(1,15) = 8.15$ ,  $p = 0.012$ ,  $\eta_p^2 = 0.35$ . Additionally, accuracy was higher for targets at 3° eccentricity (79.1%) as compared to targets at 6° eccentricity (45.8%),  $F(1,15) = 189.44$ ,  $p < .001$ ,  $\eta_p^2 = 0.93$ . There was no significant interaction of task condition and eccentricity,  $F(1,15) = 1.59$ ,  $p > 0.10$ .

To compare accuracy performance between Experiments 1 and 2, we computed a further ANOVA with experiment as an additional independent variable. However, there was no overall accuracy difference,  $F < 1$ . Furthermore, there was no significant interaction of experiment with either eccentricity,  $F(1,30) = 1.80$ ,  $p > 0.10$ , or with task condition,  $F < 1$ . The three-way interaction of experiment, eccentricity, and task condition was also not significant,  $F(1,30) = 2.12$ ,  $p > 0.10$ . In sum, Experiment 2 replicated the perceptual gap effect also in the absence of overtly executed saccades. This is consistent with the claim that perceptual demands are linked to the (non-observable) programming of saccades, as stated by several theoretical accounts (e.g., the premotor theory). However, additional independent evidence in favor of common resources involved in peripheral perception and the programming of eye movements is desirable.

## Experiment 3

Experiment 3 was conducted to clarify whether the saccadic gap effect in Experiment 1 was modulated by the concurrent perceptual task, which would indicate common resources involved in oculomotor control and perception in the periphery. We used the same setting as in Experiment 1,

but subjects were asked to saccade to the peripheral letters only, without the need for identification.

## Method

### Participants

Since the gap effect on saccade response times is a well-established phenomenon, we tested only 12 new students from RWTH Aachen University with normal or corrected-to-normal vision, 10 female and 2 male. Mean age was 25 years ( $SD = 5.33$ ), ranging from 22 to 32. They gave informed consent and received credits.

### Apparatus, stimuli, procedure, and design

The apparatus, stimuli, procedure, and design was identical to Experiment 1, except that subjects were not instructed to identify the letters in the periphery. Within each trial, we therefore did not display the visual keyboard. As dependent variables, we only measured latencies and saccadic gain.

## Results and discussion

Because of measurement errors, 3.9% of trials were discarded. Furthermore, additional 11.7% of trials were discarded because of blinks, saccade landing positions that did not fall into a region  $\pm 1^\circ$  of the visible target, or anticipations ( $RTs < 70$  ms). Only the remaining trials were further analyzed.

An ANOVA yielded a significant main effect for task condition (gap vs. overlap),  $F(1,11) = 55.93$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.85$ , indicating longer RTs in the overlap condition (182 ms) than in the gap condition (131 ms). There was also a main effect of eccentricity,  $F(1,11) = 17.26$ ,  $p = 0.002$ ,  $\eta_p^2 = 0.63$ , with shorter response times to targets at  $6^\circ$  eccentricity (149 ms) as compared to targets at  $3^\circ$  eccentricity (164 ms). Although this effect was not present in Experiment 1, it resembles previous data on effects of eccentricity on saccade RTs in primates for a similar range of eccentricities (Bell et al. 2000). However, there was no significant interaction of task condition and eccentricity,  $F(1,11) = 4.01$ ,  $p > 0.05$ , indicating that the gap effect did not significantly differ between the two eccentricity conditions. Since the interaction data pattern even showed a trend into the opposite direction as compared to Experiment 1 (see Fig. 1), it appears unlikely that the interaction was only non-significant due to low statistical power.

An analysis of saccadic gain revealed an overall undershoot of about  $0.05^\circ$ . Gain differed slightly but significantly as a function of eccentricity, with a tendency to undershoot targets at  $6^\circ$  eccentricity of about  $0.095^\circ$  as compared to

a slight overshoot of  $0.055^\circ$  for targets at  $3^\circ$  eccentricity,  $F(1,11) = 5.70$ ,  $p = 0.035$ ,  $\eta_p^2 = .345$ . Although this effect was quite small and not present in Experiment 1, previous studies also reported a tendency of subjects to overshoot near targets and undershoot far targets (i.e., the range effect, see, e.g., Kapoula and Robinson 1986). However, there was neither an effect of task condition (overlap vs. gap) on saccadic gain,  $F(1,11) = 1.36$ ,  $p > 0.10$ , nor a significant interaction of eccentricity and task condition,  $F < 1$ .

To compare saccade latency performance between Experiments 1 and 3, we computed a further ANOVA with experiment as an additional independent variable. There was no overall difference in latency between experiments,  $F < 1$ . Furthermore, there was no significant interaction of experiment with target eccentricity,  $F(1,26) = 1.88$ ,  $p > 0.10$ . Most importantly, however, the gap effect was significantly greater in Experiment 3 (51 ms) as compared to Experiment 1 (41 ms),  $F(1,26) = 11.43$ ,  $p = 0.002$ ,  $\eta_p^2 = 0.305$ , indicating that the additional demands of the perceptual task in Experiment 1 may have compromised the ability to take full advantage of the fixation cross offset in gap conditions. The three-way interaction was also significant,  $F(1,26) = 8.00$ ,  $p = 0.009$ ,  $\eta_p^2 = 0.235$ , indicating that the modulation of the gap effect across experiments was especially pronounced for targets at  $3^\circ$  eccentricity.

## Experiment 4

Experiment 4 was conducted to rule out a general warning explanation of the perceptual gap effect. We basically replicated the setting of Experiment 2, but additionally included general warning trials, in which 200 ms before target onset the luminance of the central fixation cross was substantially increased. In contrast to the gap condition, this should provide a warning signal without releasing fixation as in the gap trials. Instead, the luminance increase may even hold fixation when compared to the overlap condition. If the general warning account is true, the size of the perceptual warning effect (overlap accuracy minus warning accuracy) should be equal to or greater than the perceptual gap effect (overlap accuracy minus gap accuracy). If the general warning account is wrong, the warning effect should be smaller than the gap effect.

## Method

### Participants

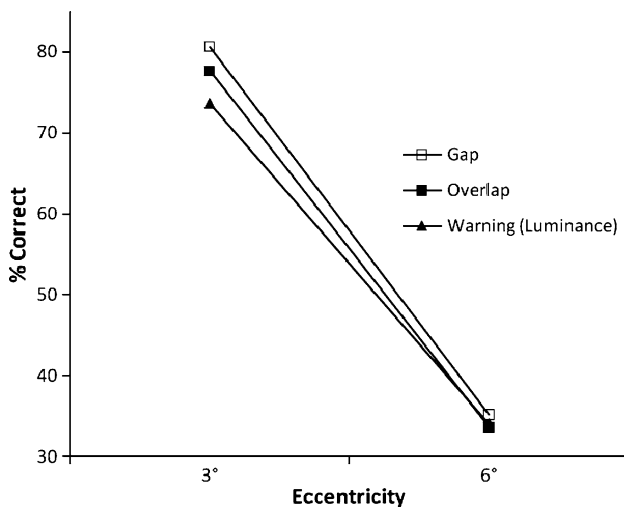
We tested 13 new subjects with normal or corrected-to-normal vision, seven female and six male. Mean age was 25 years, ranging from 21 to 31.

### Apparatus, stimuli, procedure, and design

The apparatus, stimuli, procedure, and design was identical to Experiment 2, but we added additional (randomly intermixed) warning trials in which 200 ms before target onset the luminance of the central fixation cross was substantially increased (RGB 0,130,0 to 0,255,0), resulting in 390 equally distributed trials altogether. All other stimuli (including those in gap and overlap trials) were presented at the lower luminance level. To directly test our hypothesis, we conducted a  $2 \times 2$  ANOVA with effect type (gap vs. warning) and eccentricity ( $3^\circ$  vs.  $6^\circ$ ) as independent variables and the effect on accuracy (gap effect vs. warning effect) as a dependent variable.

### Results and discussion

Trials with erroneously executed saccades were excluded from the analysis (4.5%). Figure 2 depicts the mean accuracy (% correct) across experimental conditions. The ANOVA revealed a significant main effect of effect type,  $F(1,12) = 7.25$ ,  $p = 0.02$ ,  $\eta_p^2 = 0.38$ , indicating that the gap effect was significantly greater ( $M = 3.3\%$ ) than the warning effect ( $M = -1.1\%$ ). There was no main effect of eccentricity on the effect size,  $F(1,12) = 2.19$ ,  $p > 0.10$ , but a significant interaction,  $F(1,12) = 7.25$ ,  $p = 0.02$ , indicating that the difference between the gap effect and the warning effect was especially pronounced for near targets (2.9 vs.  $-3.9\%$ ) compared with far targets (3.8 vs. 1.7%), possibly because the greater luminance of the central fixation cross specifically interfered with perceiving nearby targets. Taken together, these results effectively rule out the general warning account as an alternative explanation of the perceptual gap effect.



**Fig. 2** Perceptual accuracy (%) as a function of task condition (overlap vs. gap vs. warning/luminance) and target eccentricity ( $3^\circ$  vs.  $6^\circ$ ) in Experiment 4. Note that an accuracy of 10% equals guessing rate

### General discussion

The results from the first two experiments are compatible with the prediction that the offset of central visual information prior to the onset of a target in peripheral vision enhances perceptual performance. More specifically, the insertion of a temporal gap that speeded up saccade RTs also led to significantly higher perceptual performance at positions up to  $6^\circ$  away from the current fixation position. Experiment 2 further qualified the result by showing that this perceptual gap effect appears even in the absence of overtly executed eye movements.

Experiment 3 demonstrated that the additional perceptual task in Experiment 1 significantly altered the saccadic gap effect, which increased by about 25% from Experiment 1 to Experiment 3. This difference was mainly due to longer RTs in the gap trials of Experiment 1, indicating that the ability to take advantage of the fixation cross offset may be compromised under dual-task conditions. This may be explained in terms of interference between perceptual demands and the ongoing temporal saccade preparation, which is well in line with previous findings suggesting that the same brain areas (and thus, similar resources) are involved in input- and output related functions of selective visual attention (e.g., De Haan et al. 2008). This interpretation is also in line with the observation that perceptual accuracy nominally decreased under the dual-task demands in Experiment 1 as compared to the single-task demands in Experiment 2 in all four experimental conditions (see Fig. 1), even though the overall accuracy difference (of about 5%) between experiments was not statistically significant. Similar “concurrency costs” on performance caused by additional working memory tasks were previously reported in other fields, such as visual search (e.g., Schneider and Shiffrin 1977) and manual response time tasks (see, e.g., Pashler 1998).

One frequent explanation of the gap effect refers to the assumption that the gap period might partly serve as a warning signal (e.g., Ross and Ross 1980). However, such an explanation is comparatively broad and needs a further specification of the precise mechanisms involved, especially since the temporal onset of the target is to some extent predictable due to constant response–stimulus intervals. Since the central fixation stimulus offset does not contain any information regarding the spatial location of the forthcoming letter, the perceptual enhancement cannot be explained in terms of a spatial cueing effect (MacKeben 1999). However, it is possible that the temporal gap generally contributes to perceptual enhancement, irrespective of the spatial position. Indeed, a recent study by Rolke (2008) showed that temporal preparation facilitated the identification of letters. However, in her study letters were always presented at predictable (central) positions, allowing the attentional

system to focus on a specific location. In the present study, it does not seem reasonable to assume that visual attention is spread across all possible four letter positions in advance, given the high spatial selectivity of visual attention (e.g., Posner 1980). This reasoning was corroborated by Experiment 4, which demonstrated that general warning conditions (induced by luminance change) produced a significantly smaller effect on accuracy compared to gap conditions. Thus, a more specific mechanism needs to be put forward that is able to account for the fact that in gap conditions peripheral vision is enhanced even at distances of up to 6°.

A more specific framework of the mechanisms at play can be grounded on previous studies that revealed a strong spatial coupling of the location of prioritized perceptual processing and the location of saccade targets in both the behavioural (e.g., Deubel and Schneider 1996; Hoffman and Subramaniam 1995; Kowler et al. 1995; Shepherd et al. 1986) and the neuroscience domain (e.g., Beauchamp et al. 2001; Corbetta et al. 1998; De Haan et al. 2008; Eimer et al. 2007; Ignashchenkova et al. 2004; Nobre et al. 2000; Ohlendorf et al. 2007; Rosen et al. 1999; Van der Lubbe et al. 2006). These findings led to the development of theories postulating a strong spatial coupling of perceptual processing to the planning of motor responses, like the oculomotor readiness theory (Klein 1980), the premotor theory of attention (Rizzolatti et al. 1987), and the visual attention model (VAM; Schneider and Deubel 2002). The present study can be interpreted as behavioral evidence for such a coupling also with respect to temporal properties. Note that these accounts of peripheral perceptual enhancement do not require overt execution of saccades and thus are compatible with the results from Experiment 2.

More specifically, it seems that the perceptual gap effect is due to a fixation disengagement mechanism, which in turn leads to faster attentional disengagement, allowing more processing time for peripheral stimuli. The findings in Experiment 2 indicate that the triggering of a shift of perceptual attention might be coupled to a processing stage that involves the selection of a saccade target, but not overt response execution. This interpretation of the results is in line with recent findings regarding the gap effect by Pratt et al. (2006). They implemented a traditional gap paradigm, but asked subjects to attend to different portions of a complex central fixation stimulus. They compared saccade latencies in trials where the attended portion of the fixation stimulus was removed prior to the onset of the saccade target with latencies in trials in which the unattended portion was removed. As a result, subjects were faster to initiate saccades when the attended stimulus was removed, suggesting that a temporal gap does not only lead to fixation disengagement, but also attentional disengagement. It is therefore reasonable to assume that in the present study

perceptual enhancement in the periphery is indeed due to a faster initiation of an attentional shift, allowing more time to process peripheral information for better performance. On the basis of the present study, we cannot determine the exact timeline of saccade programming and attention shifts. However, it is likely that attentional disengagement always precedes oculomotor disengagement, since mean saccade latencies by far exceeded target presentation times, and attention shifts after fixation release would come too late for target processing. Thus, one might either conclude that attention shifts happen around the time of saccade programming, or (according to the premotor theory) both processes might be regarded as identical.

Previous research indicated that shifts of attention elicited by peripheral stimuli can be completed after about 70 ms (Nakayama and Mackeben 1989). If we assume that attention benefits in a similar way from gap conditions as do saccades (about 40 ms in Experiment 1), this leaves a temporal window large enough for target processing to occur. Consequently, the mechanism underlying the perceptual gap effect proposed here is in line with previous estimations of the speed of attention shifts in comparable experimental setups.

Current accounts of the saccadic gap effect assume either one unitary underlying mechanism (Story and Carpenter 2009), two independent components (Kingstone and Klein 1993; Reuter-Lorenz et al. 1991), or even three distinct sources of influence (Taylor et al. 1998). The most influential two-component account is mainly based on the observation that other types of warning signals (e.g., acoustic) also reduce saccade RTs (temporal preparation or general warning component), but are less efficient compared with central visual gaps, leaving an unexplained residue that was attributed to a modality-specific visual fixation release component. Furthermore, in the step paradigm (equivalent to a 0 ms gap interval) saccade RTs are still reduced as compared with overlap conditions (see Story and Carpenter 2009), a finding that cannot be explained in terms of temporal preparation. Thus, two-component accounts assume that a temporal preparation component and a specific visual fixation offset component sum up to elicit the full gap effect. In the present study, both sources of influence likely contributed to a faster release of ocular fixation. However, the present study only hinges on the use of the gap paradigm as an effective way of manipulating fixation release times in order to study corresponding effects on peripheral vision, irrespective of the specific components that may be involved to achieve this effect. While future research might reveal whether perceptual gap effects might also be achieved by manipulating fixation release times without temporal preparation cues (e.g., by using a step paradigm), the explanation of the perceptual gap effect provided here would remain unaffected by both the specific source of the



saccadic gap effect (e.g., general temporal preparation or modality-specific fixation release) and the specific explanatory framework of the saccadic gap effect (e.g., one-, two-, or three-component accounts).

As an alternative explanation of the perceptual gap effect one might consider that in gap conditions only one item is present on the screen, whereas in overlap conditions the presence of the fixation cross might make the target letter less conspicuous. Thus, overlap trials resemble the situation in the Eriksen flanker task (Eriksen 1995), where perceptual accuracy is typically poorer when a target letter is surrounded by additional distracting stimuli. However, such flankers need to be conceptually related to the target and target-flanker distance needs to be small ( $<3^\circ$ ) for the flanker effect to occur (Eriksen 1995). In the present study the distance between target and fixation cross was too large and target letters were not conceptually related to the fixation cross, so that one would not expect a flanker effect to play a major role.

In sum, the present study demonstrated that perception in the periphery was enhanced when the central stimulus was extinguished prior to peripheral target onset, irrespective of concurrent oculomotor demands. These results strengthen the claims of recent theories assuming a strong coupling between the preparation of goal-directed saccades and shifts of the location of enhanced visual processing by extending the existing evidence from the spatial to the temporal domain.

**Acknowledgment** We thank Elena Zettelmeyer for data collection, Ralph Radach for his involvement in developing the paradigm, three anonymous reviewers for their helpful comments on earlier drafts of the manuscript and those who kindly volunteered to participate in the study.

## References

- Allport DA (1987) Selection for action: some behavioral and neurophysiological considerations of attention and action. In: Heuer H, Sanders AF (eds) *Perspectives on perception and action*. Lawrence Erlbaum, Hillsdale, pp 395–419
- Beauchamp MS, Petit L, Ellmore TM, Ingelholm J, Haxby JV (2001) A parametric fMRI study of overt and covert shifts of visuospatial attention. *NeuroImage* 4:310–321
- Bekkering H, Pratt J, Abrams RA (1996) The gap effect for eye and hand movements. *Percept Psychophys* 58:628–635
- Bell AH, Everling S, Munoz DP (2000) Influence of stimulus eccentricity and direction on characteristics of pro- and antisaccades in non-human primates. *J Neurophysiol* 84:2595–2604
- Broadbent DE (1958) *Perception and communication*. Oxford University Press, New York
- Castiello U (1996) Grasping a fruit: selection for action. *J Exp Psychol Hum Percept Perform* 22:582–603
- Clark JJ (1999) Spatial attention and latencies of saccadic eye movements. *Vis Res* 39:585–602
- Corbetta M, Akbudak E, Conturo TE, Snyder AZ, Ollinger JM, Drury HA, Linenweber MR, Petersen SE, Raichle ME, Van Essen DC, Shulman GL (1998) A common network of functional areas for attention and eye movements. *Neuron* 21:761–773
- Craighero L, Rizzolatti G (2005) The premotor theory of attention. In: Itti L, Rees G, Tsotsos JK (eds) *Neurobiology of attention*. Elsevier, San Diego, pp 181–195
- Craighero L, Fadiga L, Rizzolatti G, Umiltà C (1999) Action for perception: a motor-visual attentional effect. *J Exp Psychol Hum Percept Perform* 25:1673–1692
- De Haan B, Morgan PS, Rorden C (2008) Covert orienting of attention and overt eye movements activate identical brain regions. *Brain Res* 1204:102–111
- Desimone R, Wessinger M, Thomas L, Schneider W (1989) Effects of deactivation of lateral pulvinar or superior colliculus on the ability to selectively attend to a visual stimulus. *Soc Neurosci Abs* 15:162
- Deubel H, Schneider WX (1996) Saccade target selection and object recognition: evidence for a common attentional mechanism. *Vis Res* 36:1827–1837
- Deubel H, Schneider WX, Paprotta I (1998) Selective dorsal and ventral processing: Evidence for a common attentional mechanism in reaching and perception. *Vis Cogn* 5:81–107
- Dorris MC, Munoz DP (1995) A neural correlate for the gap effect on saccadic reaction times in monkey. *J Neurophysiol* 73:2558–2562
- Eimer M, van Velzen J, Gherri E, Press C (2006) Manual response preparation and saccade programming are linked to attention shifts: ERP evidence for covert attentional orienting and spatially specific modulations of visual processing. *Brain Res* 1105:7–19
- Eimer M, van Velzen J, Gherri E, Press C (2007) ERP correlates of shared control mechanisms involved in saccade preparation and in covert attention. *Brain Res* 1135:154–166
- Eriksen CW (1995) The flankers task and response competition: a useful tool for investigating a variety of cognitive problems. *Vis Cog* 2:101–118
- Findlay JM, Gilchrist ID (2003) *Active vision: the psychology of looking and seeing*. Oxford University Press, Oxford
- Fischer B, Weber H (1993) Express saccades and visual attention. *Behav Brain Sci* 16:553–610
- Henderson JM (1992) Visual attention and eye movement control during reading and scene perception. In: Rayner K (ed) *Eye movements and visual cognition*. Springer, New York, pp 260–283
- Hoffman JE, Subramaniam B (1995) The role of visual attention in saccadic eye movements. *Percept Psychophys* 57:787–795
- Ignashchenkova A, Dicke PW, Haarmeier T, Thier P (2004) Neuron-specific contribution of the superior colliculus to overt and covert shifts of attention. *Nat Neurosci* 7:56–64
- Juan C-H, Muggleton N, Hung D, Tzeng O, Cowey A, Walsh V (2008) Segregation of visual selection and saccades in human frontal eye fields. *Cereb Cortex* 18:2410–2415
- Kapoula Z, Robinson DA (1986) Saccadic undershoot is not inevitable: saccades can be accurate. *Vis Res* 26:735–743
- Khan AZ, Blangero A, Rossetti Y, Salemm R, Luauté J, Deubel H, Schneider WX, Laverdure N, Rode G, Boisson D, Pisella L (2009) Parietal damage dissociates saccade planning from pre-saccadic perceptual facilitation. *Cereb Cortex* 19:383–387
- Kingstone A, Klein RM (1993) Visual offsets facilitate saccadic latency: does predisengagement of visuospatial attention mediate this gap effect? *J Exp Psych Hum Percept Perform* 19:1251–1265
- Klein RM (1980) Does oculomotor readiness mediate cognitive control of visual attention? In: Nickerson R (ed) *Attention and performance VIII*. Erlbaum, Hillsdale, pp 259–276
- Kowler E, Anderson E, Doshier B, Blaser E (1995) The role of attention in the programming of saccades. *Vis Res* 35:1897–1916
- Kustov AA, Robinson DL (1996) Shared neural control of attentional shifts and eye movements. *Nature* 384:74–77
- MacKeben M (1999) Sustained focal attention and peripheral letter recognition. *Spat Vis* 12:51–72

- MacKeben M, Nakayama K (1993) Express attentional shifts. *Vis Res* 33:85–90
- Moore T, Armstrong KM (2003) Selective gating of visual signals by microstimulation of frontal cortex. *Nature* 421:370–373
- Moore T, Fallah M (2004) Microstimulation of the frontal eye field and its effects on covert spatial attention. *J Neurophysiol* 91:152–162
- Nakayama K, Mackeben M (1989) Sustained and transient components of focal visual attention. *Vis Res* 29:1631–1647
- Neumann O (1987) Beyond capacity: a functional view of attention. In: Heuer H, Sanders AF (eds) *Perspectives on perception and action*. Erlbaum, Hillsdale, pp 361–394
- Nobre AC, Gitelman DR, Dias EC, Mesulam MM (2000) Covert visual spatial orienting and saccades: overlapping neural systems. *Neuroimage* 11:210–216
- Ohlendorf S, Kimmig H, Glauche V, Haller S (2007) Gaze pursuit, ‘attention pursuit’ and their effects on cortical activations. *Eur J Neurosci* 26:2096–2108
- Pashler H (1998) *The psychology of attention*. MIT Press, Cambridge
- Peterson MS, Kramer AF, Irwin DE (2004) Covert shifts of attention precede involuntary eye movements. *Percept Psychophys* 66:398–405
- Posner MI (1980) Orienting of attention. *Q J Exp Psychol* 32:3–25
- Pratt J, Nghiem T (2000) The role of the gap effect in the orienting of attention: evidence for express attentional shifts. *Vis Cogn* 7:629–644
- Pratt J, Bekkering H, Leung M (2000) Estimating the components of the gap effect. *Exp Brain Res* 130:258–263
- Pratt J, Lajonchere CM, Abrams RA (2006) Attentional modulation of the gap effect. *Vis Res* 46:2602–2607
- Reuter-Lorenz P, Hughes HC, Fendrich R (1991) The reduction of saccadic latency by prior offset of the fixation point: an analysis of the gap effect. *Percept Psychophys* 49:167–175
- Rizzolatti G, Riggio L, Dascola I, Umilta C (1987) Reorienting attention across the horizontal and vertical meridians: evidence in favor of a premotor theory of attention. *Neuropsychologia* 25:31–40
- Rizzolatti G, Riggio L, Sheliga BM (1994) Space and selective attention. In: Umilta C, Moscovitch M (eds) *Attention and performance XV*. MIT Press, Cambridge, pp 231–265
- Rolke B (2008) Temporal preparation facilitates perceptual identification of letters. *Percept Psychophys* 70:1305–1313
- Rosen AC, Rao SM, Caffarra P, Scaglioni A, Bobholz JA, Woodley SJ, Hammeke TA, Cunningham JM, Prieto TE, Binder JR (1999) Neural basis of endogenous and exogenous spatial orienting: a functional MRI study. *J Cogn Neurosci* 11:135–148
- Ross LE, Ross SM (1980) Saccade latency and warning signals: stimulus onset, offset, and change as warning events. *Percept Psychophys* 27:251–257
- Saslow MG (1967) Effects of components of displacement-step stimuli upon latency for saccadic eye movement. *J Opt Soc Am* 57:1024–1029
- Schneider WX (1995) VAM: A neuro-cognitive model for visual attention control of segmentation, object recognition and spacebased motor actions. *Vis Cogn* 2:331–376
- Schneider WX, Deubel H (2002) Selection-for-perception and selection-for-spatial-motor-action are coupled by visual attention: a review of recent findings and new evidence from stimulus-driven saccade control. In: Prinz W, Hommel B (eds) *Attention and performance XIX: common mechanisms in perception and action*. Oxford University Press, Oxford, pp 609–627
- Schneider W, Shiffrin RM (1977) Controlled and automatic human information processing: 1. Detection, search, and attention. *Psychol Rev* 84:1–66
- Shafiq R, Stuart GW, Sandbach J, Maruff P, Currie J (1998) The gap effect and express saccades in the auditory modality. *Exp Brain Res* 118:221–229
- Sheliga BM, Riggio L, Rizzolatti G (1995) Spatial attention and eye movements. *Exp Brain Res* 105:261–275
- Shepherd M, Findlay JM, Hockey RJ (1986) The relationship between eye movements and spatial attention. *Q J Exp Psychol* 38A:475–491
- Smith DT, Rorden C, Jackson S (2004) Exogenous orienting of attention depends upon the ability to execute eye movements. *Curr Biol* 14:792–795
- Song J-H, Nakayama K (2007) Fixation offset facilitates saccades and manual reaching for single but not multiple target displays. *Exp Brain Res* 177:223–232
- Spence C, Driver J (1996) Audiovisual links in endogenous covert spatial attention. *J Exp Psychol Hum Percept Perform* 22:1005–1030
- Sperling G (1960) The information available in brief visual presentations. *Psychol Monogr* 74:1–28
- Story GW, Carpenter RHS (2009) Dual LATER-unit model predicts saccadic reaction time distributions in gap, step and appearance tasks. *Exp Brain Res* 193:287–296
- Tam WJ, Stelmach LB (1993) Viewing behaviour: ocular and attentional disengagement. *Percept Psychophys* 54:211–222
- Taylor T, Kingstone AF, Klein RM (1998) Visual offsets and oculomotor disinhibition: endogenous and exogenous contributions to the gap effect. *Can J Exp Psychol* 52:192–200
- Tipper SP, Lortie C, Bayliss GC (1992) Selective reaching: evidence for action centered attention. *J Exp Psychol Hum Percept Perform* 18:891–905
- Treisman A (1988) Features and objects: the fourteenth Bartlett memorial lecture. *Q J Exp Psychol* 40:201–237
- Van der Heijden AHC (1992) *Selective attention in vision*. Routledge, London
- Van der Lubbe RHJ, Neggers SFW, Verleger R, Kenemans JL (2006) Spatiotemporal overlap between brain activation related to saccade preparation and attentional orienting. *Brain Res* 1072:133–152
- Wurtz RH, Mohler CW (1976) Organization of monkey superior colliculus: enhanced visual response of superficial layer cells. *J Neurophysiol* 39:745–765