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Attention Strikes Back: A Pre-saccadic Attentional Effect Opposite from the Saccade Target

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Abstract

In the present paper we report a novel pre-saccadic phenomenon. Just before the execution of an eye movement, attention shifts in the direction opposite from the intended saccade. We offer a tentative explanation in terms of predictive remapping, or, analogously, shifting “attention pointers”. This finding is discussed in the context of other pre-saccadic phenomena, such as localization errors and the pre-saccadic shift of attention towards the saccade target. Finally, we discuss the implications of the current finding for existing theories of pre-saccadic processes.

Keywords: Visual Attention, Predictive Remapping, Attention Pointers, Eye Movements, Pre-saccadic processes

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The moment just before an eye movement is a turbulent time for the visual system, and for visual attention in particular. For example, there is a gross distortion of perceptual space, which leads to localization errors during the pre-saccadic interval (Ross, Morrone, Goldberg, & Burr, 2001). In addition, a number of now-classic studies have shown that each eye movement is preceded by a covert shift of attention to the saccade target, as though the visual system takes a "sneak peak" at what is about to be brought into fixation (Chelazzi et al., 1995; Deubel & Schneider, 1996; Kowler, Anderson, Dosher, & Blaser, 1995).

These pre-saccadic phenomena have traditionally been studied in isolation. However, there is a growing suspicion that most or perhaps all of these phenomena are intricately related. A number of competing theories have been put forward that aim to provide a unifying description of pre-saccadic processes. A recent series of lively comments in Trends in Cognitive Sciences (Cavanagh, Hunt, Afraz, & Rolfs, 2010b, 2010c; Mayo & Sommer, 2010; Melcher, 2010) attests to the lack of consensus about which theory, if any, is correct. With the present paper we do not aim to resolve this debate, but to add a well-needed piece to the puzzle by describing a novel pre-saccadic phenomenon. First, we provide a brief outline of three theories around which the debate currently revolves (for a review see Mathôt & Theeuwes, in press a).

According to one framework, which has found an eloquent proponent in Wurtz (2008), visual receptive fields (RFs) shift in the interval preceding an eye movement (Duhamel, Colby, & Goldberg, 1992). Specifically, RFs shift in parallel with the impeding saccade, a phenomenon called predictive remapping. It has been shown that, if cortical magnification is taken into account, predictive remapping can account for localization errors (VanRullen, 2004). Predictive remapping is also associated with the pre-saccadic shift of attention (e.g., Hunt & Cavanagh, 2009), although the precise nature of this relationship is unclear. In addition, the concept of (predictive) remapping is consistent with a large amount of neurophysiological (Duhamel et al., 1992; Nakamura & Colby, 2002) and behavioral data (Mathôt & Theeuwes, in press b, 2010; Melcher, 2007; Rolfs, Jonikaitis, Deubel, & Cavanagh, in press).

Hamker and colleagues (Hamker, Zirnsak, Calow, & Lappe, 2008; Zirnsak, Lappe, & Hamker, 2010) have challenged the concept of predictive remapping by constructing a computational model which accounts for much of the same data in a very different, but elegant way. According to them, RFs do not shift in parallel with the impending eye movement, but shift towards the saccade target (Tolias et al., 2001). Consider, for example, a RF encompassing a location above the target of an intended left-wards saccade. Predictive remapping predicts that the RF will shift to the left, in parallel with the saccade, whereas Hamker and colleagues (2010) predict that the RF will shift downwards, towards the saccade target. However, for many parts of the visual field, a shift towards the saccade target resembles a shift in parallel with the saccade, and for this reason it has proven difficult to dissociate these two types of RF shifts. Importantly, Hamker and colleagues (2010) show that localization errors and the pre-saccadic shift of attention emerge naturally from their model.

Cavanagh and colleagues have proposed a third view (Cavanagh, Hunt, Afraz, & Rolfs, 2010a). They suggest that the visual system anticipates which retinal locations will be relevant after an eye movement, and that "attention pointers" are predictively shifted to those locations. Again, this theory can account for much of the available data. A possible way to dissociate predictive remapping from shifting attention pointers is to investigate whether low level visual features (e.g., color or orientation) are preserved across saccades, since this is not predicted by Cavanagh and colleagues (2010a). However, it is exactly on this point that evidence is mixed, if not contradictory (e.g., Knapen, Rolfs, Wexler, & Cavanagh, 2010; Melcher, 2007).

In summary, there are several frameworks that are compatible with the available data. The present study is instrumental in the debate on pre-saccadic processes, as it presents a novel pre-saccadic phenomenon. Informally, we had noted in previous experiments that attentional effects seem to appear (as well) at the location opposite from where you would expect them (e.g., Godijn & Theeuwes, unpublished data). For example, if an eye movement is made from a central fixation dot to one corner of a surrounding square, there appears to be a small pre-saccadic attentional effect at the corner opposite from the target corner (in addition, of course, to a much larger effect at the target corner itself). We designed a paradigm to investigate this “opposite attention” effect more rigorously. Participants made an eye movement towards a saccade target. In addition, they reported the identity of a probe which appeared briefly at the fixation point just before the saccade. A task-irrelevant distractor was presented, which could be either identical to, or different from, the probe. This resulted in a congruency effect (i.e., faster responses if the distractor and the probe were identical than if they were not). The size of the congruency effect can be used as a measure of the extent to which the distractor is attended, since an unattended distractor will cause little or no congruency effect (e.g., Schreij, Owens, & Theeuwes, 2008). The location of the distractor was manipulated. On some trials, the distractor was presented “opposite” from the saccade target (i.e., if the saccade was upwards, the target was presented below the fixation dot, at the same distance from the fixation dot as the saccade target). We expected to find a larger congruency effect in these “opposite” trials, than in “flank” trials, in which the distractor was placed slightly off-axis with respect to the saccade, but at the same retinal distance from the fixation dot. Finally, in "near" trials, the distractor was presented on-axis, but slightly closer to the fixation dot than in "opposite" trials. We did not have any a-priori expectation about the relative strength of the congruency effect in "near" trials.

Method

16 observers, between the ages of 18 and 20 years, participated in the experiment. All observers reported normal or corrected vision. Eye movements were recorded using an Eyelink II (SR-Research, Mississauga, ON, Canada), a video-based eyetracker, sampling at 1,000 Hz.

Before the start of each trial, a gray cross was presented against a dark background. Drift correction was executed automatically when participants fixated this cross (except for the first trial of each block, in which a key press was required), after which the trial was initiated. Each trial started with the presentation of a gray fixation dot (Figure 1a). After 400 ms, a saccade target (a small gray circle, identical to the fixation dot) was presented at a random location 6° from the fixation dot. Participants were instructed to make a saccade to the target as quickly as possible. This display (i.e., the fixation dot and the saccade target) was presented for a variable duration, which was determined online. Specifically, the duration was set to the average saccade latency of the participant minus 70 ms. This way, on a large proportion of trials the probe display appeared just before the initiation of the saccade. In the probe display two gray line-segments (length = 1.4°) were presented, which were tilted 45° to the right or the left from a vertical orientation. The probe display was presented for 30 ms, after which only the saccade target remained visible. The location of the saccade target served as the location of the fixation dot on the next trial.

One of the line-segments in the probe display (the probe) was presented at the location of the fixation dot (which was no longer visible). Participants were instructed to report the orientation of the probe as fast as possible by pressing the “Z”-key if it was tilted to the left (\) and the “/”-key if it was tilted to the right (/). The second line-segment (a task-irrelevant distractor) was presented in one of three possible arrangement (Figure 1b): On Opposite trials the distractor was presented at the “opposite” location, which mirrored the saccade target (i.e., the opposite location was equally far (6°) from the fixation dot as the saccade target, but in the opposite direction); On Near trials the distractor was presented at 3.9° from the fixation dot, but “on-axis” (i.e., on the line that connected the fixation dot and the opposite location); On Flank trials the distractor was presented equally far from the fixation dot as on Opposite trials, but 20° (angular degrees) “off-axis”. In the Near and Flank conditions the distractor was presented at the same distance (2.1°) from the opposite location. Distractor Location was the first experimental factor and was randomized within blocks.

On Congruent trials, the orientation of the probe and the distractor was identical. On Incongruent trials, the orientations of the probe and the distractor were different. Congruency was the second experimental factor and was also randomized within blocks. The experiment consisted of 48 practice trials, followed by 576 experimental trials. Experimental source code and participant data is available from http://www.cogsci.nl/smathot [while under review, see http://files.cogsci.nl/resources/Mathot_Theeuwes_APP_under_review.zip]

Results

Trials were excluded based on the following criteria: The probe was still visible after the saccade (11.4%); Fixation was lost, no saccade was executed (participants occasionally kept fixating throughout the trial, presumably because it is counterintuitive to saccade away from the probe) or the saccade deviated more than 15° from the straight line between the fixation dot and the saccade target (9.7%); The saccadic latency was less than 50 ms or more than 500 ms (1.8%); Reaction times (RTs) were less 50 ms or more than 1500 ms (1.5%). In total 75.6% of the trials were included in the analysis.

We conducted a Repeated Measures Analysis of Variance (ANOVA) with mean correct RT as dependent variable and Distractor Location (Opposite, Near and Flank) and Congruency (Congruent and Incongruent) as within-subject factors (see Figure 2). This analysis revealed a main effect of Congruency ($F(1, 15) = 23.3$, $p < .001$), reflecting that participants responded faster when the distractor was identical to the probe, than when it was not. Crucially, there was also an interaction between Distractor Location and Congruency ($F(2, 30) = 3.3$, $p < .05$), reflecting that the congruency effect varied with Distractor Location. To investigate this interaction further, we determined the congruency effect (mean RT on Incongruent trials minus mean RT on Congruent trials) for each Distractor Location. Planned comparisons revealed that the congruency effect was smaller on Flank trials ($M = 14$ ms, $SE = 6.8$) than on Opposite trials ($M = 36$ ms, $SE = 8.7$, $t(15) = 2.9$, $p < .05$) and Near trials ($M = 48$ ms, $SE = 12.0$, $t(15) = 2.5$, $p < .05$). There was no difference between Opposite and Near trials ($t(15) = .5$, $p = .6$).

We conducted the same repeated measures ANOVA with mean accuracy as dependent variable. This revealed only a main effect of Congruency ($F(1, 15) = 13.1$, $p < .005$).

Discussion

The results clearly show that, just before the execution of an eye movement, attention shifts in the direction opposite of the saccade. We presented a distractor, which was either identical to or different from the probe stimulus, to elicit a congruency effect. We assumed that the size of the congruency reflected the amount of attention devoted to the distractor (e.g., Schreij et al., 2008). We found an increased congruency effect when the distractor was presented in line with, but in the opposite direction of, the intended saccade, relative to when the distractor was positioned at an equidistant control location, but not in line with the impending saccade.

What are the implications of this highly surprising result for current models of pre-saccadic processes? A tentative explanation follows from Cavanagh and colleagues' (2010a) suggestion that, just before a saccade, "attention pointers" shift to retinotopic locations that are likely to be of interest after the saccade. In general, but particularly in our experiment (since the probe was presented at fixation), the fixation point is a location of interest. An impending saccade will retinotopically displace the current fixation point in the direction opposite from the saccade, to the "opposite location". It is conceivable that an attention pointer is shifted predictively to the opposite location, to anticipate the retinal displacement. This has been implicitly tested in a recent study by Rolfs and colleagues (in press). In contrast to our own results, they found no evidence for an attentional shift in the direction opposite from the saccade. However, in their study, the opposite location served as a control location for the fixation point and the saccade target. This may have obscured any attentional effects specific to the opposite location.

It is difficult to explain the current results without invoking shifting attention pointers (or, analogously, predictive remapping of attention). However, some cautionary notes are in order. First, the data does not show a distinct focus of attention at the location opposite from the saccade target, but a pattern suggestive of spreading along the axis of the saccade. This may be due to a counteracting effect of eccentricity, since on "near" trials the distractor was presented closer to the probe than on opposite trials. However, a positive finding would certainly have strengthened the case for shifting attention pointers. Second, the distance between the distractor locations in the various conditions was small (2.1°), especially considering the large RFs (approximately 10°) of neurons in areas which are believed to be involved in attention and remapping (Ben Hamed, Duhamel, Bremmer, & Graf, 2001; for a similar point, see Mayo & Sommer, 2010), although the resolution at the population level in these areas may be much higher than the size of the individual RFs suggest. Third, remapping is typically investigated by presenting stimuli in the visual periphery (but see Rolfs et al., in press). In the present study, foveal vision played a crucial role, since the probe was presented at fixation. Very little, if anything, is known about the effects of pre-saccadic processes on foveal vision.

How does the present study relate to previous studies, which have shown a pre-saccadic shift of attention towards the saccade target (Chelazzi et al., 1995; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler et al., 1995)? Attentional effects at the saccade target are large and various functional explanations have been offered (e.g., Currie, McConkie, Carlson-Radvansky, & Irwin, 2000; Hollingworth, Richard, & Luck, 2008). In contrast, the strength of the effect reported here is modest and its nature is largely mysterious. It is a tantalizing possibility that both effects are related to predictive remapping. An alternative, equally intriguing possibility is that just before an eye movement, attention spreads along the entire axis of the saccade, culminating at the saccade target.

In a heroic effort, an experiment consisting of 25,330 trials per subject, Tse, Sheinberg and Logothetis (2003) systematically mapped out attention (measured by detection performance in a change detection task; manipulated by a task irrelevant onset stimulus) across a large part of the visual field. To their own amazement, they found that the onset caused attention to spread over a large elliptical area, which encompassed both the onset location and the location opposite from the onset. This bears some resemblance to the present study, but there are two crucial differences. First, in the study by Tse et al. (2003) participants did not make eye movements. Second, they found that attention was very broadly distributed. This stands in contrast with our finding that attention is relatively confined, at least along the axis of the saccade. Therefore, we think it is doubtful that the findings reported by Tse and colleagues (2003) are directly related to the findings reported here.

In summary, we report that in the interval preceding saccade execution, attention spreads to the location opposite from the saccade target. This may be an axial effect, in the sense that attention spreads along the axis, but in the opposite direction, of the saccade. We have provided a tentative explanation in terms of shifting attention pointers (or predictive remapping of attention). However, there are many open questions and pre-saccadic processes are still largely a mystery. How does the present “opposite attention” effect relate to the pre-saccadic shift of attention towards the saccade target? Is predictive remapping a real phenomenon or is it merely a useful description of the data, not unlike how the spotlight provides a useful, but fallible metaphor for visual attention? These are important questions that future research will need to address, in order to resolve the current debate on pre-saccadic processes.

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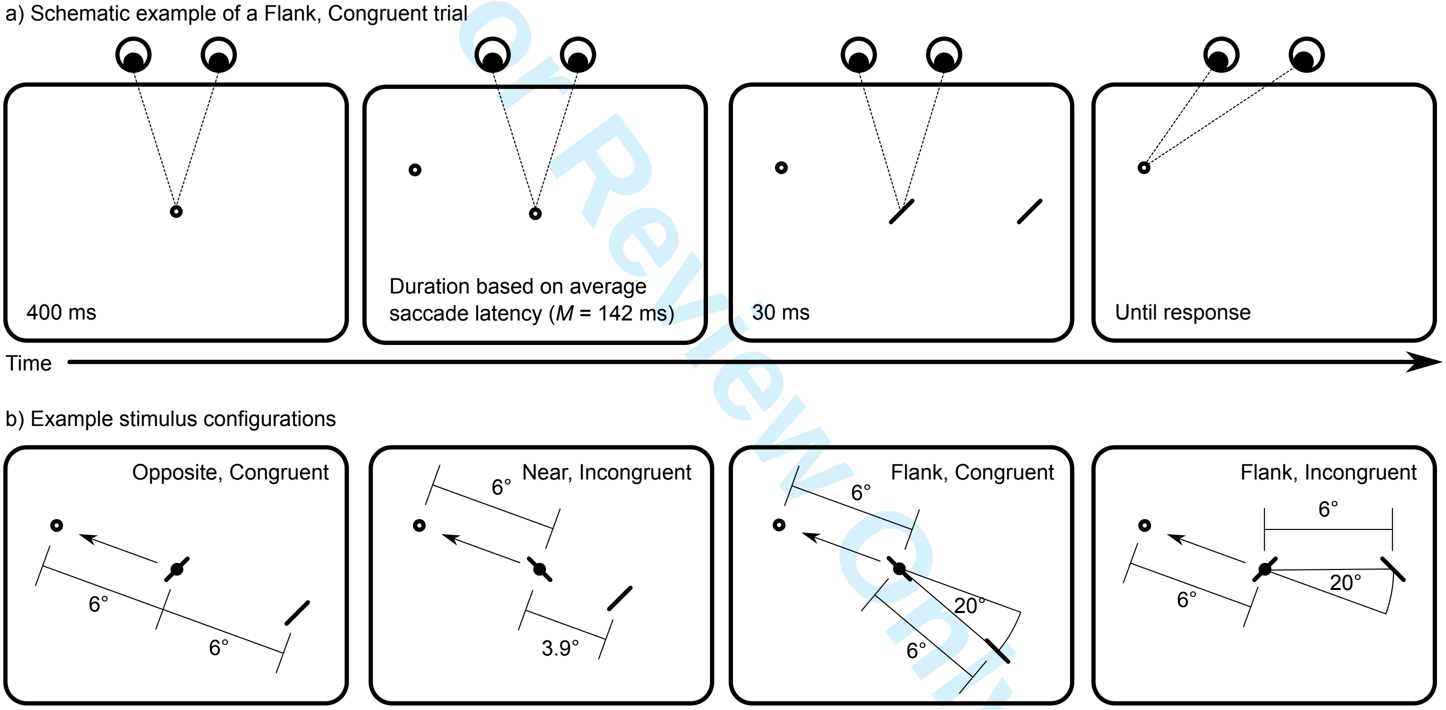
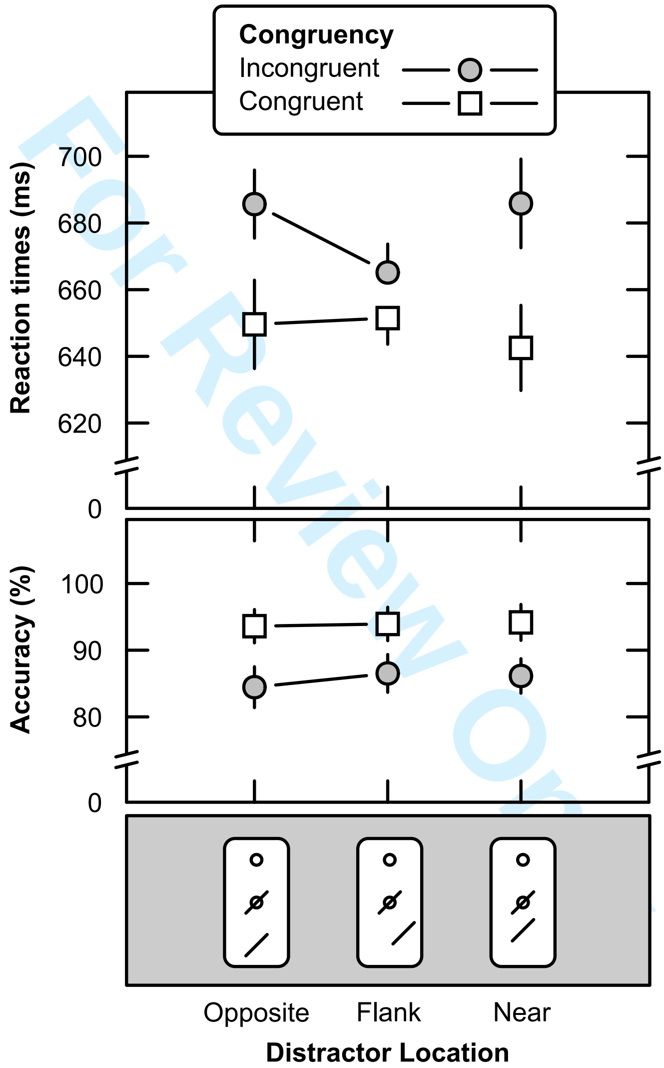
Figure Captions

Figure 1. a) A schematic example of a Flank, Congruent trial. Participants were instructed to report the orientation of the line-segment that replaced the fixation dot (the probe) and ignore the other line-segment (the distractor). b) Four example stimulus configurations. Distractor Location (Opposite, Near or Flank) was based on the relative positioning of the stimuli. The location and rotation of the stimulus configurations was random.

Figure 2. Mean correct reaction times (RTs) and mean accuracy as a function of Congruency and Distractor Location. Participants were faster and more accurate in Congruent than in Incongruent trials. Crucially, RTs showed that this congruency effect was substantially reduced in Flank trials, relative to Opposite and Near trials. The error bars reflect 95% within-subject confidence intervals (Cousineau, 2005). Overlapping portions of the error bars have been removed for clarity.


a) Schematic example of a Flank, Congruent trial
400 ms
Duration based on average saccade latency (M = 142 ms)
30 ms
Until response
Time
b) Example stimulus configurations
Opposite, Congruent
6°
6°
Near, Incongruent
6°
3.9°
Flank, Congruent
6°
20°
6°
Flank, Incongruent
6°
20°
6°


Congruency
Incongruent
Congruent
Reaction times (ms)
700
680
660
640
620
0
Accuracy (%)
100
90
80
0
Opposite
Flank
Near
Distractor Location