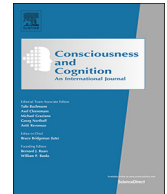




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All is not lost: Post-saccadic contributions to the perceptual omission of intra-saccadic streaks

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ABSTRACT

Saccades rapidly jerk the eye into new positions, yet we rarely experience the motion streaks imposed on the retinal image. Here we examined spatial and temporal properties of post-saccadic masking—one potential explanation of this perceptual omission. Observers judged the motion direction of a target stimulus, a Gaussian blob, that moved vertically upwards or downwards and then back to its initial position, just as observers made a saccade. We manipulated the onset and offset of the target and of distractors in various spatial relations to the target, and assessed their effect on performance and subjective confidence. Although the presence of the target after the saccade caused the strongest omission, the offset of spatially distant distractor stimuli upon saccade offset also impaired performance. The temporal properties of these two separate effects suggest that, in addition to masking, an independent effect of attentional distraction further accentuates perceptual omission of intra-saccadic motion streaks.

1. Introduction

Our visual experience of the world is stable and continuous despite the frequent and large interruptions that blinking and eye movements cause to the retinal input. With saccadic eye movements, the puzzle of maintaining a stable experience is especially complex. Large eye movements create streaks of light across the retina that generally escape phenomenal visual experience. On top of this, visual information may be integrated across the displacements of the retinal image from one fixation to the next, such that perception remains continuous in real world spatial coordinates despite changes to retinal spatial coordinates. This description generates three distinct challenges for our understanding of visual processing around saccades: (1) Why do we lack awareness of the streaks created by saccadic eye movements, (2) Why do we not perceive the temporal gap in the visual input, and (3) How do we maintain perceptual stability in spatial coordinates (Bridgeman, Van der Heijden, & Velichkovsky, 1994; Rolf, 2015). An ideal mechanism would account for all three of these challenges, but it is likely that a number of distinct mechanisms contribute. Detailed reviews and discussions of the many theoretical accounts of how a stable and continuous world can be maintained despite the disruptions caused by saccadic eye movements can be found in the seminal BBS paper by Bruce Bridgeman and his colleagues (Bridgeman et al., 1994), in Castet, Jeanjean, and Masson (2001) and the response of Ross and colleagues in the same issue (Ross, Morrone, Goldberg, & Burr, 2001), and more recently in Wurtz (2008). The experiments presented in this manuscript seek to

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explicate one such potential mechanism: backward masking.

Backward masking describes the reduced visibility of a target stimulus by the subsequent presentation of a ‘mask’ stimulus, presented to a participant during fixation (Kahneman, 1968; for reviews see Enns & Di Lollo, 2000; Breitmeyer & Ögmen, 2000, 2006; Bachmann, 2015). Based on this effect, typically observed during fixation, it has been suggested that the post-saccadic visual scene acts to backward mask the intra-saccadic retinal image, thereby creating saccadic omission, or a complete lack of awareness of intra-saccadic retinal stimulation. Indeed, a wealth of evidence suggests that simply removing post-saccadic input restores performance on a range of tasks involving perception during saccades (Campbell & Wurtz, 1978; Castet & Masson, 2000; Castet, Jeanjean, & Masson, 2002; Matin, Clymer, & Matin, 1972). Campbell and Wurtz (1978) found that by illuminating the observer’s surroundings only during their saccades, observers were able to clearly perceive the retinal stimulation during saccadic eye movements – a blurred or ‘greyed out’ image of the observer’s surroundings. However, if the room was illuminated for longer than 40 ms after the saccade, the brief ‘grey out’ was completely eliminated from their phenomenal perception.

The fact that there is ‘grey out’, caused by the rapid movement of the retinal image over slowly-integrating photoreceptors, may indeed be important for masking to occur. During fixation, Corfield, Frosdick, and Campbell (1978) found that the presentation of a blank grey screen, lasting as long as the duration of a saccade or more, could be eliminated from awareness if it was preceded and followed by a sinewave grating. High contrast patterns or lines could not be eliminated from awareness with these same masking stimuli. This evidence suggests that backward masking could limit the visibility of intra-saccadic retinal stimulation *in the same manner* as backward masking during fixation, with the exception that the stimulation around the time of the saccade is itself responsible for masking, as opposed to the specific experimental manipulation that occurs to induce masking during fixation. This comparison suggests that our understanding of visual perception around the time of a saccade can be enriched by what we know from backward masking studies during fixation. In turn, our understanding of the natural function of backward masking may benefit greatly from a potential relation to post-saccadic masking in active vision.

Extensive research into backward masking during fixation has detailed the complex relationship between the properties of the target and effective mask stimuli (see Breitmeyer & Ögmen, 2006). The most prominent of these properties is the temporal relationship between target and mask. The stimulus onset asynchrony (SOA) describes the time between target stimulus onset and mask onset. Target visibility varies substantially as a function of SOA and usually follows one of two functions: a non-monotonic U-shaped function, where visibility first decreases (up to around 30–70 ms) and then increases again with increasing SOAs; or a monotonic function, where visibility is poorest when the mask follows immediately after the target stimulus and then increases with increasing SOA (Bachmann, 1994; Breitmeyer & Ögmen, 2006). Effective saccadic omission of intra-saccadic stimuli requires a monotonic masking function, where the high-contrast, broadband spatial frequency retinal input immediately after the saccade strongly masks the streaky/smear out retinal input during the saccade.

During fixation, the monotonic masking function is normally produced by a mask that spatially overlaps with a target (see Breitmeyer & Ögmen, 2006; Bachmann, 1994; though not necessarily retinally overlapping: McFadden & Gummerman, 1973). In some post-saccadic masking experiments, however, a rather sparse stimulus display is used and the simple removal of a small target stimulus by the end of the saccade is sufficient to allow for the perception of that target across the streak of the retina during the saccade (Matin et al., 1972; Deubel, Schneider, & Bridgeman, 1996, 2002; Bedell & Yang, 2001; Duyck, Collins, & Wexler, 2016). In these cases, the target had *masked itself* in neither the same retinal nor spatial location, which is unlike backward masking during fixation. For example, Duyck et al. (2016) found the intra-saccadic smear of a small LED could be masked by the presence of a similar LED after the saccade, located up to 6° away from the static target. Thus, the masking of intra-saccadic retinal stimulation could be more complex than is suggested by studies of backward masking during fixation. Put differently, the post-saccadic retinal input may reduce intra-saccadic omission in more ways than just those captured by traditional backward masking.

Although in natural environments a high-contrast, full field mask impinges on the retina after each saccade, it remains unclear which properties of this input give rise to saccadic omission. The systematic investigation of interactions between post-saccadic stimuli and intra-saccadic retinal input can provide insight into the processing of visual information during saccades. The following experiments therefore seek to examine the spatial and temporal relationships between intra-saccadic motion streaks and post-saccadic visual information. We created an objective discrimination task by moving a full contrast Gaussian blob either up or down and back to its original location during saccadic eye movements (Fig. 1a). Previous literature suggests that the streak of the stimulus will be clearly visible if that stimulus is removed from the screen before the end of the saccade (Duyck et al., 2016; Bedell & Yang, 2001; Deubel et al., 1996, 2002; Matin et al., 1972). Full masking of the intra-saccadic retinal input would mean that intra-saccadic stimulation does not yield a conscious percept, and performance in the task would be at chance level. We then manipulated the temporal and spatial relations of target and mask stimuli to examine the specific constraints for effective saccadic omission (Fig. 1b and c). First, we sought to replicate the effect of a reduction in performance when the target remains on screen after the end of the saccade. Second, we manipulated the presence of the additional distractor stimuli before, during, and after the saccade to examine at what time the presence, or onset, of other stimuli reduced performance. That is, could omission be elicited by stimuli occurring during the saccade, or only those appearing after, or some specific combination? Third, we investigated whether performance in the task was affected by the distance of the post-saccadic distractors to the target in terms of both real world spatial coordinates and retinal coordinates, by manipulating the location of the distractor stimuli relative to the target stimulus and the direction of the saccade. We specified four distractor locations: a ‘close’ distractor that was just outside the end of target movement, a ‘far’ distractor that should not affect performance if spatial proximity is necessary, as well as ‘inside’ and ‘outside’ distractors, where the ‘inside’ distractor would be close to the retinal streak of the target stimulus but the ‘outside’ distractor would not, to test whether proximity to the retinal trace of the target is important (Fig. 1c).

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