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Attention modulates trans-saccadic integration

Emma E.M. Stewart*, Alexander C. Schütz

Allgemeine und Biologische Psychologie, Philipps-Universität Marburg, Marburg, Germany

A R T I C L E I N F O

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A B S T R A C T

With every saccade, humans must reconcile the low resolution peripheral information available before a saccade, with the high resolution foveal information acquired after the saccade. While research has shown that we are able to integrate peripheral and foveal vision in a near-optimal manner, it is still unclear which mechanisms may underpin this important perceptual process. One potential mechanism that may moderate this integration process is visual attention. Pre-saccadic attention is a well documented phenomenon, whereby visual attention shifts to the location of an upcoming saccade before the saccade is executed. While it plays an important role in other peri-saccadic processes such as predictive remapping, the role of attention in the integration process is as yet unknown. This study aimed to determine whether the presentation of an attentional distractor during a saccade impaired trans-saccadic integration, and to measure the time-course of this impairment. Results showed that presenting an attentional distractor impaired integration performance both before saccade onset, and during the saccade, in selected subjects who showed integration in the absence of a distractor. This suggests that visual attention may be a mechanism that facilitates trans-saccadic integration.

1. Introduction

Every second, we make multiple eye movements, shifting the high-resolution sampling of the fovea across the world to survey our surroundings in greater detail than our low-resolution peripheral vision can provide. In order to achieve a stable percept of the world, the brain needs to reconcile the differences in this pre- and post-saccadic information by integrating the peripheral information gathered before the saccade, and the foveal information obtained once the saccade has reached the target. While there is ample evidence that integration of this information does indeed occur (Cicchini, Binda, Burr, & Morrone, 2013; Demeyer, De Graef, Wagemans, & Verfaillie, 2010; Ganmor, Landy, & Simoncelli, 2015; Melcher, 2005, 2007; Niemeier, Crawford, & Tweed, 2003; Oostwoud Wijdenes, Marshall, & Bays, 2015; Wittenberg, Bremmer, & Wachtler, 2008; Wolf & Schütz, 2015), it is unclear as to the potential mechanisms that may underpin this integration process. Visual attention starts to build up at the upcoming location of a saccade around 150 ms before the saccade is executed (Deubel, 2008; Deubel & Schneider, 1996; Kowler, Anderson, Dosher, & Blaser, 1995; Rolfs & Carrasco, 2012), and it has been suggested that this pre-saccadic attention acts as a guide for other peri-saccadic stabilising processes such as predictive remapping (Cavanagh, Hunt, Afraz, & Rolfs, 2010; Mathot & Theeuwes, 2011). It may also therefore be the case that attention additionally guides or supports the integration of peripheral and foveal vision across a saccade. We aimed to investigate the role of attention in trans-saccadic integration by presenting an attentional distractor at multiple timepoints during a saccade, to determine first whether this disruption to pre-saccadic attention affected integration performance, and secondly to determine at which point around the saccade this had the greatest impact on integration.

1.1. *Trans-saccadic integration*

The retina is a non-homogenous structure, with greater photoreceptor density in the fovea than in the periphery. This results in a decline in visual sensitivity in the periphery (Rovamo, Virsu, & Näsänen, 1978), as well as a decline in the ability to process certain stimulus attributes such as orientation (Mäkelä, Whitaker, & Rovamo, 1993). However, humans do not actively perceive these differences in acuity across the visual field (as discussed in Herwig and Schneider (2014)), even though in everyday life people make constant eye movements to bring relevant areas of the world into greater focus (for reviews see Schutz, Braun, & Gegenfurtner, 2011; Tatler, Hayhoe, Land, & Ballard, 2011). This raises the question of how this pre-saccadic peripheral information and post-saccadic foveal information may be integrated to achieve such perceptual stability. While early studies argue against the existence of trans-saccadic fusion of information (for example: Irwin, Yantis, & Jonides, 1983; O'Regan & Lévy-Schoen, 1983; Rayner & Pollatsek, 1983), evidence is mounting to suggest that people are actually very good at combining information presented before and

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* Corresponding author.
E-mail address: emma.stewart@staff.uni-marburg.de (E.M. Stewart).

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after a saccade. It has been shown that certain stimulus attributes, such as orientation and form are integrated across fixations (Demeyer et al., 2010; Paeye, Collins, & Cavanagh, 2017), as well as colour (Oostwoud Wijdenes et al., 2015; Wittenberg et al., 2008). Additionally, location information can be integrated, for example information about the position of line segments can also be retained and fused across a saccade (Prime, Niemeier, & Crawford, 2005), and the positions of lines flashed during the saccade can be integrated (Cicchini et al., 2013). Evidence further suggests that the outcome of integration is reliant on the reliability of both peripheral and foveal information (Demeyer, De Graef, Wagemans, & Verfaillie, 2009; Oostwoud Wijdenes et al., 2015).

While this provides evidence that information can be transferred across saccades, a number of studies have investigated the degree to which this integration occurs. One method of measuring whether integration occurs in an optimal manner is to consider the peripheral and foveal information as two separate sources of sensory information. Two studies (Ganmor et al., 2015; Wolf & Schütz, 2015) investigated the degree to which individual peripheral and foveal percepts are integrated using the maximum likelihood estimation model (MLE). MLE provides a model for estimating the integration of different sources of sensory information, by summing the reliabilities of two independent sources (Ernst & Bülthoff, 2004) – in this case peripheral and foveal information. This model thus provides a predicted value for integrated performance if peripheral and foveal information are perfectly integrated. Both studies (Ganmor et al., 2015; Wolf & Schütz, 2015) compared this predicted integration performance from the MLE model, and the observed experimental performance on integration tasks to show that the visual system integrates peripheral and foveal information in a statistically nearly optimal way across saccades.

While there is evidence suggesting that this integration of peripheral and foveal information does indeed occur, it is unclear what mechanisms may underlie this integration process. One such candidate is visual attention – a process that is not only inextricably linked with the planning and execution of saccades, but which is also implicated in numerous peri-saccadic processes that have been shown to play a key role in maintaining a homogenous view of the world across saccades.

1.2. What underlies trans-saccadic integration?

It is well-established that when a saccade is being planned, attention will shift to the location of the upcoming saccade before the saccade is initiated (Deubel & Schneider, 1996; Kowler et al., 1995). This pre-saccadic attentional shift builds up from around 150 ms to 100 ms before the onset of the saccade, with attentional performance plateauing for the duration of the saccade's journey to the target (Deubel, 2008). Pre-saccadic attention results in perceptual benefits such as improved performance in letter discrimination tasks (Deubel & Schneider, 1996; Kowler et al., 1995), luminance discrimination (White, Rolfs, & Carrasco, 2013), and orientation discrimination tasks (Rolfs & Carrasco, 2012), and it has been shown that this attentional shift leads to an increase in both sensitivity and perceived contrast at the location of an upcoming saccade (Rolfs & Carrasco, 2012). This increased acuity at the pre-saccadic target location could act as a predictive mechanism to enhance the peripheral information which then has to be integrated with the post-saccadic foveal information at that location.

The pre-saccadic attentional shift may also be implicated in a number of processes that are attributed to visual stability across eye movements, and this may also provide evidence for a potential link between attention and trans-saccadic integration. Indeed, Hamker, Zirnsak, and Lappe (2008) suggest that peri-saccadic processes such as the pre-saccadic attentional shift, predictive remapping, receptive field shifts and peri-saccadic compression, are all linked via a single neural mechanism, and that attention may act as a bridge between these phenomena that allow us a stable perception of the world. Processes such as remapping may act as an important mechanism that facilitate the transfer of information from pre- to post- saccadic locations in the visual field, with potential consequences for how information is integrated across saccades (Cavanagh et al., 2010). Predictive remapping suggests that before a saccade is made, the receptive field will shift to the site of the impending movement (Duhamel, Colby, & Goldberg, 1992), and is a crucial part of maintaining a stable view of the world across eye movements. Pre-saccadic attention has been linked to the remapping process (Rolfs, 2015), and it has been suggested that attention creates a retinotopically organised map of both target locations and features at the upcoming saccade location, which is then used to determine which locations are remapped (for review see Cavanagh et al., 2010; Mathot & Theeuwes, 2011). There is evidence that receptive fields from locations that are attended before a saccade are then remapped, from both neurophysiological studies (Gottlieb, Kusunoki, & Goldberg, 1998), and behavioural studies (Melcher, 2009). Additionally, the locus of attentional facilitation can be remapped across saccades: studies have shown that attention can be allocated to both the original locus of attention before a saccade, and the retinotopic equivalent of this cued location after the saccade (Golomb, Chun, & Mazer, 2008; Mathôt & Theeuwes, 2009), and that attention can be predictively allocated to the future retinotopic location of a saccade target (Rolfs, Jonikaitis, Deubel, & Cavanagh, 2011). A disruption to pre-saccadic attention could affect the saccadic remapping process: Jonikaitis, Szinte, Rolfs, and Cavanagh (2013) found that attentional capture by a transiently presented, salient distractor could also influence the location of predictive remapping such that it coincided with the remapped distractor location. This suggests a strong link between attention and one of the fundamental processes underlying trans-saccadic stability. Indeed, direct evidence of the role of remapping in trans-saccadic integration comes from a recent study by Szinte, Jonikaitis, Rolfs, Cavanagh, and Deubel (2016), who showed that motion integration occurred for pre-saccadic stimuli, between an attended location and its remapped location prior to the saccade: this suggests that these two processes are closely linked.

So, attention seems to play a crucial role in the guidance of trans-saccadic process such as remapping, which are implicated in the maintenance of perceptual stability. The question then is whether attention also plays a role in the integration of trans-saccadic visual information. This study utilises an attentional distractor to disrupt attention during the critical integration point during the saccade: salient distractors have been demonstrated to capture attention (Muller & Rabbitt, 1989; Yantis & Jonides, 1990), and the onset of a salient, coloured distractor has been used by numerous studies to manipulate attention (Jonikaitis et al., 2013; Peterson, Kramer, & Irwin, 2004; Puntiroli, Kerzel, & Born, 2015; Schreij, Theeuwes, & Olivers, 2010). If attention is needed to integrate the pre- and post-saccadic information, disrupting attention during the saccade should impair integration performance. We measured orientation discrimination performance on stimuli presented in peripheral and foveal vision alone, and stimuli presented for the duration of the saccade (integration trials). We then compared observed integration performance across the time-course of the saccade with the predicted optimal performance obtained using MLE, to determine firstly whether the presentation of an attentional distractor impaired integration performance, and secondly at which time-point during the saccade the attentional distractor had the most effect.

2. Method

2.1. Equipment

Stimuli were presented using a back projection setup with a 91 × 51 cm screen from Stewart Filmscreen, and PROPixx projector from VPixx Technologies with a resolution of 1920 × 1080, and refresh rate of 120 Hz. The screen was calibrated to ensure a linear gamma correction and background luminance was 92 cd/m^2 at the screen centre. To minimise hot spots, we were using a screen material with a