Brain and Cognition 81 (2013) 345–351

Contents lists available at SciVerse ScienceDirect

Brain and Cognition

journal homepage: www.elsevier.com/locate/b&c

The effect of repetitive saccade execution on the attention network test: Enhancing executive function with a flick of the eyes

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ARTICLE INFO

Article history:
Accepted 30 December 2012
Available online 1 March 2013

Keywords:
Saccadic eye movements
Handedness
Executive function
Cognitive enhancement
Attentional control
Attention network test

ABSTRACT

The simple act of repeatedly looking left and right can enhance subsequent cognition, including divergent thinking, detection of matching letters from visual arrays, and memory retrieval. One hypothesis is that saccade execution enhances subsequent cognition by altering attentional control. To test this hypothesis, we compared performance following repetitive bilateral saccades or central fixation on the revised attention network test, which measures the operation of three distinct attentional networks: alerting, orienting, and executive function. The primary finding was that saccade execution increased the subsequent operation of the executive function network, which encompasses attentional control. Specifically, saccade execution decreased response time to target stimuli in the presence of response-incongruent flankers. A secondary finding was that saccade execution decreased response time to targets when an invalid location was cued prior to target onset. These findings suggest that saccades are an effective means of improving attentional control. Of greater theoretical importance, the study establishes attentional enhancement as a potential mechanism by which saccades enhance other aspects of cognition. Although some saccade execution effects have been found to depend on consistency of handedness (i.e., the consistency with which an individual uses one hand over the other), saccade-induced enhancement of attentional control occurred independently of handedness consistency.

1. Introduction

The simple act of repeatedly looking left and right can enhance subsequent cognition. This surprising effect has been established in numerous studies that have compared cognitive performance following 30 s of repetitive bilateral saccade execution to performance following 30 s of either central fixation or spontaneous, unrestrained eye movement. Saccade execution enhances subsequent divergent thinking on the Alternate Uses Task (Shobe, Ross, & Fleck, 2009), detection of matching letters in briefly flashed arrays (Lyle & Martin, 2010), and, most commonly, memory retrieval (e.g., Christman, Garvey, Propper, & Phaneuf, 2003; Lyle, Logan, & Roediger, 2008). For example, in Lyle et al., subjects recalled more studied words, and falsely recalled fewer nonstudied words, following saccades vs. fixation. The effect of saccade execution on memory retrieval has been dubbed saccade-induced retrieval enhancement (SIRE; Lyle & Martin, 2010), but the broader phenomenon may be called saccade-induced cognitive enhancement (SICE).

Although SICE is well documented empirically, its cause is unknown. An initial hypothesis (Christman et al., 2003) that saccades enhance cognition by increasing functional coordination of the left and right cerebral hemispheres (i.e., the interhemispheric interaction account) has received mixed support, which we now review. Lyle and Martin (2010) tested whether saccade execution would increase subjects' ability to detect an identity match between two letters that differed in case (e.g., *A* and *a*) when the two letters were briefly flashed in separate visual fields and hence were initially processed by separate hemispheres. The authors reasoned that, if saccades increase the functional coordination of the hemispheres, then they should enhance match detection under these conditions, which require interhemispheric interaction (Eviatar & Zaidel, 1994). However, saccade-induced enhancement was not obtained under these conditions. Rather, saccades increased match detection when the two letters were presented in the same visual field and hence processing of the match was primarily intrahemispheric. Subsequently, Lyle and Orsborn (2011) tested whether saccade execution would increase bilateral gain for famous faces, which is the effect whereby such faces are more quickly or accurately identified when they are initially processed by both hemispheres simultaneously (given bilateral visual presentation) vs. when they are initially processed by only a single hemisphere (given unilateral presentation). Bilateral gain is thought to depend on interhemispheric interaction (Mohr, Pulvermuller, Rayman, & Zaidel, 1994), but its magnitude was unaffected by saccades in Lyle

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http://dx.doi.org/10.1016/j.bandc.2012.12.006

and Orsborn's study. In contrast, saccades increased identification of novel faces, which do not show a bilateral gain effect. Hence, in two behavioral studies, saccades enhanced cognition (intrahemispheric letter matching and novel-face identification) without affecting indices of interhemispheric interaction.

In addition to the behavioral data, electrophysiological findings relevant to the interhemispheric interaction account have been reported, but are inconclusive. Propper, Pierce, Geisler, Christman, and Bellorado (2007) found that saccades decreased gamma-band coherence between the hemispheres, which suggests that saccades may indeed affect interhemispheric interaction in some way, but two caveats are necessary. First, Propper et al.'s study did not have a behavioral component, and so could not reveal whether saccade-induced changes in coherence were accompanied by cognitive enhancement. Second, it is not clear whether decreased coherence represents an increase in interhemispheric interaction, as the interhemispheric interaction hypothesis stipulates, or a decrease. Following up on this finding, Samara, Elzinga, Slagter, and Nieuwenhuis (2011) conducted a combined behavioral and electrophysiological study and found that saccades increased retrieval but had no significant effect on interhemispheric coherence. From this we may conclude that, even if saccades sometimes do affect interhemispheric interaction, as suggested by Propper et al.'s finding, a change in interaction is not necessary for SICE to occur.

As an alternative to the interhemispheric interaction account, Lyle and Martin (2010) hypothesized that saccade execution might enhance subsequent cognition by altering the top-down allocation or control of attention. Top-down attentional control is theoretically vital to much of complex cognition, including those tasks that have shown SICE, as we detail next. First, multiple authors have recently suggested that attentional control may play a role in episodic memory retrieval when stimulus-driven mental events alone are insufficient for a desired memory judgment or experience (Cabeza, 2008; Ciaramelli, Grady, & Moscovitch, 2008; Wagner, Shannon, Kahn, & Buckner, 2005). These situations would include those that require multiple retrieval attempts, post-retrieval monitoring, or goal-driven maintenance or shifting of attention on or between mnemonic representations. Specific retrieval phenomena posited to involve attentional control include source recollection, rejection of related/similar lures in recognition, and correct recognition of high vs. low frequency words (Ciaramelli et al., 2008). Second, the Alternate Uses Task studied by Shobe et al. (2009), while broadly characterized as a test of creativity, is more specifically a measure of divergent thinking, which is the ability to generate diverse solutions to a problem (see Dietrich & Kanso, 2010, for discussion of separable processes in creativity). In Shobe et al.'s version of the task, subjects saw the name and one common use of 15 different objects. Subjects were instructed to list as many uses for each object as possible, other than the common use they were given, in 60 s. There is a role for episodic memory retrieval in this task, because many subjects initially produce uses by retrieving instances in which they saw the objects used in uncommon ways (Gilhooly, Fioratou, Anthony, & Wynn, 2007). This type of retrieval may require a high level of attentional control, because subjects must ignore the common use and not become fixated on uses similar or identical to previously given uses. Third and finally, Banich (1998) argued that detecting letter-identity matches intrahemispherically is more attentionally demanding than detecting them interhemispherically. In sum, while each of the tasks on which SICE has been observed depend on multiple perceptual and cognitive processes, the top-down control of attention may be a shared process that is common to all.

In developing their attentional control hypothesis, Lyle and Martin (2010) drew on the well-established finding that making goal-directed saccades activates a frontoparietal network of brain regions, including the frontal eye field, intraparietal sulcus, and superior parietal lobe (Corbetta & Shulman, 2002). The frontoparietal network is hypothesized to be involved in the implementation of top-down attentional control. Lyle and Martin hypothesized that, by activating brain regions involved in attentional control immediately prior to task onset, saccade execution may increase control and thereby enhance subsequent task performance. Critically, functional neuroimaging has revealed that the intraparietal sulcus and superior parietal lobe, which are activated by saccade execution, are also activated during episodic memory retrieval, and especially for retrieval tasks that require a high degree of attentional control, such as source recollection, rejection of similar/related lures, and correct recognition of high frequency words (Cabeza, 2008; Ciaramelli et al., 2008; Wagner et al., 2005). Furthermore, the intraparietal sulcus has also been implicated in detecting identity-matches between letters (Pollmann, Zaidel, & von Cramon, 2003) and the superior parietal lobe has been implicated in the Alternate Uses Task in one investigation (Abraham et al., 2012), albeit not another (Fink et al., 2010).

Lyle and Martin's (2010) attentional control hypothesis predicts that SICE should not occur for tasks that do not require a high degree of top-down attentional control. Consistent with this, Brunyé, Mahoney, Augustyn, and Taylor (2009, Experiment 2) did not find enhancement when old items (in this case, aerial maps) had to be discriminated from rearranged items in a two-alternative forced-choice procedure. Brunyé et al. posited that performance on their forced-choice task may have been driven primarily by bottom-up differences in familiarity between the two stimuli and may not have depended on executive function, which subsumes top-down attentional control. Also, Christman et al. (2003, Experiment 1) did not find enhancement on an implicit retrieval task. Subjects saw word fragments that they could (and sometimes did) complete with previously studied words, but they were not required to attend to the old/new status of the words used to complete fragments.

Lyle and Martin's (2010) idea that goal-directed saccade execution might improve attentional control is interesting in its own right, regardless of whether such improvement is actually the cause of previously documented SICE effects. Saccade execution can be conceptualized as a minimal attentional control task insofar as control is required to repetitively shift attention according to a pre-established agenda. Lyle and Martin's idea, therefore, is that exercising attentional control in the service of saccades and for as little as 30 s, may produce measurable improvement in control. Could merely exercising attentional control lead to its improvement? The answer is yes according to studies of training attention (e.g., Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005) and the closely related construct of working memory (for reviews, see Klingberg, 2010; Morrison & Chein, 2011). Training regimens that involve the repetitive performance of tasks requiring attentional control have been found to produce improvement on other, non-trained tasks. In those studies, the improvement has occurred following hours of repetitive practice. Furthermore, the demands placed on control processes often have not been static, but rather have increased throughout training. Hence, while those studies demonstrate the possibility of improving attentional control, it is an open question whether improvement can be achieved following performance of an attentional control task that is very brief and has low and static demands, such as 30 s of saccade execution.

No previous study has directly examined possible effects of saccade execution on attentional processing. Therefore, in the present study, we compared performance following saccades or central fixation on the revised attention network test (ANT-R; Fan et al., 2009), which measures the operation of three dissociable attentional networks: alerting, orienting, and executive function (for review, see Posner & Petersen, 1990). On each trial in the ANT-R (see Fig. 1 for an example), subjects indicate the direction that a