Research Article

The Search for Oculomotor Inhibition

Interactions with Working Memory

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Abstract. When a saccadic target is presented simultaneously with a distractor, the distractor has to be inhibited in order to successfully perform an eye movement to the target. Insufficient inhibition results in an erroneous eye movement to the distractor. This study investigated whether the influence of a distractor on eye movements is mediated by working memory. A working memory task was added to a saccadic paradigm in which an irrelevant element had to be inhibited. Results show that participants made more erroneous saccades to the distractor when working memory was occupied. This suggests that working memory is involved in the oculomotor inhibition of saccadic distractors.

Keywords: eye movements, working memory, inhibition

In order to successfully complete a complex task in our dynamic visual environment, it is crucial to make eye movements to locations that are relevant for the task demands. For instance, while driving a car, it is essential to keep your eyes on the road and to fixate landmarks that might guide steering. However, this process also constitutes ignoring the parts of the visual scene that are distracting for completing the task. So, while driving, it is important not to fixate elements that might interfere with driving, like flashing billboards located along the route. How does the brain prevent eye movements to salient elements that interfere with the current task settings?

Experimental evidence has shown that observers are not always able to prevent an eye movement to a distracting element. For instance, it has been found in visual search experiments that in a large portion of trials participants first make an eye movement to an abrupt visual onset when the task is to make an eye movement to a predefined target (Theeuwes, Kramer, Hahn, & Irwin, 1998; Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999). On these trials, the eyes are "captured" by the new object and observers are unable to prevent executing an eye movement to the distracting element (distractor). On the remaining trials, the observers successfully select the target and ignore the distractor.

The ability to prevent the execution of erroneous eye movements is called "oculomotor inhibition" and has generally been investigated using the antisaccade task. In this task participants are presented with an abrupt visual onset in the periphery after which they have to execute an eye movement away from the onset location to its mirror opposite position (an "antisaccade", Everling & Fischer, 1998; Hallet, 1978; Munoz & Everling, 2004). In this task, observers frequently make an erroneous saccade toward the onset location. Successful performance on the antisaccade task requires two processes: Oculomotor inhibition of an automatically evoked response to the onset location and the subsequent execution of a goal-driven eye movement to the mirror location of the onset. Because an erroneous saccade to the onset can be seen as a failure to inhibit a strong behavioral response, this task has been used to measure oculomotor inhibition.

Based on various types of studies, it has been suggested that oculomotor inhibition in the antisaccade task relies heavily on frontal structures (for a review, see Munoz & Everling, 2004). Clinical studies have, for instance, shown that patients with frontal lesions perform worse on the antisaccade task than controls (Pierrot-Deseilligny, Milea, & Muri, 2004; Pierrot-Deseilligny, Rivaud, Gaymard, & Agid, 1991). Furthermore, neurophysiological studies have identified various frontal areas that are active during the antisaccade task (Everling & Munoz, 2000; Funahashi, Chafee, & Goldman-Rakic, 1993), whereas applying TMS over frontal regions during the antisaccade task has been shown to result in an increased number of errors (Nyffeler et al., 2007; Terao et al., 1998).

Although the evidence for frontal contributions to oculomotor inhibition seems to be consistent in the antisaccade task, it is unknown whether these same operations are also involved in other tasks that require oculomotor inhibition. This is not trivial, since there is ample evidence that different types of oculomotor inhibition can be dissociated (Kramer, Gonzalez de Sather, & Cassavaugh, 2005; Kramer, Hahn, Irwin, & Theeuwes, 2000; Van der Stigchel et al., 2007). For instance, ignoring distractors in an oculomotor distractor experiment might rely on different processes than preventing erroneous eye movements to the onset in the antisaccade task. The onset in the antisaccade task is task relevant, because participants must direct their attention to the onset and use this object to direct their attention and eyes in the opposite direction. Errors in the antisaccade task are partly goal driven, because there is an explicit instruction not to look at the onset, but to saccade to the opposite direction. In contrast, the status of the onset is fundamentally different in oculomotor distractor experiments in which the

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to-be-inhibited onset is irrelevant and does not need to be attended in order to correctly perform the task. Therefore, errors are purely stimulus driven, since neither the presence nor the location of the onset predicts anything about the target (see e.g., Godijn & Kramer, 2006).

Evidence for the idea that different types of processes underlie performance in the antisaccade and the oculomotor distractor task was further provided by studies comparing behavior on these paradigms in different groups. For instance, children with ADHD perform worse than controls on the antisaccade task (Klein, Raschke, & Brandenbusch, 2003; Mostofsky, Lasker, Cutting, Denckla, & Zee, 2001; Munoz, Armstrong, Hampton, & Moore, 2003), whereas ignoring distractors in an oculomotor distractor task seems unaffected (Van der Stigchel et al., 2007). Furthermore, it was shown that older adults do not have more difficulty inhibiting an oculomotor distractor compared to younger adults but do have more difficulty in suppressing the onset in the antisaccade task (Kramer et al., 2000). Similarly, for a group of younger and older children it was found that they were not differently captured by the onset in an oculomotor search task, whereas antisaccade performance improved with age (Kramer et al., 2005).

As it is unknown whether frontal operations play a role in the inhibition of oculomotor distractors, this study will apply an experimental manipulation that has been used to provide evidence for the involvement of frontal operations in the mechanisms underlying successful performance in the antisaccade task. In particular, it will be investigated whether *working memory*, one of the important frontal processes (i.e., Smith & Jonides, 1997), is involved in the inhibition of oculomotor distractors. To investigate this, an additional working memory task was added to a basic oculomotor paradigm in which an irrelevant distractor had to be ignored. By adding a secondary task to a paradigm, possible behavioral differences can be contributed to the processes involved in executing the additional task. Indeed, various studies have shown that performance on the antisaccade task is impaired when a concurrent working memory task is executed (a higher amount of erroneous saccades toward the onset, Mitchell, Macrea, & Gilchrist, 2002; Roberts, Hager, & Heron, 1994; Stuyven, Van der Goten, Vandierendonck, Claeys, & Crevits, 2000). It was therefore inferred that working memory plays a critical role in the oculomotor inhibition involved in the antisaccade task (Mitchell et al., 2002). The same rationale will be applied here with respect to the inhibition of oculomotor distractors.

In this study, the same dual-task setting will be used as in the study by Mitchell et al. (2002), but instead of an antisaccade, participant had to make a saccadic eye movement to a target, while a distractor was presented simultaneously on half the trials. Simultaneously with the saccadic task, participants performed either a working memory task (a 2-back task) or a task that did not require a strong working memory component (a 0-back task). Indeed frontal areas show increased activity when the 2-back task is performed in an fMRI scanner (Jonides et al., 1997). If an occupied working memory influences the amount of inhibition applied to the distractor, differences should be observed in the amount of trials in which participants make an erroneous eye movement to the distractor.

Method

Participants

Twelve students (four male), aged between 18 and 24 years old, served as paid volunteers. All reported having normal or corrected-to-normal vision. They were naïve as to the purpose of the experiment. All persons gave their informed consent prior to their inclusion in the study.

Apparatus

Eye movements were registered by means of a video-based eye tracker (SR Research Ltd., Canada). The Eyelink2 system has a 500 Hz temporal resolution and a spatial resolution of 0.025°. The system uses an infrared video-based tracking technology to compute the pupil center and pupil size of the eyes. An infrared head-mounting tracking system tracked head motion. The left eye was recorded and analyzed. An eye movement was considered a saccade either when the movement velocity exceeded 35°/s or when the movement acceleration exceeded 9500°/s2. Although the system compensates for head movements, the participant's head was stabilized using a chin rest. The distance between monitor and chin rest was 65 cm. Participants performed the experiment in a sound-attenuated and dimly lit room.

Stimuli

See Figure 1 for an illustration of the display sequence. All figures were presented in light gray (CIE *x*, *y* chromaticity coordinates of .291/.314; 26.4 cd/m^2) on a black background (0.0 cd/m^2). Each trial started with the presentation of a "star" character (1.17° × 1.17°) in the center of the screen that functioned as the fixation stimulus. After 800 ms the target (a light gray filled circle with a diameter of 1.17°) appeared. There were six possible target locations and six possible distractor locations positioned on an imaginary

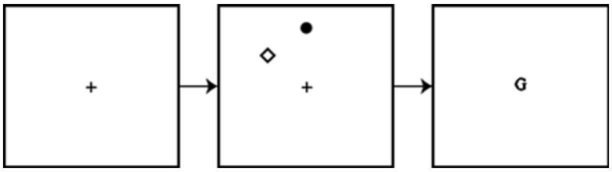

Figure 1. Example of the display sequence. Participants had to execute an eye movement to the target circle. In half the trials a distractor was presented simultaneously. After the trial, a letter was presented centrally. Depending on the experimental block, participants had to perform an additional task. For instance, in the crucial 2-back block, participants had to indicate whether this letter was the same as two trials earlier.

circle with a radius of 9.75° around the central fixation point. The possible target locations were two, four, six, eight, ten, or twelve o'clock. Simultaneously with the target onset, a light gray diamond-shaped distractor (1.17° × 1.17°) appeared in half of trials. The possible distractor locations were one, three, five, seven, nine, and eleven o'clock.

Procedure and Design

Participants first received oral instructions. They were instructed to fixate the center fixation point until target onset and to then move their eyes to the target location. It was stressed that one had to make a single accurate saccade toward the target element. Participants heard a short tone when the saccade latency was higher than 600 ms or shorter than 80 ms. Each target and distractor location were equally probable.

After the eye movement task an additional screen appeared. There were three blocks: in one block the additional screen was blank (no-back block). In the second block a letter appeared and participants had to indicate whether the presented letter was a "F" (0-back block). Participants pressed the "z"-key for yes and the "/"-key for no. The letter "F" appeared in one third of trials. In the remaining trials, the letter was picked randomly from the remaining letters in the alphabet. The letter stayed on the screen until a response was made. In the third block a letter appeared and participants had to indicate whether this letter was the same letter as two trials before (2-back block). Participants pressed the "z"-key for yes and the "/"-key for no. The letter was the same as two trials before in one third of trials. In the remaining trials, the letter was picked randomly from the remaining letters in the alphabet. Again, the letter stayed on the screen until a response was made. Feedback on the performance on the additional task was given after every 30 trials.

The order of blocks was counterbalanced. Each block consisted of a training session of 24 trials and an experimental session of 192 trials. Each session started with a nine-point grid calibration procedure. Participants were required to saccade toward nine fixation points sequentially appearing at random in a 3 × 3 grid. In addition, simultaneously fixating the center fixation point and pressing the space bar recalibrated the system by zeroing the offset of the measuring device at the start of each trial. The sequence of trials was counterbalanced and randomized for each participant.

Data Analysis

Saccade latency was defined as the interval between target onset and the initiation of a saccadic eye movement. If saccade latency was lower than 80 ms, higher than 600 ms, or further than two and a half standard deviations away from the mean latency the trial was removed from the analysis. Moreover, trials were excluded from analysis in which no saccade or a too small first saccade (< 3°) was made. Furthermore, the initial saccade starting position had to be within 1° from the center fixation point.

To investigate the amount of erroneous eye movements, the landing location of the first eye movement was computed. If the endpoint of the first saccade had an angular deviation of less than 15° from the center of the target or the distractor, the saccade was classified as landed on the target or the distractor, respectively. In other situations, the saccade was classified as an error and not analyzed.

Results

The exclusion criteria led to a total loss of 9.9% of trials in the no-back, 11.5% of trials in the 0-back, and 14.5% of trials in the 2-back block.

Saccade Direction

When no distractor was presented, saccade accuracy to the target was high (mean = 0.99; *SD* = 0.02). Saccade accuracy in these distractor absent trials was not different for the three experimental blocks, $F(2, 22) = 0.71$; $p > 0.50$. Therefore, any difference in saccade direction in the dual-task conditions cannot be explained by less accurate overall saccade targeting.

For distractor present trials, it was determined whether the percentage of trials in which an erroneous first eye movement was made to the distractor differed for the three experimental blocks. An analysis of variance (ANOVA) with Task (no-back, 0-back, and 2-back) as a factor showed a main effect (see Figure 2, $F(2, 22) = 10.38$; $p < 0.001$). Post hoc tests showed a significant difference in capture between the no-back (0.09) and 2-back block (0.17; $t(11) = 4.47$; $p < 0.001$) and between the 0-back (0.11) and the 2-back block (0.17; $t(11) = 2.50$; $p < 0.03$).

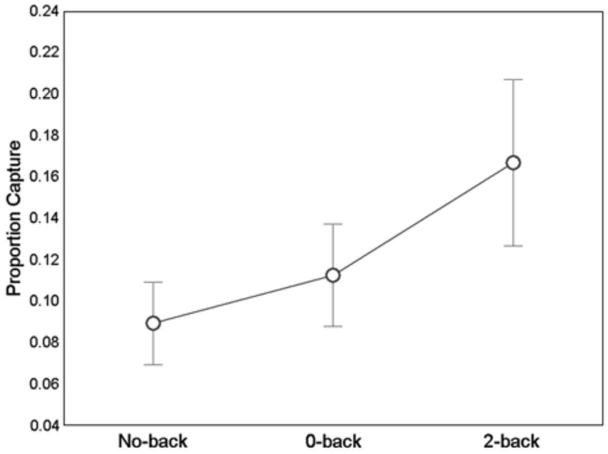

Figure 2. Mean proportion capture for the three different experimental blocks. This constitutes trials in which participants made an erroneously first saccade to the distractor. Error bars represent standard deviations.

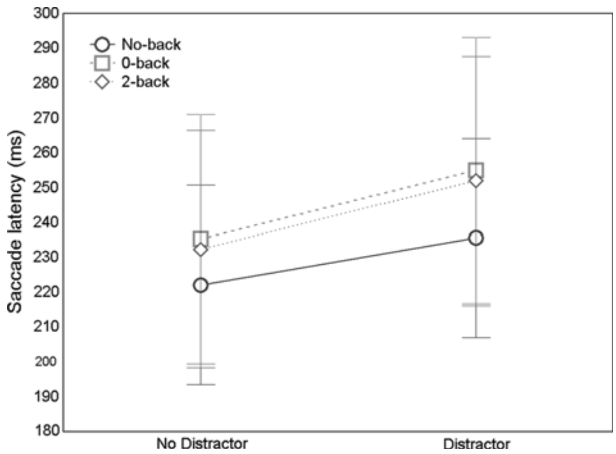

Figure 3. Mean saccade latency of the three different experimental blocks for the distractor absent and distractor present conditions. Error bars represent standard deviations.

Saccade Latency

To determine whether the different conditions had an effect on saccade latency, an ANOVA with Task (no-back, 0-back, and 2-back) and Distractor Condition (present, absent) as factors was performed. There was no main effect of Task, $F(2, 22) = 1.04$; $p > 0.30$. Distractor Condition had an effect on saccade latency, $F(1, 11) = 88.54$; $p < 0.0001$, in that distractor present trials were slower (247 ms) than distractor absent trials (230 ms). There was no interaction between Task and Distractor Condition (see Figure 3, $F(2, 22) = 2.30$; $p > 0.10$). To exclude the possibility that this absence of interaction was due to a lack of statistical power, additional t-tests were run on the difference between distractor present and distractor absent trials. This "distractor effect" was compared between the various blocks. Only the difference between the no-back and the 2-back task was significant ($t(11) = 2.21$; $p < 0.05$). Importantly, the difference between the 0-back and the 2-back task was far from significance ($t(11) = 0.03$; $p > 0.90$) indicating that the lack of an increased distractor effect with a high memory load was not due to a low statistical power.

Saccade Velocity

To determine whether the different conditions had an effect on saccade peak velocity, an ANOVA with Task (no-back, 0-back, 2-back) and Distractor Condition (present, absent) as factors was performed. There was no main effect of Task, $F(2, 22) = 1.14$; $p > 0.30$. Distractor Condition had an effect on saccade velocity, $F(1, 11) = 8.38$; $p < 0.02$, in that the peak velocity in distractor present trials was higher (338°/s) than distractor absent trials (333°/s). Importantly, there was no interaction between Task and Distractor Condition, $F(2, 22) = 2.30$; $p > 0.10$.

Distance Between Target and Distractor

An analysis was run to investigate whether the distance between target and distractor had an influence on the various measures. The distance between target and distractor was considered small if target and distractor were aligned within an angle of 30° (e.g., target at four o'clock, distractor at five o' clock). In all other configurations, the distance was considered large. With respect to saccade direction, an ANOVA on distractor present trials with Task (no-back, 0-back, 2-back) and Distance (small, large) as factors revealed a main effect of Task, $F(2, 22) = 10.58$; $p < 0.001$, and Distance, $F(1, 11) = 43.62$; $p < 0.001$. Saccade errors were higher when the target and distractor were closely aligned (0.20) compared to when the distance between target and distractor was large (0.09). The interaction between Task and Distance was marginally significant, $F(2, 22) = 3.30$; $p = 0.056$. The difference in saccade errors between small versus large distance increased with increasing working memory load (see Table 1).

With respect to saccade latency, the ANOVA on distractor present trials only revealed a main effect of Distance, $F(1, 11) = 28.10$; $p < 0.001$, with latencies being slower when the distance was large (253 ms) compared to when the distance was small (234 ms). The interaction between Task and Distance was not significant, $F(2, 22) = 0.97$; $p > 0.30$.

For saccade velocity in distractor present trials, there was only a main effect of Distance, $F(1, 11) = 5.73$; $p < 0.05$, with peak velocity being higher when distance was large (340°/s) compared to when the distance was small (334°/s). The interaction between Task and Distance was not significant, $F(2, 22) = 2.82$; $p > 0.05$.

N-Back Performance

Accuracy on both the 0-back and the 2-back tasks was high, but performance on the 0-back task was significantly higher

Table 1. The effect of task and the distance between target and distractor on the various measures

Task	No-back		0-back		2-back	
Distance	Small	Large	Small	Large	Small	Large
Saccade direction	0.14 (0.07)	0.06 (0.03)	0.18 (0.07)	0.08 (0.05)	0.27 (0.11)	0.12 (0.06)
Saccade latency	226 ms (51)	240 ms (43)	243 ms (66)	260 ms (59)	234 ms (48)	259 ms (58)
Saccade velocity	326°/s (45)	337°/s (49)	339°/s (43)	344°/s (44)	337°/s (25)	338°/s (29)

(.996) than on the 2-back task (.959; $t(11) = 4.25$; $p < 0.01$).

General Discussion

This study investigated whether the influence of a distractor on eye movements is mediated by working memory. If oculomotor inhibition of distractors relies on working memory, an additional working memory task should increase the interfering effects of a distractor. Results showed that participants made more saccades to the distractor when the additional task tapped into working memory capacities. This effect was stronger when target and distractor were closely aligned. This shows that working memory interferes with ignoring a distractor: when elements are stored in working memory, the ability to correctly saccade to the target in the presence of a competing element is impaired.

Overall, the present results are consistent with reports from the antisaccade task in which working memory is known to mediate successful suppression of unwanted eye movements (Mitchell et al., 2002; Roberts et al., 1994; Stuyven et al., 2000). This has interesting implications for the mechanisms underlying oculomotor inhibition. Kramer and colleagues distinguished two qualitatively different types of inhibition with an automatic/implicit form of inhibition playing a central role in oculomotor distractor tasks and an intentional/effortful inhibition mostly subserving performance in the antisaccade task (Kramer et al., 2005; Kramer et al., 2000). Based on the present results of an oculomotor distractor task and previous findings with the antisaccade task (Mitchell et al., 2002; Roberts et al., 1994; Stuyven et al., 2000), this seems to indicate that both types of inhibition are mediated by working memory.

In contrast to the amount of saccade errors to the distractor, no effect of working memory was observed on saccade latency. Although saccade latencies were higher when a distractor was present, this difference was not elevated when working memory was occupied. This is consistent with findings of Mitchell et al. (2002) who used the same dual-task setting as this study: They observed an increase of saccade errors in the antisaccade task when working memory was occupied, but no effect on saccade latencies. This suggests that working memory only influences the oculomotor inhibition underlying errors in saccade direction. In line with this idea, a limited review of the literature also points to a dissociation between effects on latency costs and errors in saccade direction. For instance, applying TMS to the dorsolateral prefrontal cortex only influences the amount of errors and not saccade latency (Nyffeler et al., 2007). This same effect is observed in studies of patients with lesions in this area (Pierrot-Deseilligny et al., 1991). However, applying TMS to the frontal eye fields increases the latency costs, but does not lead to a higher amount of errors (Muri, Hess, & Meienberg, 1991; Olk, Chang, Kingstone, & Ro, 2006). Again, this converges with lesion studies of the frontal eye fields (Gaymard, Ploner, Rivaud, & Pierrot-Deseilligny, 1994; Rivaud, Muri, Gaymard, Vermersch, & Pierrot-Deseilligny, 1994).

Errors in saccade direction constitute a more direct measure of oculomotor inhibition than an increase of saccade latency. Saccade latency reflects the time necessary to inhibit an automatically evoked eye movement to the onset and to initiate an eye movement to the target location. This is most likely not a serial process, as models of saccade generation assume that the programming of the eye movement to the target occurs in parallel with the inhibition of the eye movement to the onset (Findlay & Walker, 1999; Godijn & Theeuwes, 2002; Trappenberg, Dorris, Munoz, & Klein, 2001). Because these processes operate in parallel, it is difficult to disentangle possible effects of oculomotor inhibition as the programming of the eye movement to the target is unlikely to be influenced by oculomotor inhibition. Errors in saccade direction therefore constitute a more direct measure of oculomotor inhibition, because they reflect the amount of trials in which oculomotor inhibition was not successful.

This study is in line with the idea that working memory and visual attention are closely intertwined (for a review, see Awh, Vogel, & Oh, 2006). Although it has been argued that visual search is not influenced by nonspatial working memory load (Woodman, Vogel, & Luck, 2001), recent research has shown that the effect of a distractor in visual search does increase when working memory is occupied if the distractor is a unique singleton distractor (Boot, Brockmole, & Simons, 2005; Lavie & de Fockert, 2005). Because this singleton evokes strong competition rejection requires higher-level cognitive control. In line with this idea, frontal areas have been shown to be involved in the successful rejection of a singleton distractor (De Fockert, Rees, Frith, & Lavie, 2004). This seems to indicate that the capacity to inhibit a singleton distractor is influenced by working memory processes. This study extends these findings by showing that inhibiting an eye movement to a single distractor is also mediated by working memory, which is in line with the claim that the mechanisms underlying attentional and oculomotor system strongly overlap (Rizzolatti, Riggio, & Sheliga, 1994; Van der Stigchel & Theeuwes, 2007).

One alternative explanation for the current findings is the idea that the higher number of saccade errors is not due to inhibition failures, but failures of goal maintenance[1]. Because working memory is important for maintaining a template of the target object, an occupied working memory might result in more eye movements to the distractor, because the target is incorrectly identified. Recent findings, however, have suggested that working memory templates of the target are not necessary when the target identity remains constant (Rossi, Harris, Bichot, Desimone, & Ungerleider, 2001; Woodman, Luck, & Schall, 2007), like in this study. When participants performed a visual search task during the delay of a working memory task, these tasks only interfered with each other when the search target changed from trial to trial, but not when target identity remained constant (Woodman et al., 2007). Furthermore, a study in monkeys with prefrontal lesions showed that these monkeys

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[1] I thank an anonymous reviewer for this suggestion.

performed poorly on a visual search task when the target identity changed on every trial. With less frequent switches, performance was less impaired compared to monkeys with an intact prefrontal cortex (Rossi et al., 2001). This suggests that a target template is stored in working memory only when the target varies from trial to trial; in line with idea that performance in visual search might be a "prepared reflex" that can become automatized (Logan, 1978). Because the target remained constant during all blocks in this study, it is unlikely that the target template was stored in working memory which is consistent with the claim that saccade errors were the result of inhibition failures.

Although the neural circuits involved in working memory processes show increased activity when the 2-back task is performed (Jonides et al., 1997; Owen, McMillan, Laird, & Bullmore, 2005), it is important to clarify which working memory operations are addressed in this study. Baddeley and Hitch (1974) proposed a multiple-component model of working memory consisting of a "central executive" and two "slave systems": the phonological loop and the visuospatial sketchpad. These slave systems are specialized in the processing and temporary storage of verbal and spatial information, respectively. Although the involvement of the phonological loop in the n-back task is probable (Collette & Van der Linden, 2002), the n-back task is generally considered as tapping into the central executive (Baddeley, 2003). Because the central executive has been hypothesized to be important for executive attention and performing explicit computations to guide upcoming actions (see, e.g., Kane, Poole, Tuholski, & Engle, 2006), it is the likely candidate for the component involved in oculomotor inhibition.

To summarize, the present results showed that the interfering effects of an irrelevant distractor increased when a working memory task was added to a distractor paradigm, because participants made more saccades to the distractor. This suggests that working memory is involved in the oculomotor inhibition of saccadic distractors.

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