Horizontal but not vertical saccades enhance memory retrieval: a meta-analysis and systematic review

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Abstract

BACKGROUND: Saccade-induced retrieval enhancement (SIRE) refers to the phenomenon that active engaging of horizontal eye movements before recall would enhance subsequent memory performance. This effect is generally thought to be the result of interhemispheric interaction stimulated by saccades. Nonetheless, recent findings do not fully support this hypothesis. An alternative explanation is that saccades promote memory retrieval by improving top-down attention control. Thus, the mechanisms of SIRE are unclear, the present meta-analysis quantitatively analyzed the effect of saccades on memory performance and examined the mechanisms of SIRE through moderator analysis. METHODS: We searched "Web of Science", "PubMed", and "Springer" for peer reviewed papers using the keywords "eye movements + memory" and "saccades + memory". Twenty-two papers were included in the final analysis. RESULTS: There was a significant facilitation of horizontal saccades on overall memory performance, with a pooled effect size (Cohen' s d) of 0.45 ($p < 0.001$). However, the overall effect of vertical saccades was not significant ($d = 0.1$, $p = 0.14$). Moderation analysis showed that the handedness of participants was a significant moderator of the SIRE, with strongly right-handed individuals benefited more from horizontal saccades than non-strongly right-handed individuals ($p < 0.01$). CONCLUSION: Horizontal saccades improved memory performances, particularly for the strongly right-handed individuals, these results support the interhemispheric interaction hypothesis.

Full Text

Horizontal but not Vertical Saccades Enhance Memory Retrieval: A Meta-Analysis and Systematic Review

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Abstract

Background: Saccade-induced retrieval enhancement (SIRE) refers to the phenomenon whereby engaging in horizontal eye movements before recall enhances subsequent memory performance. This effect is generally thought to result from interhemispheric interaction stimulated by saccades. Nonetheless, recent findings do not fully support this hypothesis. An alternative explanation proposes that saccades promote memory retrieval by improving top-down attentional control. Thus, given the unclear mechanisms of SIRE, the present meta-analysis quantitatively analyzed the effect of saccades on memory performance and examined the mechanisms of SIRE through moderator analysis.

Methods: We searched Web of Science, PubMed, and Springer for peer-reviewed papers using the keywords "eye movements + memory" and "saccades + memory." Twenty-two papers were included in the final analysis.

Results: Horizontal saccades showed significant facilitation of overall memory performance, with a pooled effect size (Cohen' s d) of 0.45 ($p < 0.001$). However, the overall effect of vertical saccades was not significant ($d = 0.10$, $p = 0.14$). Moderation analysis revealed that participants' handedness was a significant moderator of SIRE, with strongly right-handed individuals benefiting more from horizontal saccades than non-strongly right-handed individuals ($p < 0.01$).

Conclusion: Horizontal saccades improved memory performance, particularly for strongly right-handed individuals. These results support the interhemispheric interaction hypothesis.

Keywords: memory, saccades, meta-analysis, interhemispheric interaction

1. Introduction

Saccade-induced retrieval enhancement (SIRE) refers to the phenomenon whereby engaging in horizontal eye movements before recall enhances subsequent memory performance (Lyle & Martin, 2010). Christman, Garvey, Propper, and Phaneuf (2003) first described SIRE in a study where participants learned a word list and then visually followed a black dot moving horizontally on a screen for 30 seconds before recalling the list. Their results showed higher sensitivity (d' in signal detection theory) following horizontal saccades compared to a no-eye-movement condition. Since then, SIRE has been examined in numerous studies, most of which found that horizontal saccades promoted recognition (Christman, Garvey, Propper, & Phaneuf, 2003, Experiment 1; Parker, Relph, & Dagnall, 2008; Lyle, Logan, & Roediger, 2008), free recall (Lyle & Edlin, 2015; Lyle, Logan, & Roediger, 2008; Nieuwenhuis et al., 2013; Parker, Relph, & Dagnall, 2008; Samara, Elzinga, Slaghuter, Nieuwenhuis, 2011), reduced false memories (Christman, Propper, & Dion, 2004; Parker & Dagnall, 2012), and facilitated autobiographical memory (Christman, Garvey, Propper, & Phaneuf, 2003, Experiment 2; Christman, Propper, & Brown, 2006; Parker & Dagnall, 2010; Parker, Parkin, & Dagnall, 2013).

Nonetheless, SIRE has been challenged by contradictory empirical evidence. For example, a pre-registered collaborative study failed to replicate the enhancing effect of horizontal saccades on memory retrieval and reported that participants' free recall performance after induced eye movements was even worse compared to the no-eye-movement condition (Matzke et al., 2015). Additionally, whether horizontal saccades are necessary for SIRE remains unclear. Vertical saccades, often used as a control condition, were also found to enhance word recognition (compared with no eye movement condition, $d = 0.68$) (Lyle et al., 2008; also see Parker et al., 2008). Furthermore, handedness has been suggested as an important factor affecting SIRE. According to the interhemispheric interaction hypothesis, strongly right-handed people have lower baseline levels of interhemispheric interaction and should therefore benefit more from horizontal saccades in memory performance (Christman, Garvey, Propper, & Phaneuf, 2003), though some research findings do not fully support this view (Lyle & Jacobs, 2010). Generally speaking, inconsistencies in SIRE research results necessitate a quantitative review of existing evidence to clarify whether SIRE exists and to examine potential mechanisms.

According to the interhemispheric interaction hypothesis proposed by Christman, Garvey, Propper, and Phaneuf (2003), horizontal saccades improve memory retrieval by enhancing interhemispheric interaction in the brain, which is crucial for episodic memory retrieval. Previous studies used two methods to distinguish levels of interhemispheric interaction. One method selected mixed-handed individuals through handedness tests. Since mixed-handed individuals have larger corpus callosum (Luders et al., 2010), their level of interhemispheric

interaction should be higher than that of right- or left-handed individuals, resulting in better memory performance. The other method used visual stimuli to guide horizontal saccades, which could temporarily improve interhemispheric interaction and enhance subsequent memory retrieval. While debatable whether these methods can effectively separate individuals with different levels of interhemispheric interaction, previous studies have shown superior memory in mixed-handed individuals compared to strongly right-handed individuals (Christman et al., 2006; Christman et al., 2004; Propper, Christman, & Phaneuf, 2005). Moreover, memory performance in strongly right-handed individuals could be temporarily improved following horizontal saccades, whereas horizontal saccades failed to improve memory performance for non-strongly right-handed individuals and were sometimes even detrimental (Lyle, Logan, & Roediger, 2008). These results provided some support for the interhemispheric interaction hypothesis.

The interhemispheric interaction hypothesis was based on the hemispheric encoding/retrieval asymmetry (HERA) model, which suggested that encoding and retrieval of episodic memory involve asymmetrical brain areas. Specifically, encoding is associated with increased activity in the left prefrontal lobe, while retrieval is associated with increased activity in the right prefrontal lobe (Tulving, Kapur, Craik, Moscovitch, & Houle, 1994). Cabeza and Nyberg (2000) summarized PET/fMRI findings showing that episodic memory encoding involved the left hemisphere, while retrieval involved bilateral hemispheres or tended to be right-lateralized. Studies on split-brain individuals also showed that cutting connections between hemispheres hindered episodic memory recognition (Cronin Golomb, Gabrieli, & Keane, 1996). Based on this evidence, Christman and colleagues (2003) suggested that interaction between hemispheres provides a basis for accurate episodic memory.

To test the interhemispheric interaction hypothesis, several studies examined the influence of eye movements on electroencephalogram (EEG) coherence. Propper and colleagues (2007) compared EEG coherence between left and right frontal lobes across eye movement and control conditions but observed no increased interhemispheric EEG coherence following horizontal saccade manipulation. In Samara' s (2011) study, using a within-group design to compare changes in EEG coherence before and after saccades, results showed that although recognition of emotional words was better following horizontal saccades relative to no eye movements, they failed to observe increased EEG coherence between hemispheres, and memory enhancement was not correlated with changes in EEG coherence. In a more recent study examining effects of eye movement manipulation on EEG power and coherence (Fleck et al., 2018), researchers similarly failed to observe changes in interhemispheric EEG coherence for any frequency bands examined.

Taken together, although many studies have demonstrated the enhancing effect of saccades on memory retrieval, no direct evidence indicates that this effect is contributed by interhemispheric interaction. Lyle and Edlin (2015) proposed that saccades may improve memory retrieval by promoting top-down atten-

tional control. From this perspective, SIRE can be regarded as the effect of a short attention control "exercise." If the subsequent memory test primarily relies on top-down attentional control, the effect of this eye movement "exercise" would be manifested. Conversely, if the memory test is simple and depends more on bottom-up spontaneous processing, eye movements would not benefit performance (Lyle & Edlin, 2015). This theory explains why eye movement manipulation can also enhance performance on other cognitive tests such as attention (Edlin & Lyle, 2013) and creativity (Shobe, Ross, & Fleck, 2009). The "top-down attentional control hypothesis" was derived from early neuroimaging studies suggesting that saccades are associated with activations of the frontal eye field, intraparietal sulcus, and superior parietal lobe—brain regions long implicated in top-down attentional control (Corbetta & Shulman, 2002). However, no studies have established a direct relationship between manipulation of horizontal saccades and activations of attention-related brain regions that lead to memory performance enhancement.

The two theories differ in several key aspects. First, according to the interhemispheric interaction hypothesis, eye movements specifically improve memory performance, particularly memory retrieval, and this effect is mainly manifested in strongly right-handed individuals who have lower levels of interhemispheric interaction. Only horizontal saccades are effective, whereas vertical saccades do not affect interhemispheric interaction and therefore do not benefit memory retrieval (Christman, Garvey, Propper, & Phaneuf, 2003). Second, from the perspective of top-down attentional control theory, the effect of eye movements is not specific to memory but extends to all cognitive activities related to top-down attentional control (Lyle & Edlin, 2015). The direction of eye movements does not affect this enhancing effect.

Despite accumulating studies, the mechanisms of SIRE remain unclear. The present study aimed to clarify three questions through meta-analysis: (1) whether horizontal saccades can enhance memory performance; (2) whether handedness moderates this effect; and (3) whether vertical saccades can enhance memory performance. These analyses would help elucidate the underlying mechanisms of SIRE.

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2. Methods

2.1 Literature Search We searched Web of Science, PubMed, and Springer using the keyword combinations "eye movements + memory" or "saccades + memory" for articles published from January 2001 (when Christman & Propper (2001) conducted the first study examining the relationship between memory performance and interhemispheric interaction) to April 1, 2018. The paper selection process is illustrated in Fig.1. Included studies needed to meet the following criteria: (1) published peer-reviewed studies; (2) manipulation of eye movements with comparison of memory performance differences between eye

movement and control conditions; (3) use of standardized procedures to manipulate saccades (e.g., participants watched a dot alternately appearing on the left and right side of the screen every 0.5 seconds); and (4) reporting of sufficient data to calculate effect sizes. For studies meeting other criteria but not reporting enough data for effect size calculation, authors were contacted for potential provision of additional data.

Studies investigating the effect of eye movement desensitization and reprocessing (EMDR; Shapiro, 1989) on the emotionality and vividness of traumatic memory were excluded. Four additional studies met inclusion criteria for eye movement manipulation but were excluded because they focused mainly on the promotion effect of eye movements on attention (Edlin & Lyle, 2013), creativity (Shobe et al., 2009), or only on EEG signal changes after saccades without relevant behavioral data (Fleck et al., 2018; Propper et al., 2007).

2.2 Data Extraction and Study Characteristics Our final analysis included 22 articles with 28 pairs of data, of which 16 focused on episodic memory, 6 on false memory, 5 on autobiographical memory, and 1 on face memory (see Table 1). The following information was extracted for each study: (1) first author and year of publication; (2) type of experimental design and number of participants in each experimental group; (3) materials used in the memory test (sentences, figures, or words); (4) direction of eye movement manipulation (horizontal or vertical); (5) whether handedness was measured; and (6) type of memory and main indicators of memory performance.

We classified memory tasks into four categories: (A) episodic memory tasks including recognition or free recall of words or pictures; (B) false memory tasks inducing false recall or false recognition; (C) autobiographical memory tasks requiring recall of self-related daily life events; and (D) tasks not belonging to any of the above categories classified as "Not clear to be classified." The current meta-analysis distinguished these four memory types when calculating effect sizes.

We selected indexes for each memory type as follows: For episodic memory tasks, the main indexes were accuracy, discrimination index d' , and number of correct recollections, with d' as the primary indicator. For studies not reporting d' , accuracy or number of correct recollections were used as alternatives. For false memory, the main indicator was discrimination index d' for lure words; if d' was not reported, the number of false alarms for critical lure words was used. For autobiographical memory, indicators were more subjective, including number of events recalled and vividness of recalled events. The unweighted average effect size of the main indexes of autobiographical memory was used as the indicator of eye movement effects on autobiographical memory.

2.3 Meta-Analyses Comprehensive Meta-Analysis (CMA, version 2.0) (http://www.meta-analysis.com/index.php) was used for data analysis. We used means, standard deviations, and sample sizes to calculate effect sizes

(Cohen' s d). For studies not reporting means or standard deviations, effect sizes were calculated using t or F statistics and sample sizes. Heterogeneity was assessed using Q-statistics, while publication bias was measured by combining funnel plots and Egger' s intercept. Duval and Tweedie' s trim and fill procedure (Duval & Tweedie, 2000) was also adopted to obtain adjusted effect sizes. Due to significant heterogeneity among included studies, random-effects models were used (Hedges & Vevea, 1998).

We first evaluated the pooled effect size of horizontal saccades on memory retrieval. We then conducted moderator analyses examining: (1) memory type, comparing effects of eye movements on different memory performance types (including only episodic memory, false memory, and autobiographical memory); (2) handedness, as the interhemispheric interaction hypothesis predicts that strongly right-handed individuals are more likely to benefit from horizontal saccades; studies not reporting handedness effects or distinguishing strongly right-handed from non-strongly right-handed individuals were classified as handedness unknown; and (3) whether vertical saccades have beneficial effects on memory performance, to understand whether the SIRE effect is selectively caused by horizontal saccades. Finally, publication bias was analyzed. Data for the meta-analysis are available upon request.

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3. Results

3.1.1 Overall Effect and Subgroup Analysis on Different Types of Memory There was a significant overall effect of horizontal saccades on memory retrieval (Cohen' s d = 0.45; 95% CI = [0.29-0.62], Z = 5.40, $p < 0.001$). Study heterogeneity was significant (Q = 113.96, $p < 0.001$, see Table 2), indicating nonnegligible differences among studies.

Analysis of different memory types showed that horizontal saccades had a medium-to-large effect on autobiographical memory (d = 0.68; 95% CI = [0.31-1.06], Z = 3.57, $p < 0.001$), a medium effect on reducing false memory (d = 0.57; 95% CI = [0.23-0.72], Z = 3.28, $p < 0.01$), and a small-to-medium effect on episodic memory (d = 0.37; 95% CI = [0.14-0.59], Z = 3.22, $p < 0.001$). There was no significant difference among the three memory categories (Q = 2.37, p = 0.31).

3.1.2 The Moderator Effect of Handedness Fourteen contrasts in strongly right-handed individuals showed a near-medium effect size (d = 0.45; 95% CI = [0.22-0.68], Z = 3.81, $p < 0.001$) with significant heterogeneity (Q = 36.35, $p < 0.01$). Eleven contrasts in non-strongly right-handed individuals showed a nonsignificant effect (d = -0.06; 95% CI = [-0.20-0.09], Z = -0.77, p = 0.44) with nonsignificant heterogeneity (Q = 10.12, p = 0.43). Fourteen contrasts in unknown handedness individuals showed a medium-to-large effect size (d = 0.60; 95% CI = [0.36-0.85], Z = 4.76, $p < 0.001$; see Table 3)

with significant heterogeneity (Q = 52.41, p < 0.001). The moderator effect of handedness was significant (Q = 34.71, p < 0.001). Further pairwise comparisons revealed that memory performance of strongly right-handed individuals benefited more from horizontal saccades compared to non-strongly right-handed individuals (Q = 23.82, p < 0.001).

Studies on false memory and episodic memory included different test types. We conducted another subgroup analysis on test type: nine contrasts with free recall tests showed a nonsignificant effect (d = 0.26; 95% CI = [-0.01-0.54], Z = 1.86, p = 0.06); nine contrasts with recognition tests showed a medium effect (d = 0.61; 95% CI = [0.30-0.92], Z = 3.79, p < 0.001); and four contrasts with other tests showed a small effect (d = 0.17; 95% CI = [0.02-0.31], Z = 2.29, p = 0.02).

3.2 Effects of Vertical Saccades on Memory Retrieval The overall effect size was calculated based on 12 pairs of data comparing vertical saccades with no-eye-movement conditions. The overall effect of vertical saccades was not significant (d = 0.10; 95% CI = [-0.03-0.23], Z = 1.47, p = 0.14), with insignificant heterogeneity (Q = 7.33, p = 0.77). This suggests that memory performance benefits only from horizontal saccades.

According to Lyle, Hanaver-Torrez, Hacklander, and Edlin (2012), what matters for SIRE is not the direction of handedness (left or right) but whether individuals are consistent-handers. Consistent handers (including strongly right-handed and strongly left-handed) may show larger SIRE than inconsistent handers (neither strongly right-handed nor strongly left-handed). Several studies divided subjects into consistent-handed and inconsistent-handed groups based on the absolute value of handedness tests (e.g., Lyle, 2018; Lyle & Edlin, 2015; Lyle et al., 2012; Phaf, 2017). We therefore conducted another subgroup analysis on handedness consistency. Five contrasts with consistent-handed individuals showed a small effect (d = 0.18; 95% CI = [0.01-0.34], Z = 2.13, p = 0.03), while five contrasts with inconsistent-handed individuals showed the opposite but nonsignificant effect (d = -0.17; 95% CI = [-0.38-0.04], Z = -1.56, p = 0.12).

3.3 Publication Bias Analyses For the overall effect, funnel plots showed asymmetrical graphics, and Egger' s linear regression analysis further suggested notable publication bias (intercept = 2.04, 95% CI = [0.04-4.04], p = 0.02). After adjusting for missing studies (N = 8, see Fig.2) using Duval and Tweedie' s trim and fill procedure (Duval & Tweedie, 2000), the overall effect size decreased from 0.38 to 0.20 but remained significant (95% CI = [0.03-0.36]). For the strongly right-handed group, adding 5 missing studies reduced the effect size from 0.45 to 0.26, which remained significant (95% CI = [0.03-0.50]). Similarly, after adjustment (N = 5), the effect for unknown handedness individuals decreased from 0.60 to 0.31 (95% CI = [0.03-0.6]) but remained significant. Detailed results are shown in Table 4 . Generally speaking, despite publication bias and reduced effect sizes after adjustment, our results demonstrated that strongly right-handed individuals could benefit from horizontal eye movement

manipulation, while non-strongly right-handed individuals were insensitive to this procedure. The overall effect was relatively small (d = 0.20), perhaps due to inclusion of non-strongly right-handed participants, but the effect remained robust.

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4. Discussion

The current study synthetically and quantitatively analyzed previous research on the effect of saccades on memory performance. The main findings were: (1) horizontal saccades improved memory performance irrespective of memory type; (2) strongly right-handed individuals benefited from horizontal saccade implementation while non-strongly right-handed individuals did not; and (3) vertical saccades showed negligible memory enhancement, indicating that episodic memory retrieval was selectively enhanced by horizontal saccades. Results were influenced by publication bias to some extent; however, conclusions did not change after eliminating publication bias.

The current study yielded a medium effect (d = 0.45) of horizontal saccades on memory retrieval, though with considerable heterogeneity ($Q = 113.96$, $p < 0.001$). Moderator analysis revealed that handedness was an important source of difference, with SIRE effect sizes of d = 0.45 for the strongly right-handed group but d = -0.06 for the non-strongly right-handed group, the latter indicating a null effect. Together with previous evidence, we propose three potential reasons for inconsistencies in this research field: (1) some studies failed to consider handedness, which our results suggest is a moderating factor of SIRE; (2) there was large variability in paradigms and memory types across empirical studies, and although the moderating effect of memory type was not significant, studies within each memory type were heterogeneous; and (3) differences in time duration between saccade manipulation completion and memory task completion may be another reason for inconsistent results, as the enhancing effect of eye movements may be temporary and benefits may not be maintained if the interval between saccades and recall is too long (Samara et al., 2011).

Despite these variabilities, the enhancing effect of saccades persists after accounting for publication bias, suggesting it might serve as a strategy to temporarily improve memory in daily life.

As mentioned in the introduction, two main theories address the underlying mechanisms of SIRE. The interhemispheric interaction hypothesis proposes that horizontal saccades improve memory retrieval by facilitating interhemispheric brain interaction (Christman, Garvey, Propper, & Phaneuf, 2003), whereas the top-down attentional control hypothesis suggests that eye movements promote memory by improving attentional control (Lyle & Edlin, 2015). The present meta-analysis partly elucidates the controversy between these hypotheses. The interhemispheric interaction hypothesis posits that episodic memory retrieval relies on interhemispheric interaction levels and that any facilitation of inter-

hemispheric interaction would improve memory retrieval. According to this theory, strongly right-handed individuals with lower interhemispheric interaction levels should benefit more from saccades—a prediction supported by our results. Another important discrepancy between theories concerns whether saccade direction affects memory retrieval. The interhemispheric interaction hypothesis suggests that only horizontal saccades facilitate interhemispheric interaction beneficial to memory retrieval, whereas the top-down attentional control hypothesis proposes that activation of the frontoparietal network caused by saccades is the primary reason for memory improvement, predicting that saccades would enhance memory retrieval regardless of direction. Our results demonstrated that only horizontal saccades benefit memory retrieval, again supporting the interhemispheric interaction hypothesis. Although three EEG studies (Fleck et al., 2018; Propper, Pierce, Geisler, Christman, & Bellorado, 2007; Samara, Elzinga, Slagter, & Nieuwenhuis, 2011) did not reveal increased interhemispheric coherence after horizontal saccade manipulation, these studies had limitations including small sample sizes, limited electrodes for measuring coherence, and lack of behavioral measures. Further neuroimaging studies with stricter experimental designs are warranted to examine the neural mechanisms of SIRE.

Another factor worth mentioning is that interhemispheric interaction level is not an all-or-none phenomenon but a continuous one. If the interhemispheric interaction hypothesis is true, then visual angle and saccade duration should also affect interhemispheric interaction levels, but previous studies have not considered these variables. Future studies should clarify these issues.

Several limitations of the current study should be noted. First, studies included in this meta-analysis had narrow age ranges since most were conducted with university students; whether the effect appears in other age groups requires further research. Second, criteria for strongly right-handed versus non-strongly right-handed classification varied across studies, and different indexes were used for memory performance (such as for autobiographical memory), which may have contributed to study heterogeneity. Third, due to the small number of studies, moderator analyses on factors such as emotional valence of words or events and participant age were not possible.

In conclusion, the present study demonstrated that horizontal saccades can improve overall memory performance, with strongly right-handed individuals being more sensitive to this effect. Vertical saccades cannot improve memory performance. These results provide support for the interhemispheric interaction hypothesis.

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Fig.1 Flow chart of selection and inclusion process following the PRISMA statement

Fig.2 Funnel plots for the trim and fill procedure. (a) Results for all comparisons including strongly right-handed, non-strongly right-handed, and handedness unknown groups; (b) Results for strongly right-handed group only. White dots represent all studies included in the meta-analysis; black dots indicate studies adjusted for publication bias.

Table 1 Summary of studies included in the meta-analysis

Table 2 Saccade-induced retrieval enhancement for all studies and different types of memory

Table 3 Saccade-induced retrieval enhancement for different handedness groups

Table 4 Publication bias and adjusted effect sizes

Note: Figure translations are in progress. See original paper for figures.