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Bilateral saccadic eye movements and tactile stimulation, but not auditory stimulation, enhance memory retrieval

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ABSTRACT

Recent research has shown superior memory retrieval when participants make a series of horizontal saccadic eye movements between the memory encoding phase and the retrieval phase compared to participants who do not move their eyes or move their eyes vertically. It has been hypothesized that the rapidly alternating activation of the two hemispheres that is associated with the series of left–right eye movements is critical in causing the enhanced retrieval. This hypothesis predicts a beneficial effect on retrieval of alternating left–right stimulation not only of the visuomotor system, but also of the somatosensory system, both of which have a strict contralateral organization. In contrast, this hypothesis does not predict an effect, or a weaker effect, on retrieval of alternating left–right stimulation of the auditory system, which has a much less lateralized organization. Consistent with these predictions, we replicated the horizontal saccade-induced retrieval enhancement (Experiment 1) and showed that a similar retrieval enhancement occurs after alternating left–right tactile stimulation (Experiment 2). Furthermore, retrieval was not enhanced after alternating left–right auditory stimulation compared to simultaneous bilateral auditory stimulation (Experiment 3). We discuss the possibility that alternating bilateral activation of the left and right hemispheres exerts its effects on memory by increasing the functional connectivity between the two hemispheres. We also discuss the findings in the context of clinical practice, in which bilateral eye movements (EMDR) and auditory stimulation are used in the treatment of post-traumatic stress disorder.

1. Introduction

Previous research has revealed intrigu′ing relationships between saccadic eye movements and memory. First, rapid eye movements (REMs) during sleep, of which the majority are in the horizontal direction (Hansotia et al., 1990), are critical for memory consolidation (Poe, Walsh, & Bjorness, 2010). Second, during demanding memory retrieval, people tend to make more saccades than during simple retrieval (Ehrlichman, Micic, Sousa, & Zhu, 2007). Third, patients with post-traumatic stress disorder, which is characterized by prolonged and inappropriate recurrence of traumatic memories, can be treated with a therapy called eye-movement desensitization reprocessing (EMDR). This treatment involves having the patient think about his traumatic memories while simultaneously moving his eyes back and forth between left and right. In many patients, repetition of the procedure gradually changes the traumatic (sensory) memory into a more (verbal) declarative memory, while at the same time reducing emotional arousal and avoidance. Meta-analyses indicate that EMDR is equally effective as cognitive-behavioral therapy and superior to other therapies (Bisson et al., 2007; Bradley, Greene, Russ, Dutra, & Westen, 2005; Seidler & Wagner, 2006). Other studies have reported that horizontal eye movements performed during retrieval also decrease the vividness and distress of emotional autobiographical memories in healthy adults (e.g., van den Hout, Muris, Salemink, & Kindt, 2001). These three real-life phenomena suggest that horizontal saccades are important for efficient consolidation and retrieval of memories, and some researchers have speculated that the phenomena may be intimately related (Stickgold, 2002).

Here, we focus on a fourth phenomenon, dubbed saccade-induced retrieval enhancement (Lyle & Martin, 2010), that was discovered in a series of laboratory studies and that ultimately may cast light on the mechanisms underlying the real-life phenomena described above. In these studies (reviewed in Christman & Propper, 2010; Propper & Christman, 2008), cognitive psychologists found that a brief period of bilateral saccadic eye movements,

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prior to the retrieval phase of a memory experiment, improves memory retrieval in a wide array of tasks, including recall and recognition of words (Christman, Garvey, Propper, & Phaneuf, 2003; Lyle, Logan, & Roediger, 2008; Parker, Relph, & Dagnall, 2008; Samara, Elzinga, Slagter, & Nieuwenhuis, 2011), recall of early childhood memories (Christman, Propper, & Brown, 2006), recognition of details in a visual event narrative (Lyle & Jacobs, 2010; Parker, Buckley, & Dagnall, 2009), and recall and recognition of landmark shape and location information (Bruyné, Mahoney, Augustyn, & Taylor, 2009; Parker et al., 2008). In these studies, the critical eye-movement procedure was similar to that used in EMDR: participants watched a dot that alternately appeared on the left and right side of the screen, changing position twice per second. This procedure was compared with a control condition, in most studies consisting of vertical saccadic eye movements or a centrally presented dot changing color twice per second.

The goal of the current study was to examine if the beneficial effect on memory retrieval is specific for eye movements or generalizes to other types of bilateral stimulation. This question is partly motivated by clinical practice: Over the past decade, EMDR therapists have started to replace eye movements with other forms of alternating left–right sensory stimulation, in particular auditory or tactile stimuli (Shapiro, 1994, 2002). For example, a recent survey suggested that in around 50% of all EMDR sessions, eye movements have been replaced by binaural stimulation (van den Hout et al., 2011). Although there have been no large controlled studies of clinical efficacy, recent studies have found some evidence that these other forms of alternating left–right stimulation can reduce subjective distress in patients with post-traumatic stress disorder (Servan-Schreiber, Schooler, Dew, Carter, & Bartone, 2006) and reduce the vividness of negative memories in healthy volunteers (although this effect was inferior to that of eye movements; van den Hout et al., 2011).

The execution of lateral eye movements is associated with strong activation of parts of the hemisphere contralateral to the direction of the eye movement (Dean, Crowley, & Platt, 2004; Kastner et al., 2007)[1], which reflects the contralateral organization of the visuomotor system. Ipsilateral activation occurs a bit later (due to the time needed for transcallosal transfer) but is much weaker in magnitude and far more localized. Therefore, a sequence of alternating left–right eye movements results in a pronounced (though not all-or-none) pattern of rapidly alternating activation of the two hemispheres. Christman and colleagues hypothesized that this alternating pattern of hemispheric activation causes the beneficial effect of alternating left–right eye movements on normal memory retrieval, possibly by stimulating the communication between the hemispheres (Christman et al., 2003; Propper & Christman, 2008). According to this hypothesis, alternating left–right *tactile* stimulation should also enhance memory retrieval, because of the strict contralateral organization of the somatosensory system (Kandel, Schwartz, & Jessel, 2000; Nieuwenhuys, Voogd, & van Huijzen, 2007). Interestingly, Christman's alternating hemispheric activation hypothesis predicts somewhat different results for alternating left–right *auditory* stimulation: Although studies consistently show a contralateral dominance of brain activations to monaural stimuli (King & Carlisle, 1995; Langers, van Dijk, & Backes, 2005; Pantev, Lütkenhöner, Hoke, & Lehnertz, 1986), the contralateral dominance is not nearly as pronounced as in the visuomotor and somatosensory systems. This is because the ascending pathways of the mammalian auditory system project to both the ipsilateral and the contralateral auditory cortices, and hence monaural sound stimuli directly activate both hemispheres (Brodal, 1981). Thus, intermittent left–right auditory stimulation does not activate the two hemispheres in a strictly alternating fashion, and therefore Christman's hypothesis predicts a smaller or absent effect on memory retrieval.

We conducted three experiments to test these predictions of the alternating hemispheric activation hypothesis. In Experiment 1, we replicated previous studies that examined the effect of bilateral eye movements on memory retrieval. In Experiment 2, we examined the effect of alternating left–right tactile stimulation compared to a control condition with intermittent simultaneous bilateral tactile stimulation. Finally, in Experiment 3, we compared the effects on memory retrieval of intermittent alternating versus simultaneous stimulation of the two ears. In all three experiments, half of the words to be encoded were emotionally aversive, the other half emotionally neutral. This allowed us to explore whether potential beneficial memory effects, usually obtained with neutral material, generalize to the emotional domain. Mixed-handed individuals were excluded from participation because the beneficial effect of eye movements sometimes does not occur in these individuals (Bruyné et al., 2009; Lyle et al., 2008).

2. Method Experiment 1: Eye movements

2.1. Subjects

Fifty students at Leiden University (aged 18–26) participated for course credit or €4.50. All participants were native speakers of Dutch. Handedness was assessed using a modified version of the Edinburgh Handedness Inventory (Oldfield, 1971): Participants indicated the hand they prefer to use for each of 10 activities (e.g., writing, throwing) by choosing "always left" (−10), "usually left" (−5), "no preference (0), "usually right" (+5) or "always right" (+10). This results in scores ranging from −100 for perfectly left-handed to +100 for perfectly right-handed. Only participants scoring +80 and above were classified as strongly right-handed and included. Of the 50 included subjects, 25 were randomly assigned to the experimental condition (*M* handedness score = 92.6; 7 men) and 25 to the control condition (*M* handedness score = 90.6; 7 men).

2.2. Stimuli

In the experimental condition, a black dot with a 4° diameter appeared sequentially on the left and right sides of the computer screen (at 27° apart) for 30 s. The dot changed position every 500 ms, leading to two saccadic eye movements per second. In the control condition, a colored circle appeared in the center of the screen and changed color twice per second, alternating between green and red (cf. Christman, Propper, & Dion, 2004; Christman et al., 2006).

Stimuli for the recall procedure consisted of 144 common Dutch nouns and infinitives. The valence of the words was validated in a perceptual clarification task (Ter Laak, 1992, unpublished Master's thesis), in which they were recognized most consistently as neutral and negative words. The words were divided in two sets of 72 words, matched in length (*M* = 7.3, SD = 1.8) and frequency (*M* = 781.2, SD = 1053.6), that were counterbalanced across the two conditions. Each set consisted of 36 neutral words (e.g., flute, archive) and 36 negative emotional words (e.g., crisis, anger). Sample stimuli are listed in Table 1.

2.3. Procedure

Subjects completed the Edinburgh Handedness Inventory and then received task instructions. Subjects were told they were participating in a memory experiment, and asked to concentrate on the words that would be presented on the computer screen. Words

[1] Many previous studies have cited Bakan and Svorad (1969), but this reference is inappropriate: that article reports the effects of lateral eye movements on a global, not lateralized, measure of EEG activation.

Table 1
Example memory stimuli.

List 1		List 2	
Dutch	Translation	Dutch	Translation
Neutral words			
Appel	Apple	Legpuzzel	Jigsaw
Grammatica	Grammar	Aankleden	To dress
Document	Document	Handtas	Handbag
Driehoek	Triangle	Bestek	Cutlery
Elleboog	Elbow	Centimeter	Centimeter
Portret	Portrait	Dossier	File
Potlood	Pencil	Etiket	Label
Meubel	Furniture	Badkamer	Bathroom
Supermarkt	Supermarket	Deurbel	Doorbell
Mechanisch	Mechanical	Ademhaling	Breathing
Emotional words			
Sadist	Sadist	Afgrijzen	Horror
Tranen	Tears	Tumor	Tumor
Fobie	Phobia	Bloed	Blood
Trauma	Trauma	Mislukking	Failure
Verraad	Betrayal	Verdriet	Grief
Inbraak	Burglary	Woede	Rage
Kanker	Cancer	Gevaar	Danger
Armoede	Poverty	Sterven	To die
Bom	Bomb	Pistool	Pistol
Moord	Murder	Haat	Hate

Note: Sample of the Dutch words included in the study lists with their English translation.

were presented randomly, one at a time, at a rate of 2 s/word. The word list was preceded by 3 additional (neutral) words that served as buffer against the primacy effect, and followed by 3 additional (neutral) words to guard against recency effects.

After the encoding phase, participants were asked to count backwards from 300 in steps of 3 for 1 min. Then, subjects engaged in either the experimental procedure or the control procedure. In the experimental condition, subjects were instructed to focus on the dot appearing on the screen and follow it by moving their eyes and not their head. In the control condition, participants were told to keep their eyes at the colored dot. The experimenter closely monitored participants' compliance with the instructions. Immediately after this procedure, subjects were asked to write down as many words as they could remember from the study list.

3. Method Experiment 2: Tactile stimulation

Details of the method were the same as in Experiment 1, except as noted below.

3.1. Subjects

Fifty-three students (aged 18–25) participated in the study. Twenty-six were randomly assigned to the experimental condition (*M* handedness score = 91.9; 5 men) and 27 to the control condition (*M* handedness score = 92.7; 5 men).

3.2. Stimuli and procedure

Subjects were instructed to fixate a central cross on the screen (which was verified by the experimenter) and rest their hands comfortably on their thighs, palms up. The experimenter wore headphones, through which metronome clicks were presented twice per second. In the experimental condition, the experimenter tapped the subject's hands, alternating between right and left at a frequency of 2 taps per second. In the control condition, the experimenter tapped the subject's hands at the same frequency, but both sides simultaneously.

4. Method Experiment 3: Auditory stimulation

Details of the method were the same as in Experiment 1, except as noted below.

4.1. Subjects

Seventy-five students (aged 18–25) participated in the study. Thirty-seven were randomly assigned to the experimental condition (*M* handedness score = 93.8; 6 men) and 38 to the control condition (*M* handedness score = 93.1; 5 men).

4.2. Stimuli and procedure

Subjects were instructed to fixate a central cross on the screen (which was verified by the experimenter) and listen to metronome clicks presented through headphones twice per second. In the experimental condition, the clicks were presented in an alternating left–right pattern. In the control condition, the clicks were presented to both ears simultaneously.

5. Results Experiment 1: Eye movements

Table 2 presents the number of recalled items in the experimental and control conditions. An analysis of variance indicated that subjects recalled more emotional than neutral items, $F(1,48) = 23.0$, $p < .001$, $\eta_p^2 = .32$: the typical emotional superiority effect on memory. More importantly, subjects in the experimental condition recalled more items than subjects in the control condition, $F(1,48) = 4.5$, $p = .039$, $\eta_p^2 = .09$. The interaction between the two factors was not significant, $F(1,48) = 0.2$, $p = .66$. Finally, a separate *t*-test indicated that the two groups did not differ in the number of falsely recalled items, $t(48) = 0.4$, $p = 0.72$.

6. Results Experiment 2: Tactile stimulation

The results in Experiment 2 were similar to those in Experiment 1. As shown in Table 2, subjects recalled more emotional than neutral items, $F(1,51) = 31.2$, $p < .001$, $\eta_p^2 = .38$. More importantly, subjects in the experimental condition recalled more items than subjects in the control condition, $F(1,51) = 4.2$, $p = .045$, $\eta_p^2 = .08$. The interaction between the two factors was not significant, $F(1,51) = 0.3$, $p = .58$. The two groups did not differ in the number of falsely recalled items, $t(51) = 0.9$, $p = 0.37$.

7. Results Experiment 3: Auditory stimulation

The results in Experiment 3 showed a different pattern than those in Experiments 1 and 2 (see Table 2). As in the previous experiments, subjects recalled more emotional than neutral items, $F(1,73) = 8.4$, $p = .005$, $\eta_p^2 = .10$. However, in this experiment there was no difference between the two conditions in the number of correctly recalled items, $F(1,73) = 0.02$, $p = .88$. The interaction between the two factors was nonsignificant, $F(1,77) = 0.02$, $p = .89$, and the two groups did not differ in the number of falsely recalled items, $t(73) = 0.6$, $p = .57$.

8. Discussion

The results can be summarized as follows. Experiment 1 replicated previous studies that showed a beneficial effect of horizontal eye movements on memory retrieval (Propper & Christman, 2008), and in particular on word recall (Lyle et al., 2008; Samara et al., 2011). Experiment 2 showed a similar beneficial effect on memory retrieval of alternating left–right tactile stimulation, indicating that

Table 2
Number of recalled items in experiments 1, 2 and 3 as a function of task condition and valence.

	E1: Eye movements		E2: Tactile		E3: Auditory	
	Experimental	Control	Experimental	Control	Experimental	Control
Neutral	4.6 (0.5)	3.2 (0.5)	4.8 (0.4)	3.4 (0.4)	4.9 (0.5)	4.9 (0.5)
Emotional	6.4 (0.5)	5.3 (0.5)	6.9 (0.6)	6.0 (0.6)	6.1 (0.4)	6.0 (0.4)
False	3.4 (0.6)	3.7 (0.7)	2.6 (0.4)	3.2 (0.6)	3.7 (0.5)	3.3 (0.4)

Note. Absolute performance levels cannot be compared between the three experiments, because each of the experiments was run by a different experimenter, with slight differences in recruitment strategy. Between parentheses standard errors of the mean.

the effect generalizes to at least one other modality. However, in Experiment 3, we found that the effect does not generalize to the auditory modality: alternating left–right sound stimuli did not enhance memory retrieval compared to the control condition with simultaneous bilateral sound stimuli. This result discounts the possibility that the memory benefits observed in the first two experiments are mediated by the repeated redirection of attention (cf. Stickgold, 2002)

The pattern of results is consistent with the alternating hemispheric activation hypothesis (Propper & Christman, 2008). This hypothesis predicts beneficial effects of alternating left–right eye movements and tactile stimulation, because of the contralateral organization of the visuomotor and somatosensory systems. Because each lateral saccadic eye movement and each lateral tactile stimulus activate the contralateral hemisphere (much more than the ipsilateral hemisphere), alternating left–right sequences of eye movements and tactile stimuli essentially result in a rapidly alternating pattern of activations in the two hemispheres. An interesting question for future research is whether *covert* shifting of attention toward visual stimuli occurring alternately on the left and the right produces similar results; this condition is more comparable with the tactile and auditory stimulation procedures used here. Christman's hypothesis also predicts that beneficial effects of alternating left–right auditory stimulation should be much smaller or absent. Although the ascending auditory pathways coming from the two ears cross to the contralateral hemispheres at various levels in the brainstem, this crossing is not complete and many fibers also project ipsilaterally. Therefore, monaural stimuli lead to both ipsilateral and contralateral hemispheric activation. The results of Experiment 3 suggest that simultaneous activation of the two hemispheres does not enhance memory performance.

If the alternating hemispheric activation hypothesis is correct, *how* may rapidly alternating activation of the left and right hemisphere induced by eye movements or tactile stimulation improve memory? Christman et al. (2003) hypothesized that alternating hemispheric activation increases interhemispheric interaction. However, the evidence for this hypothesis is limited and mixed. Positive evidence has been provided by several studies which reported saccade-induced improvements in memory retrieval in individuals who are strongly right- or left-handed, but not in individuals who are mixed-handed (Bruyné et al., 2009; Lyle, Hanaver-Torrez, Hackländer, & Edlin, 2012; Lyle et al., 2008). Mixed-handers have an enhanced corpus callosum size (Luders et al. 2010; Witelson & Goldsmith, 1991) and therefore, presumably, enhanced flow of information between the hemispheres. Eye movements allow strongly right- and left-handers to temporarily compensate for their reduced functional hemispheric connectivity. Other supporting evidence is that REM sleep is characterized by rapid horizontal saccades and increased interhemispheric EEG coherence (e.g., Dumermuth & Lehman, 1981).

Other studies have not been able to find evidence for the interhemispheric communication hypothesis. Lyle and colleagues found no effect of horizontal saccades on attentional (Lyle & Martin, 2010) and memory measures (Lyle & Orsborn, 2011) of interhemispheric processing, despite a general benefit in retrieval (Lyle & Orsborn, 2011), suggesting that this benefit was mediated by a different mechanism. Lyle and Martin found some behavioral indications that eye movements enhance *intra*hemispheric processing. Samara et al. (2011; see also Propper, Pierce, Geisler, Christman, & Bellorado, 2007) recorded baseline EEG activity just before and after the horizontal eye-movement procedure, which separated the encoding phase and retrieval phase of a memory experiment. They calculated phase and amplitude coherence between bilaterally homologous brain areas for six frequency bands and electrode pairs across the entire scalp. Although the eye-movement procedure enhanced memory performance, EEG analyses indicated no evidence that the eye movements altered participants' interhemispheric coherence or that improvements in recall were correlated with such changes in coherence.

A more principled issue left largely unaddressed by the interhemispheric interaction hypothesis is why the alternating activation of the hemispheres should enhance interhemispheric interaction more than simultaneous activation. Propper and Christman (2008) discuss some indirect behavioral evidence suggesting that bilateral eye movements equalize the activation of the two hemispheres, and they hypothesize that this may foster interhemispheric communication. However, it is unclear whether and how this mediating factor can account for the observed difference in performance between simultaneous and alternating tactile stimulation. Another outstanding question is whether the beneficial effects of alternating left–right stimulation of the two hemispheres requires stimulation of large parts of the hemispheres or whether stimulation of small (e.g., saccade-related) portions is sufficient as long as these portions are stimulated in both hemispheres.

As an alternative interpretation of how saccade execution might affect memory, Lyle and Martin (2010) built on the well-established finding that making goal-directed eye movements activates a well-defined network of brain regions (Corbetta & Shulman, 2002). One of these is the intraparietal sulcus, an area that is thought to play a role in top-down attention to episodic memory targets (Simons, Peers, Mazuz, Berryhill, & Olson, 2010) or confidence in episodic memory retrieval (Cabeza et al., 2011). Lyle and Martin proposed that horizontal eye movements might enhance retrieval by "pre-activating" the intraparietal sulcus, thereby increasing the area's subsequent contribution to memory retrieval. This hypothesis can also explain why alternating left–right auditory stimulation, which presumably results in bottom-up attentional shifts, does not enhance retrieval: the intraparietal sulcus is involved in top-down controlled, not bottom-up triggered attention shifts (Corbetta & Shulman, 2002). We are not aware of imaging studies that have directly compared the effects of simultaneous and alternating bilateral tactile stimulation. Because in Experiment 2 alternating unilateral tactile stimulation enhanced retrieval relative to simultaneous bilateral tactile stimulation, Lyle and Martin's account predicts that the former stimulation type should activate the intraparietal sulcus more than the latter stimulation type. This prediction, and the hypothesis in general, await further testing.

Finally, do our results have any implications for EMDR therapy? Perhaps. Despite the increasing popularity of auditory stimulation as an alternative to eye movements (cf. van den Hout et al., 2011), there have been no controlled studies of the efficacy of this technique. Servan-Schreiber et al. (2006) found that alternating left–right auditory stimulation reduced subjective distress in a small group of patients with post-traumatic stress disorder, but the auditory stimulation was combined with simultaneous tactile stimulation, so the unique effect of auditory stimulation was unclear. Van den Hout et al. (2011) found that auditory left–right stimulation reduced the vividness of negative memories, but the subjects were healthy volunteers and the beneficial effect was smaller than that of eye movements. If the mechanisms underlying the beneficial effects of horizontal eye movements on traumatic memories and normal memory retrieval are the same, then our results suggest that auditory stimulation in an EMDR context should have no or weaker therapeutic effect. But the possibility remains that these phenomena are caused by different mechanisms. It should be noted that the critical procedures in Experiments 1 and 2 did not interact with the valence of the encoded items (neutral vs. emotional), as one might expect in case of similar underlying mechanisms. Furthermore, recent studies suggest that eye movements may be therapeutic because they tax working memory, thus rendering the traumatic images less vivid and emotional (Gunter & Bodner, 2008; van den Hout et al., 2011). Yet, it is unclear how this working-memory account can explain the beneficial effect of horizontal eye movements on normal memory retrieval.

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