Interhemispheric Interaction and Saccadic Horizontal Eye Movements

Implications for Episodic Memory, EMDR, and PTSD

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The growing body of literature on the effects of bilateral saccadic eye movements, patterned after those employed in eye movement desensitization and reprocessing (EMDR), on memory is reviewed. Research indicates that engaging in bilateral saccadic eye movements prior to lab-based memory testing results in significant improvement in episodic memory across a wide range of memory tests. Other effects of these types of eye movements on hemispheric activation and emotional state are also discussed. The findings are interpreted within a framework suggesting that bilateral saccadic eye movements, such as those employed in EMDR, increase interaction between the left and right cerebral hemispheres. This framework is also used to explain the effects of such eye movements on memory during EMDR treatment of post-traumatic stress disorder.

Keywords: eye movements; episodic memory; eye movement desensitization therapy; handedness; interhemispheric interaction

An important advance in our understanding of the neural bases of human memory was provided by Tulving and colleagues, who proposed the Hemispheric Encoding/Retrieval Asymmetry (HERA) model of episodic memory (Tulving, Kapur, Craik, Moscovitch, & Houle, 1994). The HERA model argues that the left versus right cerebral hemispheres are specialized for the encoding and retrieval, respectively, of episodic memories (in contrast, both the encoding and retrieval of semantic memories are handled by the left hemisphere only). Subsequent brain imaging studies have provided further support for the HERA model (e.g., Babiloni et al., 2006; Cabeza & Nyberg, 2000; Habib, Nyberg, & Tulving, 2003).

Although much of the work following up on the HERA model has focused on the questions of which specific left hemisphere regions are involved in encoding and which right hemisphere regions are involved in retrieval (e.g., Buckner, 1996; Prince, Tsukiura, & Cabeza, 2007), we have focused on the implications of the HERA model for interhemispheric interaction. Specifically, the fact that episodic encoding and retrieval processes take place in different hemispheres implies an important role of the corpus callosum, the primary tract of axons connecting the left and right hemispheres, in episodic memory. Over the past several years, we have published a series of articles demonstrating an interhemispheric basis for the retrieval of episodic memories (Christman, Garvey, Propper, & Phaneuf, 2003; Christman & Propper, 2001; Christman, Propper, & Brown, 2006; Christman, Propper, & Dion, 2004; Propper & Christman, 2004; Propper, Christman, & Phaneuf, 2005).

One factor that we have found to influence episodic memory and interhemispheric interaction is saccadic horizontal eye movements (EMs), which may induce statelike changes in both the accuracy of episodic memories and in the amount or quality of interhemispheric interaction. In this article, we examine the conceptual and empirical bases for the effects of saccadic horizontal EMs on memory and on interhemispheric interaction.

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Posttraumatic Stress Disorder and Episodic Memory

The notion that saccadic horizontal EMs might (a) increase episodic memory and (b) do so via interhemispheric interaction originally came from research on posttraumatic stress disorder (PTSD). PTSD is a debilitating disorder affecting, by some accounts, up to 14% of the population and can follow an individual's exposure to a traumatic event in which "the person experienced, witnessed, or was confronted with an event or events that involved actual or threatened death or serious injury . . . [to] the self or others, and the person's response involved intense fear, helplessness, or horror" (American Psychiatric Association, p. 428). Traumatic events resulting in PTSD can include being threatened by or witnessing car accidents, natural disasters, muggings, rape, assault, military combat, or any other circumstance wherein an individual feels as if his or her life is threatened or wherein an individual learns of the life-threatening events of a loved one or friend (e.g., a mother learning of the life-threatening illness of her child).

Symptoms of PTSD vary, but one hallmark of the disorder is memory disturbance. Such disturbances can include the persistent experiencing of "recurrent and intrusive distressing" memories of the event. These reexperiencings can occur during wakefulness—for example, in the form of uncontrolled images or thoughts of the trauma—or in a sense of reliving the event. Uncontrolled memories can also occur during sleep, in the form of nightmares that seemingly accurately reflect the traumatic events. In fact, up to 50% of posttraumatic dreams may be considered to veridically represent the trauma (Wittmann, Schredl, & Kramer, 2007). Additionally, traumatized individuals may also experience physiological reactivity to events or objects that remind them of the traumatic experience (American Psychological Association, 1994).

In addition to the intrusive, uncontrollable recall of the traumatic event diagnostic of PTSD, research demonstrates evidence of impaired retrieval of other episodic memories in this disorder. For example, individuals may also have difficulty recalling specific memories that are unrelated to the trauma. When asked to report a specific memory that demonstrates the word *relax,* individuals with PTSD may state a general memory, such as "when I go for walks in the park." This is in contrast to specific, time-dated memories reported by nontraumatized individuals, such as "when I went for a walk in the park last Tuesday with my wife." Individuals with PTSD persist in reporting overgeneral memories even when repeatedly prompted for specific information (McNally, Lasko, Macklin, & Pitman, 1995).

Thus, one characteristic of PTSD is a dysfunction of episodic memory, as evidenced by intrusive recall while both awake and asleep, and in an inability to recall specific, relative to general, nontraumatic memories.

Saccadic Horizontal EMs: Relation to Memory Abilities

We reasoned that if one aspect of PTSD is a dysfunction of episodic memory, then treatments that relieve PTSD symptoms may offer clues to memory function even in the absence of trauma. One such treatment that seemed promising is eye movement desensitization and reprocessing (EMDR; Shapiro, 1989). EMDR is a structured psychotherapy approach, during which participants focus on the components of a targeted memory while engaging in simultaneous bilateral stimulation (alternating left–right tactile or auditory stimuli or, most frequently, eye movements) at the rate of approximately two movements per second, for a "set" of about 30 seconds. At the end of the set, the therapist asks the client, "what do you notice now?" This procedure is designed to elicit other aspects of the memory, or other related information, including other episodic memories. The client is then instructed to focus on the new material while engaging in another set of bilateral stimulation. The procedure continues, in accordance with standard protocols, until new, more adaptive information is integrated with the original memory.

We decided to focus on the bilateral stimulation used in EMDR; we suggest that changes in episodic memory in PTSD following EMDR (e.g., Rogers et al., 1999; Sandström, Wiberg, Wikman, Willman, & Högberg, 2008) might be based on neurophysiological mechanisms involved in memory generally. If so, then bilateral stimulation might alter episodic memory, regardless of whether such memories are traumatic.

In fact, we have published a series of articles demonstrating superior episodic memory following saccadic horizontal EMs (Christman et al., 2003, 2004, 2006) relative to vertical, smooth-pursuit, or to no EMs. In these studies, we used stimulation designed to be similar to that used in EMDR: bilateral visual stimulation with left–right alternating information, presented at the rate of two stimuli per second. Specifically, participants watched a dot appear alternately on the left and right sides of a computer screen for 30 seconds, with dots alternating left–right position every 500 milliseconds. Christman et al. (2003) contrasted this saccadic horizontal EM condition with (a) a vertical saccadic EM condition, wherein the computer screen was turned on its side; (b) two smooth-pursuit conditions—one horizontal, the other vertical—in which a dot moved smoothly and continuously from one side of the monitor to the other; and (c) a central fixation condition, wherein a dot changed colors twice a second in the center of the computer screen. In the first two conditions, participants followed a black dot as it moved continuously back and forth across the computer screen with the same spatial extent and periodicity as that of the saccadic EM conditions. The third control condition involved periodic visual stimulation but in the absence of EMs.

We report surprising, but robust, results. For example, we examined the effects of EMs on the retrieval of episodic memories (Christman et al., 2003). In Experiment 1, we used a standard laboratory-based memory procedure directly adapted from that developed by Tulving, Schacter, and Stark (1982). In this task, participants viewed a total of 36 words on a computer screen, one at a time for 5 seconds each. Then, after a 30-minute retention interval, they were given either a blank sheet of paper and asked to recall as many of the 36 words as they could, or they were given a list of 72 word fragments (36 were new, and 36 corresponded to the previously studied words) and were asked to complete as many fragments as they could (no reference was made to the list they had previously seen) as a test of implicit memory. Immediately prior to memory testing, participants were assigned to one of five EM conditions: (1) saccadic horizontal EMs, (2) saccadic vertical EMs, (3) smooth-pursuit horizontal EMs, (4) smooth-pursuit vertical EMs, or (5) a no-EM control condition (in all EM conditions, participants engaged in EMs for a 30-second period).

Episodic recall was enhanced only in the saccadic horizontal EM condition; the other four conditions were not statistically significantly different from one another (although there was a marginal trend for saccadic vertical EMs to be associated with enhanced recall relative to the smooth-pursuit and no-EM control conditions). This pattern of results likely reflects the fact that saccadic EMs generate much more activity in frontal lobe regions that have been implicated in episodic retrieval (e.g., Cabeza & Nyberg, 2000) than do smooth-pursuit EMs, which are largely controlled by subcortical structures (O'Driscoll et al., 1998). In contrast to the results for episodic memory, there were no differences among the five EM conditions in performance on the word fragment completion task, indicating that EMs have no effect on the retrieval of nonepisodic memories.

The fact that only the saccadic horizontal EM condition resulted in increased episodic memory has very important implications for the use of EMs in EMDR therapy, because many of the experimental and clinical protocols used in EMDR research and therapy appear to induce smooth-pursuit, not saccadic, EMs. For example, Montgomery and Ayllon (1994) claimed to induce bilateral saccadic eye movements by waving a finger in front of the patient. The finger was moved back and forth two times a second across a spatial extent of approximately 35°–45° of visual angle; this is similar to the stimulation employed in the current study to induce smooth-pursuit eye movements, leading to the possibility that the participants of this study may in fact have engaged in smooth-pursuit, not saccadic, eye movements. This problem is widespread, because many studies of EMDR follow Shapiro's (1995) protocol (e.g., Bates, McGlynn, Montgomery, & Mattke, 1996; Devilly & Spence, 1999; Levin, Lazrove, & van der Kolk, 1999), in which the therapist waves a finger back and forth in front of the patient—a procedure more likely to elicit pursuit than saccadic eye movements. Because pursuit eye movements did not enhance episodic retrieval in the Christman et al. (2003) study, it is possible that many of the negative reports on the efficacy of EMDR reflect the fact that procedures used induced smooth-pursuit, not saccadic, eye movements. Future work testing the efficacy of EMDR needs to explicitly distinguish between saccadic and pursuit eye movements.

Because our results indicated that it is saccadic horizontal EMs that increase memory (rather than smooth-pursuit or vertical), in other experiments we compared these types of EMs with the central fixation condition described above. In Experiment 2 (Christman et al., 2003) memory for real-world events was studied. Participants began by keeping a daily journal for a week in which they wrote down a couple of notable events each day. They were instructed to *not* write down common, everyday events (e.g., "I woke up and got dressed"), but instead to record distinctive events. Responses included statements such as "I stubbed my toe really bad," "I went to a funeral," and "I went to the park with my cousin and had some ice cream." Participants were not informed of the purpose of the journal and turned them in at the end of the week. About a week later, participants were randomly assigned to a saccadic horizontal dot condition or to a color-changing dot condition. After viewing their respective stimuli for 30 seconds, participants were asked to recall the gist of all the previous journal entries that they could remember. Once again, the results indicated that, following saccadic horizontal EMs, individuals recalled more of the journal entries and had fewer false recalls. Thus, the superior memory following saccadic horizontal EMs was observed for both lab-based and real-world memories.

In another study, we examined the effect of EMs on false memories (Christman et al., 2004). Participants engaged in the false memory task popularized by Roediger and McDermott (1995): the Deese-Roediger-McDermott paradigm. In this task, subjects listen to lists of words that are comprised of verbal associates to a critical lure item that is not included in the list. For example, participants would hear a list of words like *thread, eye, sewing, sharp, thimble, haystack, syringe,* etc.—all of which are close associates of the word *needle,* which did *not* appear in the list. Following saccadic horizontal EMs, participants demonstrated a decreased false recall for the critical lures compared to following a color-changing stimulus. Interestingly, EMs did not result in decreased false recall for words unrelated to the lists. Our findings have been replicated using a recognition task (Parker & Dagnall, 2007); following saccadic horizontal EMs, individuals had increased accurate recognition and decreased false recognition for the critical lure compared to vertical EMs and an EM movement control.

We have extended the EM paradigm to other memory tasks (Christman et al., 2006). In a study of the offset of childhood amnesia (the inability to explicitly remember events from the first few years of life), we found that the average age for earliest memory following saccadic horizontal EMs was reported 5.33 years, while the average age for earliest memory following the no-EM condition was 5.92 years—a significant difference. Given that such early memories are encoded and consolidated years previously, these differences between groups likely reflect an effect of EMs on the retrieval (and not at other memory stages such as encoding or consolidation) of episodic memories.

Others have replicated our findings of superior episodic memory following saccadic horizontal EMs (e.g., Lyle, Logan, & Roediger, 2008; Parker & Dagnall, 2007; Parker, Relph, & Dagnall, 2008). For example, as mentioned above, Parker and Dagnall (2007) reported that, following saccadic horizontal EMs, individuals had increased recognition and decreased false recognition for nonpresented critical lures in the Deese-Roediger-McDermott paradigm (Roediger & McDermott, 1995), compared to vertical EMs and a no-EM control.

Parker et al. (2008) in Experiment 1 found increased hits and decreased false alarms on a word recognition test following saccadic horizontal EMs relative to vertical or to no EMs. Additionally, they also report increased "remember" responses following saccadic horizontal EMs compared to the other two conditions, but no between-group differences in the number of "know" responses. Because "remember" responses are thought to be indicative of episodic memory processes, while "know" responses are analogous to semantic memory (Gardiner, 1988; Tulving, 1985), these results offer direct support for the hypothesis that saccadic horizontal EMs are involved in episodic memory processes. Parker et al. (2008) also reported increased hits and decreased false alarms for paired associates following the saccadic horizontal EMs condition. In Experiment 2, following saccadic horizontal EMs, individuals were more accurate in recalling the spatial location and the color of previously presented words compared to vertical and no-EM conditions.

Lyle et al. (2008) report increased word list recall (Experiment 1) following saccadic horizontal EMs relative to central fixation in strongly right-handed subjects. Interestingly, these authors also report increased accuracy in recognition, and decreased false recognition (Experiment 2), following saccadic horizontal EMs and following vertical EMs, relative to spontaneous EMs or to central fixation, in strongly right-handed individuals.

Although not a direct replication of our methodology, it is worth noting that at least one study of the effects of EMs on memory reported a decrease in the vividness of personal autobiographical nontraumatic positive and negative memories following EMs, but not following finger tapping or "imagery" conditions (van den Hout, Muris, Salemink, & Kindt, 2001). It is not clear how this finding of decreased vividness might be related to increases in episodic memory recollection generally.

To summarize, a rapidly growing literature indicates that saccadic horizontal EMs, relative to non-EM control conditions such as spontaneous EMs, and smooth-pursuit EMs result in superior episodic memory. As a whole, such superior episodic memory takes the form of improved recall and/or recognition for list words; increased identification of the spatial location of previously presented stimuli; increased identification of the color of previously presented information; increased accuracy for recall of paired associates; increased accuracy for recently experienced autobiographical information; an earlier age of first childhood memory; increased recollection for previously presented stimuli in the form of increased "remember" responses during recognition; and decreased false recall or recognition of previously presented information. See Table 1 for a summary of the effects of EMs on memory.

Although the exact locus in memory processing of these effects is still not clear, two things are apparent. First, the beneficial effects of EMs are at the retrieval stage, not at other memory stages such as encoding or consolidation; in fact, there is evidence that saccadic horizontal EMs immediately prior to encoding impair subsequent memory performance (Christman & Butler, 2005). Second, the beneficial effects of EMs at retrieval appear to be driven in large part by better source memory, as evidenced by the decreased false memory rate associated with such EMs.

Although some studies have reported increased recall following other types of EMs (i.e., during vertical EMs; Christman et al., 2003, Experiment 1; Lyle et al., 2008, Experiment 2), such reports are infrequent, and it is unknown whether the mechanisms resulting in increased episodic memory following these saccadic vertical EMs are similar to those that result in increased episodic memory following saccadic horizontal EMs. For example, Stickgold (2002) has proposed an alternative neurobiological account of the effects of EMs on memory, arguing that "the repetitive redirecting of attention in EMDR induces a neurobiological state, similar to that of REM sleep, which is optimally configured to support the cortical integration of traumatic memories into general semantic frameworks" (p. 61). That is, any procedure that induces repetitive redirecting of attention, be it left–right (as with horizontal EMs) or up–down (as with vertical eye movements),

TABLE 1. Summary of Research on the Effects of Bilateral Saccadic Eye Movements on Memory Retrieval (All Studies Involve Eye Movements Immediately Prior to Retrieval Except Where Noted)

Task	Findings	Citation
Recognition of words	Eye movements are beneficial	Christman, Garvey, Propper, & Phaneuf, 2003
Recognition of words	Eye movements are beneficial for consistent-handers, detrimental for inconsistent-handers	Lyle, Logan, & Roediger, in press
Recognition of words	Eye movements are beneficial	Parker, Relph, & Dagnall, 2008
Free recall of words	Eye movements are beneficial	Christman, 2004
Free recall of words	Eye movements are beneficial for consistent right-handers, detrimental for inconsistent-handers	Lyle, Logan, & Roediger, in press
Associative recognition	Eye movements are beneficial	Parker, Relph, & Dagnall, 2008
Recall of early childhood memories	Eye movements are beneficial	Christman, Propper, & Brown, 2006
Source memory (DRM paradigm)	Eye movements are beneficial	Christman, Propper, & Dion, 2004
Source memory (DRM paradigm)	Eye movements are beneficial	Parker & Dagnall, 2007
Know vs. remember judgments of recognized words	Eye movements result in increased number of "remember" responses	Parker, Relph, & Dagnall, 2008
Color memory	Eye movements are beneficial	Parker, Relph, & Dagnall, 2008
Spatial location memory	Eye movements are beneficial	Parker, Relph, & Dagnall, 2008
Vividness of memory	Eye movements decrease vividness	van den Hout, Muris, Salemink, & Kindt, 2001
Response bias	Eye movements induce more conservative response bias	Christman, Garvey, Propper, & Phaneuf, 2003
Encoding	Eye movements are detrimental at encoding	Christman & Butler, 2005
Implicit word fragment completion (old minus new fragments completed)	Eye movements have no effect	Christman, Garvey, Propper, & Phaneuf, 2003
Semantic memory (total fragments completed)	Eye movements have no effect	Christman, Garvey, Propper, & Phaneuf, 2003

may benefit the consolidation of memory traces. The "interhemispheric interaction" (proposed here, see below) and "redirecting of attention" accounts are not mutually exclusive, and the combined results from the studies by Christman, Garvey, Propper, and Phaneuf (2003), Parker and colleagues (2008), and Lyle and colleagues (2008) suggest that both accounts may have merit.

Saccadic Horizontal EMs and Interhemispheric Interaction

Although the clinical efficacy of EMDR has been demonstrated (e.g., Russell, 2006; Tufnell, 2005), the therapy remains controversial, in large part because of a lack of knowledge of its underlying neural mechanisms (e.g., Spector & Read, 1999).We suggest that because EMDR helps patients overcome memory dysfunction associated with PTSD, it is possible that EMDR is efficacious due to its action on neuroanatomical structures involved in memory. In particular, we have proposed that the alternating left–right stimulation used in EMDR facilitates episodic memory via neural mechanisms involved in hemispheric communication. Our neurobiological framework suggests that the bilateral stimulation in EMDR enhances memory processing through increased interhemispheric interaction via the corpus callosum (Christman et al., 2003, 2004, 2006). Support for the notion that saccadic horizontal EMs in particular might increase interhemispheric interaction comes from several lines of investigation.

First, there is evidence that leftward and rightward EMs selectively activate the contralateral hemisphere (Bakan & Svorad, 1969). Thus, repeated left–right EMs should result in simultaneous activation of both hemispheres. This was confirmed by Christman and Garvey (2001), who reported that engaging in left–right EMs reduced preexisting asymmetries in hemispheric activation, as indexed by perceptual asymmetries on a free-vision chimeric faces task (Kim, Levine, & Kertesz, 1990; Levy, Heller, Banich, & Burton, 1983). Thus, leftward–rightward eye movements may equalize the activation of both hemispheres.

Second, because one hemisphere is typically more activated than the other (Klein & Armitage, 1979), such equalization may foster interhemispheric communication; if the two hemispheres possess different levels of activation, it may be difficult for the less activated hemisphere to keep pace and interact efficiently with the more active hemisphere.

Third, direct evidence linking left–right EMs and facilitation of interhemispheric interaction can be found in studies of brain activity during rapid eye movement (REM) sleep. Evidence indicates that interhemispheric electroencephalographic (EEG) coherence increases significantly during REM sleep (e.g., Barcaro et al., 1989; Dumermuth & Lehman, 1981). Furthermore, the increase in interhemispheric EEG coherence has been specifically linked to the presence of EMs (Dionne, 1986). Because the majority of eye movements during REM sleep are horizontal (Hansotia et al., 1990), this evidence suggests that left–right EMs are associated with increased interhemispheric interaction.

A direct study of the effects of saccadic horizontal EMs in particular on interhemispheric interaction also supports the hypothesis. Following saccadic horizontal EMs, individuals demonstrated increased Stroop interference, relative to pre-eye movement baseline measures (Christman & Garvey, 2003), and such interference has been shown to arise at least in part from increased interhemispheric interaction (Christman, 2001).

Our hypothesis of increased interhemispheric interaction following saccadic horizontal EMs does not preclude the possibility that such increased interaction is inhibitory in nature. That is, communication between the cerebral hemispheres may be either excitatory or inhibitory; there is no a priori reason to suspect that increased communication is by definition excitatory. Furthermore, any neurophysiological change in hemispheric communication, while presumably associated with a concomitant change in behavior, is not necessarily associated with a *similar* change in behavior. Therefore, increased excitatory interaction at the physiological level will not necessarily be associated with increased excitatory interaction at the behavioral level (however excitatory behavioral interaction might be defined). For example, a behavioral study (Christman & Garvey, 2003) suggested that increased interaction following saccadic horizontal EMs is associated with interference between the two processing modes of the hemispheres, a result that could be interpreted as indicative of either excitatory interaction (e.g., the hemispheric processing modes are directly interfering with each other) or inhibitory interaction (e.g., the hemispheres are independently competing for response). For example, in that study, participants demonstrated increased Stroop interference following saccadic EMs; it was suggested that left hemisphere word-naming processes and right hemisphere color-detection processes interfered with each other, resulting in increased reaction times. Such decreased performance following EMs may have occurred because the left and right hemispheres actively attempted to suppress, via the corpus callosum, the other hemisphere's response (i.e., excitatory interaction), or because each hemisphere attempted to respond independently, with information within a given hemisphere actively kept separate from the other (i.e., inhibitory interaction) resulting in a bottleneck, and decreased performance, at the level of response.

The distinction between physiological versus behavioral interaction is especially important to consider in light of the results of a recent study. We directly tested the hypothesis that saccadic horizontal EMs result in a change of interhemispheric connectivity by examining interhemispheric EEG coherence following saccadic horizontal EMs versus following central fixation (Propper, Pierce, Geisler, Christman, & Bellorado, 2007). Interhemispheric EEG coherence compares the relationship between EEG signals from (usually) homologous sites in the two hemispheres as a function of the signals' frequencies. Interhemispheric EEG coherence is thought to reflect corpus callosum–mediated communication between the two cerebral hemispheres (Montplaisir et al., 1990; Nielsen, Montplaisir, & Lassonde, 1992). Increased levels of coherence are believed to reflect increased callosal activity and thus indicate increased hemispheric connectivity, while decreased levels of coherence are thought to reflect the opposite. Some evidence supporting this interpretation of interhemispheric EEG coherence comes from Montplaisir et al. (1990), who reported decreased coherence in epileptics following partial callosotomy, and Nielsen et al. (1992), who reported decreased coherence in individuals with agenesis of the corpus callosum—particularly at frontal, parietal, and temporal sites compared to individuals with an intact corpus callosum.

We recorded EEG from the left and right anterior frontal lobes (Fp1 and Fp2) prior to and immediately following either saccadic horizontal EMs or a central fixation condition (eye movements cause artifact in frontal sites, and EEG could not therefore be examined during eye movements). We examined theta (4–8 Hz) and gamma (35–54 Hz) frequencies because they have frequently been associated with episodic memory processing (e.g., Babiloni et al.; 2004; Burgess & Gruzelier, 1997; Klimesch, Schimke, & Schwaiger, 2004; Weiss, Müller, & Rappelsberger, 2000). Because alpha has been associated with semantic memory processes (e.g., Klimesch et al., 2004, Mima, Oluwatimilehin, Hiraoka, & Hallett, 2001), we also examined alpha (8–13 Hz) frequency in order to rule out a general, nonepisodic memory–related effect of stimuli condition on interhemispheric interaction.

Contrary to our hypothesis of increased interhemispheric interaction following saccadic horizontal EMs, we found a decrease in gamma frequency coherence. While surprising, the findings correspond nicely with a recent functional magnetic resonance imaging study. Umeda et al. (2005) reported decreased functional connectivity between the left and right hemispheres in anterior prefrontal cortex during an episodic retrieval task. Given that the cortical locations of Fp1 and Fp2 (Brodmann's area 10; Homan, Herman, & Purdy, 1987) coincide with the location of the anterior frontal cortex in which decreased functional interhemispheric connectivity was reported (Umeda et al., 2005), it seems likely that our EEG results are related to the findings of Umeda et al. Specifically, the eye movement manipulation we used, and that has been reported to facilitate episodic memory, resulted in decreased interhemispheric EEG coherence in anterior prefrontal cortex.

As mentioned, a decrease in interhemispheric EEG coherence does not necessarily indicate a decrease in functional interhemispheric interaction. As noted by Uttal (2001), changes in measures of brain activity do not always map directly onto changes in cognitive function (i.e., increases in activation of a brain region associated with a specific task do not necessarily indicate that that region is primarily responsible for that task). To illustrate, decreases in gamma-band interhemispheric EEG coherence have been reported as subjects become better at a bimanual motor task in which the movements of the left and right hands, and hence right and left hemisphere processing, need to be coordinated (Gerloff & Andres, 2002). Thus, the current results should be interpreted as reflecting EM-induced *changes* in interhemispheric interaction, not necessarily EM-induced *decreases* in interhemispheric interaction. For example, increased interhemispheric EEG coherence implies that the two hemispheres are doing similar things, while increased interhemispheric interaction implies that the two hemispheres are doing coordinated, but not necessarily similar, things.

Finally, recent pilot data from our lab suggests that, in addition to enhancing the recall of episodic memories, saccadic horizontal EMs may also have effects on participants' emotional states (Christman & Stieber, 2005). Davidson (1992, 1995) has argued that the left and right frontal lobes are specialized for approach- versus withdrawal-related behaviors, respectively. For example, individuals with depression show decreased activation of the left frontal lobe (Henriques & Davidson, 1991), whereas individuals with high levels of well-being show increased activation of the left frontal lobe (Davidson, 2004). Accordingly, it was hypothesized that, to the extent to which saccadic horizontal EMs equalize levels of activation over the left and right frontal lobes, then such EMs should also result in a neutralization of affective state. Indirect support for this hypothesis comes from a study by Compton and Mintzer (2001), who found that interhemispheric interaction served to reduce stress and worry. More direct support comes from studies reporting that EMDR therapy is associated with reduced negative affect associated with traumatic memories (e.g., Barrowcliff, Gray, Freeman, & McCulloch, 2004; Kavanagh, Freese, Andrade, & May, 2001).

To test this hypothesis, we induced happy or sad moods in participants. Participants then rated their current mood, engaged in either our standard saccadic horizontal EM procedure or the no-EM control condition, and then rated their mood again. Among those participants for whom the mood induction procedure was effective, saccadic horizontal EMs led to significant neutralization of mood relative to controls (i.e., "happy" participants became less happy, and "sad" participants became less sad); although both the EM and no-EM groups showed neutralization of affect, this effect was significantly larger in the EM condition.. This last finding, in conjunction with the well-documented effects of saccadic horizontal EMs on episodic retrieval, suggests that the EMs employed in EMDR may work on at least two levels: (1) helping patients overcome their episodic memory dysfunction and (2) reducing their levels of negative emotion induced by retrieval of traumatic memories.

Theoretical Considerations and Future Directions

Although our research has focused on the effects of saccadic horizontal eye movements on interhemispheric interaction and memory, other types of bilateral stimuli have also been used in EMDR (e.g., bilateral tapping, bilateral tones, alternating fist clenching), as have smooth-pursuit eye movements (e.g., Rothbaum, 1997). It is not clear whether increased interhemispheric interaction occurring as a result of saccadic horizontal EMs relies on mechanisms that would be applicable to other forms of bilateral stimulation. Future research could directly compare other forms of bilateral stimulation on memory and interhemispheric interaction.

Finally, our work examining effects of saccadic horizontal EMs on memory and on interhemispheric interaction offer suggestions for theories of neurophysiological correlates of PTSD. For example, there is evidence that PTSD may be characterized by a dysfunction of interhemispheric interaction. Such evidence comes from sleep disturbances in PTSD, in individual differences in susceptibility to dissociation, from research demonstrating altered corpus callosum size in individuals with PTSD, and from our own work examining saccadic horizontal EMs.

First, REM sleep, that stage of sleep associated with increased interhemispheric interaction (Barcaro et al., 1989; Dumermuth & Lehman, 1981), may be disturbed in individuals with PTSD. Disturbances may include increased awakenings from REM (Breslau et al., 2004), increased eye movement density during REM, decreased latency to REM sleep, and increased REM sleep (see Harvey, Jones, & Schmidt, 2003, for review), although these latter two findings have not always been replicated. Furthermore, research has suggested that the PTSD-related veridical replay of the traumatic experience in dreams occurs during REM sleep (see Phelps, Forbes, & Creamer, 2007). In those who do not have PTSD, REM dreams rarely replay daily events (Stickgold, Hobson, Fosse, & Fosse, 2001). The physiological REM disturbances found in individuals with PTSD, in conjunction with the phenomenological abnormalities, suggest the possibility that the interhemispheric interaction associated with REM sleep (Barcaro et al., 1989; Dumermuth & Lehman, 1981) may be somehow altered in the sleep of individuals with PTSD.

Second, individual differences in susceptibility to PTSD also suggest that this disorder may be characterized by a dysfunction in interhemispheric interaction. Christman and Ammann (1995) reported that strong right-handedness was associated with a significantly higher frequency of dissociative experiences, suggesting that strong-handedness may be associated with increased risk for developing dissociative disorders such as PTSD. This framework is reinforced by evidence that patients with PTSD have smaller corpus callosa (Kitayama et al., 2007; Villareal et al., 2004). Moreover, strong-handedness is also associated with both smaller corpus callosum size (Clarke & Zaidel, 1994; Denenberg, Kertesz, & Cowell, 1991; Habib et al.1991; Witelson & Goldsmith, 1991) and decreased interaction between cognitive processes known to be functionally lateralized to opposite hemispheres (Christman, 1993, 2001; Christman, Bentle, & Niebauer, 2007; Christman, Geers, Kosbab, & Weiland, 2006; Jasper & Christman, 2005; Niebauer, Aselage, & Schutte, 2002).

Surprisingly, however, published reports have indicated a *decreased* incidence of PTSD among strongly handed individuals (e.g., Boscarino & Hoffman, 2007; Chemtob & Taylor, 2003; Chemtob, Taylor, Woo, & Coel, 2001). The results of the Chemtob studies are inconclusive due to the idiosyncratic way in which the degree of hand preference was assessed: participants were asked a single question concerning whether they did anything better with their nondominant hand. The problem here is that, even for very strongly right-handed people, they are likely, for example, to be better at catching objects with their nondominant hand. The handedness inventory used in our studies does not ask about catching. However, the study by Boscarino and Hoffman (2007) measured handedness in a way very similar to the studies from our lab and still found an association between mixed-handedness and PTSD. Finally, a recent study by Choudhary and O'Carroll (2007) reported that PTSD diagnoses were elevated for strongly left-handed, relative to mixed- and strongly right-handed, individuals. At present, the basis for these discrepancies remains unclear and should be addressed by further research.

Third, more direct support for the notion that alterations in interhemispheric interaction may, in part, underlie the memory disturbances associated with PTSD comes from research directly examining the corpus callosum in individuals with PTSD. In PTSD pediatric populations, there is evidence for decreased organization of the medial and posterior corpus callosum, as measured via diffusion tensor imaging, compared with children who do not have PTSD (Jackowski et al., 2008). Research examining adults with PTSD indicate decreased corpus callosum size in these individuals (Villarreal et al., 2004). Presumably, reduced size of this structure would be associated with decreased interhemispheric interaction in individuals with PTSD.

Fourth, support for the hypothesis that interhemispheric interaction may be disturbed in PTSD comes from our research on saccadic horizontal EMs and its similarity to the stimuli used in EMDR. Our proposal that saccadic horizontal EMs increase episodic memory via increased interhemispheric interaction (e.g., Christman et al., 2003, 2004, 2006), suggests that saccadic horizontal EMs, or saccadic horizontal EMs-like stimuli used in EMDR, increase interhemispheric interaction in individuals with PTSD, thereby reducing memory disturbances in PTSD. In this light, however, it is interesting to note that: (1) Forbes et al. (2006) reported that patients with PTSD and mixed lateral preference responded more poorly to treatment, and (2) the beneficial effects of saccadic horizontal EMs on episodic retrieval may be restricted to strong right-handers only (Lyle et al., 2008), suggesting that different therapeutic approaches may be more effective with different handedness groups.

It is, of course, difficult to reconcile the admittedly somewhat contradictory findings regarding the relationship between interhemispheric interaction, memory, EMDR, PTSD, and bilateral stimulation; however, we believe our hypothesis offers a first step toward understanding the cortical connections underlying episodic memory for both the mundane and the traumatic. For example, our hypothesis of increased interhemispheric interaction following saccadic horizontal EMs was not supported in our study examining interhemispheric EEG coherence in anterior frontal lobe—a finding that deserves further study.

Similarly, at a behavioral level, our, and other research groups' (e.g., Lyle et al., 2008; Parker & Dagnall, 2007; Parker, Relph, & Dagnall, 2008) findings of *increased* episodic memory following saccadic horizontal EMs seems to be in direct contrast with the *reduction* of intrusive episodic memories found following EMDR in individuals with PTSD. One possible explanation for these opposite effects of EMs on nontraumatic versus traumatic memories is that EMs reinstate an optimal level of hemispheric communication necessary for episodic memory, beyond which is detrimental to recall. This interpretation is supported by Lyle and colleagues (2008), who found a negative effect of EMs on memory in non–right-handers. This finding may help explain why mixed-handedness is associated with poorer response to treatment for PTSD (Forbes et al., 2006).

These latter findings, in conjunction with research indicating increased interhemispheric interaction and a larger corpus callosum in the non–right-handed (e.g., Christman, 1993, 2001; Christman, Bentle, & Niebauer, 2006; Clarke & Zaidel, 1994) suggest that beyond some optimal level of interhemispheric interaction, negative effects of EMs on memory may occur. Another possibility is that saccadic horizontal EMs in patients with PTSD reinstate a level of interhemispheric interaction that encourages the transformation of episodic information into semantic memory, with a concomitant reduction in the intrusive episodic memories (e.g., Stickgold, 2002). Future research could directly compare these two possible mechanisms of action of saccadic horizontal EMs in EMDR. How these findings are related to the decreased corpus callosum size found in individuals with PTSD (e.g., Villarreal et al., 2004) is currently unknown.

We leave it to others to determine the exact nature of how the saccadic horizontal EMs used in EMDR affect aspects of interhemispheric interaction and activation from both functional and neurophysiological perspectives and how those effects influence individuals' memory retrieval abilities and emotional states, especially in clinical populations such as patients with PTSD. We hope this review article stimulates interesting and fruitful avenues of investigation.

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