EFFECTS OF LONG-TERM MEMORY ACCESSIBILITY ON SACCADIC EYE MOVEMENTS

by

REBECCA S. CHEN

A dissertation submitted to the Graduate Faculty in Psychology in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The City University of New York

2007

UMI Number: 3278422

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

This manuscript has been read and accepted for the
Graduate Faculty in Psychology in satisfaction of the
dissertation requirement for the degree of Doctor of Philosophy.

Howard Ehrlichman, Ph.D.

Date

Chair of Examining Committee

Joseph Glick, Ph.D.

Date

Executive Officer

Howard Ehrlichman, Ph.D.

Nancy Foldi, Ph.D.

Jeffrey M. Halperin, Ph.D.
Supervisory Committee

THE CITY UNIVERSITY OF NEW YORK

Abstract

EFFECTS OF LONG-TERM MEMORY ACCESSIBILITY ON SACCADIC EYE MOVEMENTS

by

Rebecca S. Chen

Advisor: Professor Howard Ehrlichman

Saccadic eye movements vary in their rate depending upon the type of non-visual cognitive task. Ehrlichman et al. (2006) described “the long-term memory hypothesis” in which EMR directly reflects requirements for searching long-term memory in any non-visual cognitive task. The present study built upon this hypothesis to test whether accessibility of information to be retrieved from long-term memory (LTM) impacts eye movement rate (EMR). The primary goal was to assess whether low accessibility conditions would produce higher EMR than high accessibility conditions within a long-term memory task. Additional goals were to extend previous findings of high EMR for LTM tasks to newly learned episodic memory and include a working memory task that could be varied on the basis of difficulty.

Participants performed episodic (levels of processing) and semantic (verbal fluency) LTM tasks with two levels of accessibility, and, as a control for difficulty, a working memory (n-back) task with two levels of difficulty. Thirty-two undergraduate students participated (10 males, 22 females). The results gave equivocal support for the accessibility hypothesis. Newly learned episodic memory was associated with significantly higher rates of eye movement than working memory, and there was no difference in EMR between varying levels of difficulty for the working memory task. There was no difference in EMR between the varying levels of accessibility for the episodic memory task; however, a significant difference in EMR was found between the accessibility levels of the semantic memory tasks. In addition, the fluency tasks were compared by 15-second quartiles. There was a clear negative correlation between performance and EMR over time, with low EMR associated with high performance in the first quartile and high EMR associated with low performance in the last quartile for the semantic fluency task. In addition, three clusters of tasks were found which significantly differed in their EMR: a working memory task with a vigilance component, rote memory and working memory tasks without a vigilance component, and long-term memory retrieval tasks. The paper also reviewed possible areas of overlap between long-term memory, working memory, and eye movements in the brain.

Acknowledgements

I would like to gratefully acknowledge the work of Dr. Howard Ehrlichman who guided me throughout this process. I would also like to thank Dr. Jeffrey Halperin, Dr. Nancy Foldi, Dr. Doreen Berman, and Dr. Hilary Gomes for their good advice and suggestions. Additional thanks goes to Keith Benoff and Kate Stern. Finally, I could not have completed my Ph.D. without the love and support of my family: Eytan, Hana and Maya Chen, Anthony and Rachel Rosen, and Miriam and David Chen.

Table of Contents

List of Tables

List of Figures

Introduction

There is a vast literature on the saccadic eye movement system (Galpin & Underwood, 2005; Godijn & Theeuwes, 2002; Griffin & Bock, 2000; Henderson & Hollingworth, 1999; Rayner, 1998). Virtually all of the research involves saccades that occur in response to visual stimuli (e.g., reading, visual search, and scene perception). The focus of this study is the relationship between eye movements and cognitive tasks that do not directly involve the visual system, specifically, saccades associated with episodic and semantic long-term memory and working memory, in response to orally presented stimuli.

Considerable data indicate that eye movements vary according to cognitive task. The number of eye movements occurring per second--eye movement rate (EMR)--has been shown to decrease for some tasks and increase for other tasks. The goal of this study is to further investigate the hypothesized relationship between increased eye movement and memory search, extending previous research to include the retrieval of newly learned information, with a specific focus on the potential impact of memory accessibility on eye movement rate.

Several explanations have been proposed to account for the effects of non-visual cognition on saccadic eye movements, including the cognitive affective model (Argyle & Cook, 1976; Beattie, 1978), imagery scanning hypothesis (Lorens & Darrow, 1962), brain asymmetry hypothesis (Kinsbourne, 1972), interference hypothesis (Glenberg, Schroeder, & Robertson, 1998), general arousal hypothesis (Meskin & Singer, 1974), constraint hypothesis (Bergstrom & Hiscock, 1988), and long-term memory hypothesis (Ehrlichman, Micic, Sousa, & Zhou, 2007).

Saccadic Eye Movements

There are four main types of eye movements: pursuit, vergence, vestibular, and saccadic. Pursuit eye movements track a moving target. Vergence eye movements involve the movement of both eyes toward or away from the nose for depth perception. Vestibular eye movements maintain fixation on an object even as the head or body moves. Finally, saccadic eye movements, which are the focus of this study, are discrete, preprogrammed eye movements that shift the fovea--the center part of the retina, responsible for visual acuity--from one point of fixation to another.

Saccadic eye movements have been studied in relation to cognitive tasks that involve visual activity, such as reading, scene perception, pattern recognition, and visual search (Galpin et al., 2005; Godijn et al., 2002; Griffin et al., 2000; Henderson et al., 1999; Rayner, 1998). These eye movements, as well as antisaccades, which move the fovea away from the visual stimulus, have been studied in the realm of attention and executive functioning (Posner, 1980; Spivey & Geng, 2001).

Research on saccadic eye movements has primarily focused on the nature and timing of fixations and the dynamics of movement as they relate to specific visual stimuli. Foveal input is the main source of visual information; however, stimuli identified within the periphery provide the impetus for triggering new saccades (Rayner, 1998). The range of fixation length varies with the type of stimulus studied, 200-250 ms. for words and 275-330 ms. for scene perception and visual search. In all research on eye movements, a high level of inter-subject variability has been found. Across individuals, fixation durations range from approximately 100 to 500 ms and saccade length varies from one to 15 character spaces (Rayner, 1998).

In addition to research on visually oriented saccades, eye movement has been investigated as it relates to other cognitive functions, such as attention and inhibitory control. Some eye movements involve attention and executive functioning, such as antisaccades. They require the inhibition of prepotent responses in order to move the eyes away from the stimulus. A shift in attention in the absence of eye or head movement was described by Posner (1980) as *covert* attention. *Overt* attention involves an identifiable external shift of attention toward a stimulus. Although there is some overlap, attention and eye movements are not controlled by the same brain structures. When attention shifts before a saccade, an area of the superior colliculus becomes active, but *only* in cases when the eye movement occurs after the attentional shift (Posner, 1980). If a shift in attention occurs without an eye movement, i.e. a demonstration of covert attention, the superior colliculus remains inactive. (Covert attention stimulates the parietal lobes.)

Eye Movements and Social Dyads

In conversational dyads, individuals make eye contact (gaze) more when listening than when speaking (Argyle et al., 1976). During periods of thinking and speaking, individuals tend to look away from the listener. Some theorists suggested that these variations in eye movement are part of the pragmatics of language, such as turn taking (Doherty-Sneddon, Bruce, Bonner, Longbotham, & Doyle, 2002; Kendon, 1967). Kendon (1967) filmed seven pairs of students as they engaged in small talk during 30-minute time periods. He analyzed the beginning and ending of all statements lasting at least five seconds. The patterns of looking were closely associated with speech patterns; a prolonged gaze ended most utterances, indicating the listener’s turn to speak. Further study has shown that eye movements made by the speaker serve as a “turn holding cue,” while a return to fixation on the listener serves as a “turn-yielding cue,” indicating that the speaker is finished (Doherty-Sneddon et al., 2002).

Inter-participant viewing times during conversation vary widely. Cook (1977) noted that some individuals gaze continuously, while others gaze as little as 8% of the time. Not all eye contact by the speaker represents a willingness to switch speakers; glances during speech, for example, can serve to measure the level of attentiveness by the listener or to indicate the need for some response without yielding the floor (Bavelas, Coates, & Johnson, 2002; Beattie, 1978). Bavelas et al. (2002) described gaze as one of many types of nonverbal cues used in conversation, in addition to facial expression, voice pitch, and gestures.

Another explanation for eye movements during speech, within the context of social interaction, is the *cognitive affective model* of eye movement. This model assumes that the face is a particularly salient and arousing stimulus and that sustained gaze would lead to overarousal (Argyle et al., 1976; Beattie, 1978; Meskin et al., 1974). Individuals are likely to avert their gaze during thought and speech in order to reduce the impact of the arousing stimulus on the ability to consider a response. However, there has been no consistent finding regarding the physiological impact of gaze. For example, Kleinke (1986) noted that some studies did not find typical indicators of arousal, such as an increase in heart rate or galvanic skin response under gaze conditions. Arousal may occur with increased gaze, depending on the situation and the feelings of the viewer (Argyle et al., 1976).

Neuropsychological Approaches to Eye Movement

A neuropsychological approach to eye movement research began with the study of rapid eye movement (REM) during sleep. Aserinsky and Kleitman (1955) described a series of studies in which they measured the eye movements and brain waves of participants while they slept, using electro-oculography (EOG) and electro-encephalography (EEG). In one study, 11 participants were awakened after the notation of rapid eye movement or, conversely, a long period of ocular quiescence. They were then asked to report their last image from sleep. In 20 of 27 instances of being awakened during REM, study participants recalled vivid visual imagery. Periods of reduced eye movement, however, resulted in no visual recall in 19 of 23 instances. In a second study, participants were permitted to sleep through the night while their periods of rapid eye movements were observed. The eye movements were remarkable for high amplitudes; brain waves were notable for low amplitude in the frontal and occipital areas. Aserinsky and Kleitman interpreted the EEG and EOG findings during uninterrupted and interrupted sleep to mean that dreams were occurring during REM sleep.

Further research by Dement and Kleitman (1957a; 1957b) found that being awakened from REM sleep was associated with an 80% incidence of vivid, detailed dream recall. In contrast, vivid recall occurred following ocular quiescence only 7% of the time. Participant estimates of dream duration correlated with the actual length of the REM period. The researchers suggested that the amplitude of the eye movements correlated with the activeness or passiveness of the dream sequence. Roffwarg, Dement, Muzio, and Fisher (1962) also found a 75-80% probability of accurately predicting the direction of eye movements during REM sleep based upon the dream recall of participants.

It was hypothesized as early as 1935 that eye movements thought to occur while dreaming reflected “looking” at and tracking an internal image (Totten, 1935). Based on prior sleep research, Singer and Antrobus (1965), among others, suggested that waking imagery would also lead to high rates of eye movements. This was labeled the *imagery scanning hypothesis* of ocular motility. Looking at internal visual imagery was expected to stimulate saccadic eye movement in the absence of salient visual stimuli (Lorens et al., 1962). It was postulated that individuals move their eyes to investigate internal visualizations in much the same way they search external visual stimuli.

A study by Ganis, Thompson, and Kosslyn (2004) provided support for a link between perception and imagery. The authors conducted a study using functional magnetic resonance imaging (fMRI) in which they compared the activity of brain structures during almost-identical visual imagery and visual perception tasks. They found 92% overlap in brain structure activation, with the highest degree of overlap in the frontal and parietal lobes.

Despite the plausibility of the imagery scanning hypothesis, a great deal of research conducted over the past 40 years has failed to provide support for it. While researchers continued to associate rapid eye movement with dreaming, the pattern and direction of those eye movements did not appear to reflect “looking” behavior at any kind of internal image. Using similar methodology to Roffwarg et al. (1962), Moskowitz and Berger (1969) were able to match the last dream image reported upon waking with the direction of eye movements during REM sleep in only 18 of 56 cases, not significantly more than chance. In addition, Moskowitz and Berger found that the rapid eye movements did not systematically vary with reported dream content. Jacobs, Feldman, and Bender (1972) compared expected eye movement direction, predicted from dream reports, with actual eye movement direction before the individual was awakened. There was only an 18% correlation between expected and actual eye movement direction. Jacobs et al. described the quality of rapid eye movements in sleep as characterized by slow, roving eye movements with quick eye movements superimposed onto the slow activity. These are unlike waking eye movements, which are characterized by fast saccadic eye movements.

REM sleep was found to be associated with dreaming; however, the pattern of eye movements during sleep were not correlated to the nature of the dream sequences. Exploration of visual imagery in the awake individual also revealed conflicting results. Antrobus, Antrobus, and Singer (1964) found that instructing individuals to imagine moving events led to more eye movements than visualizing static events, which they associated with monitoring and tracking a moving image compared to a stable one. Antrobus et al. tested awake participants with their eyes closed by interrupting them after a four-second period of either ocular quiescence or increased ocular behavior for both imagery and non-imagery tasks. They found that visual imagery was associated with *reduced* eye movements.

Lateral Eye Movement

Day (1964) was the first to associate the direction of eye movements in awake individuals with internal psychological experience. He noted that when individuals are asked questions that require reflection, they tend to divert their eyes in a lateral eye movement (LEM) to either the right or left. Day suggested that LEM reflects a shift from external attention to internal attention and from passive listening to active thought. He contended that individuals could be categorized based upon the consistent direction of the eye movements as either a “left mover” or a “right mover.” Duke (1968) found that 86% of individuals could be classified as left or right movers by judging the initial movement of the eyes either to the right or to the left, immediately after a reflective question had been asked, over the course of ten trials.

Day (1964) and Bakan (1969) reported left-movers are more internally focused, while right-movers are more externally focused. They found differences between left and right movers on anxiety, visual attention, hypnotizability, and EEG alpha activity (Bakan, 1969; Bakan & Shotland, 1969; Day, 1967). On the scholastic aptitude test (SAT), left movers performed better on the verbal section and right movers perform better on the math section (Bakan, 1969). Bakan (1969) described lateral eye movements as “a reliable and easily observable correlate to individual differences” (pp. 931). However, other researchers did not find a consistent relationship between EEG alpha or personality traits and consistent direction of eye movement (Duke, 1968; Ehrlichman & Weinberger, 1978).

While some investigators considered lateral eye movement direction a reflection of personality characteristics, others investigated the possible role of lateral eye movement in the context of brain asymmetry research. In the 1960s and 1970s, research on laterality of brain function was expanding with studies among clinical populations, including lesion studies, pharmacological paralysis (in epilepsy diagnosis and treatment), and research with “split brain” (commissurotomized) patients (Beaumont, Young, &

McManus, 1984; Gazzaniga, 1995; Milner, 1971). Among right-handed individuals, these studies revealed left hemisphere dominance for language, verbal processing, mathematical abilities, and encoding and retention of verbal material. The right hemisphere was found to be dominant for spatial relationships, patterns, and location, spatial learning and memory, as well as music (Milner, 1971). The ability to study laterality in a nonclinical population was limited to dichotic listening and tachistoscopic studies. Lateral eye movement studies were suggested as a less invasive and more "real world" way of studying brain asymmetries (Kinsbourne, 1972).

Kinsbourne developed the *brain asymmetry hypothesis*, based upon the assumption that the direction of the LEM indicated the hemisphere of the brain that is activated in response to questions (Kinsbourne, 1972). When one hemisphere becomes more activated than the other in order to generate a response, eye movements are directed to contralateral space (Bakan, 1969; Kinsbourne, 1972; Kocel, Galin, Ornstein, & Merrin, 1972). A LEM to the right after a "verbal" question suggested the activation of the left hemisphere, and a LEM to the left after a "spatial" question suggested the activation of the right hemisphere. Verbal questions included word definitions, proverb interpretation, sentence generation, and semantic correction of sentences (Ehrlichman, Weiner, & Baker, 1974). Spatial questions included being asked to form a mental image and describe or manipulate it, in addition to questions of direction and orientation (e.g., recalling the direction of Lincoln's face on the penny).

Early studies appeared to be consistent with Kinsbourne's brain asymmetry hypothesis. In a series of two studies, Kinsbourne (1972) tested 20 right-handed and 20 left-handed participants. Participants were videotaped as they were asked verbal, numerical (e.g., mathematical calculation questions), and spatial questions. Questions were presented orally and the direction of the initial lateral eye movement after question presentation was scored. Eye movements were classified as left, right, up, or down movements. Among right-handed individuals, Kinsbourne found more horizontal than vertical eye movements following verbal questions, mostly to the right. Spatial questions elicited more leftward and vertical eye movements than verbal questions. Math questions showed no difference in direction of LEM. Among left-handed individuals, horizontal eye movements were common for all questions, and question type did not differentially impact gaze direction. Performance did not appear to contribute to these eye movement effects, as performance was similar across all question types.

Kocel et al. (1972) administered 20 left hemisphere questions, that is verbal and mathematical questions, and 20 right hemisphere questions, including spatial and musical questions to participants. Verbal questions elicited significantly more lateral eye movements than spatial questions overall. Of the 23 participants included in that analysis, 22 made right LEM for the verbal questions 68% of the time, which was significantly higher than the number of right LEM made for spatial questions (45% of the time). Kocel et al. suggested that this difference reflected the impact of question type on the direction of lateral eye movement.

Through the 1970s, studies did not find consistent directional effects of eye movement based on question type. Ehrlichman and Weinberger (1978) reviewed the literature on lateral eye movements between 1972 and 1977. Out of 19 studies reviewed, only nine concluded that verbal questions elicited significantly more rightward movements compared with spatial questions. Studies differed regarding the presence or absence of the experimenter in the room, method of recording eye movements, types of questions asked, and scoring criteria for the eye movements, but none of these factors were able to account for the discrepancies in results. In addition, there was no external evidence that the tasks described as right- or left-hemisphere were actually differentially targeting that area of the brain. Later reviews noted that less than half of all studies found a significant relationship between question type and LEM in the expected direction (Beaumont et al., 1984; De Gennaro & Violani, 1988).

Investigators tested different aspects of the hemispheric asymmetry model in an attempt to demonstrate the expected laterality effects. Croghan and Bullard (1975) studied the impact of direction of LEM on performance, and found no significant effect of eye movement on accuracy or response latency. In response to criticism over the use of one LEM after question presentation to reflect laterality, Saring and von Cramon (1980) scored lateral eye movements from five time periods over the question and answer sessions: before the question, during the question, immediately after the question presentation, when the answer began, and after the answer. They asked participants verbal and spatial questions, and found no significant effect of direction and question type. When the researchers looked at the direction of all eye movements during the reflection and answer periods, they found a shift to the left for verbal questions, the opposite of the expected direction predicted by the brain asymmetry model. (The reflection period is the time after question presentation, but before the answer, during which time an individual considers the question. The answer period is the time period during which the individual provides a response.)

The absence of consistent findings in LEM in the expected direction sharpened criticisms regarding the lack of independent confirmation of the brain hemisphere assumed to be activated by the questions. A study published in 1991 looked at this issue (Raine, 1991). Raine presented participants with verbal and spatial questions in a dark room to remove the potential confound of competing visual stimuli. In addition, Raine administered two tests which he claimed to be independent measures of laterality: the Digit Span subtest from the Wechsler Adult Intelligence Scale (WAIS-R) associated with left-hemisphere functioning, and the Block Design subtest, associated with right hemisphere functioning. In addition, a left hemisphere, verbal dichotic listening task, and a right hemisphere, nonverbal dichotic listening task (pitch discrimination) were used.

Raine (1991) found that verbal questions were associated with significantly more right eye movements, but there was no consistent eye movement direction for spatial questions. In addition, LEM scores were not related to either the dichotic listening tasks or the WAIS subtests, which served as independent measures of laterality. The lack of independent corroboration of tasks involving hemispheric asymmetry and lateral eye movements undermined the assumptions of the model that LEM reflects asymmetrical functioning.

While the LEM hypothesis could not withstand the lack of theoretical support nor the lack of experimental support, it did lead to an important finding. Ehrlichman, Weiner, and Baker (1974) sought to replicate the findings of the LEM studies in a series of three experiments. Participants faced either a video camera or an experimenter, and the direction of the initial gaze shift was recorded after presentation of verbal (proverb interpretation), spatial (imagery), and neutral (e.g., favorite book) questions. Verbal questions were associated with significantly more downward eye movements compared with spatial questions. Ehrlichman et al. found no significant difference in the direction of horizontal eye movements between verbal and spatial question categories. However, a significantly higher number of stares (i.e., no gaze shift) was associated with spatial questions as compared with verbal questions. Ehrlichman et al. suggested that an increase in staring was related to an overall reduction in eye movement rate (EMR) when considering and answering spatial questions.

In a re-analysis of this study, Weiner and Ehrlichman (1976) divided stares into short and long periods, with the dividing line at 2.58 seconds, the median length of a stare in the study. They found that long stares were particularly reflective of differences in question type, with spatial questions eliciting more “long” stares than verbal questions. The finding that spatial questions elicited high rates of staring has also been reported by other researchers (De Gennaro et al., 1988; Galin & Ornstein, 1974; MacDonald & Hiscock, 1992).

Ultimately, the criticisms of the use of LEM as a measure of hemispheric asymmetry overwhelmed the initial results supporting the hypothesis. The theoretical and methodological difficulties and the lack of consistent findings suggest that LEM is not an effective tool to interpret laterality of brain function. However, LEM research was important in that it revealed differences in eye movement behavior between verbal and spatial questions (Ehrlichman et al., 1978; Weiner & Ehrlichman, 1976).

Verbal / Spatial Questions and Eye Movement Rate

Weiner and Ehrlichman (1976) re-analyzed the data from the Ehrlichman, Weiner, and Baker study (1974), a lateral eye movement study that had included verbal and spatial questions, by scoring eye movement rates over the reflection and answer periods for each question. In their study, verbal questions included a wide range of linguistic and conceptual skills, such as providing words that matched definitions (e.g., "a rule which guides conduct"), traditional word definition tasks, interpretation of proverbs (e.g., "too many cooks spoil the broth"), and judgments of semantically or grammatically malformed sentences (e.g., "the man is six feet short"). Spatial questions included a variety of spatial imagery tasks (e.g., "Make a mental picture of this object and tell me when you get the picture as clear as you can: a poodle"; "What color is the top stripe of the American flag?") and spatial operations (e.g., "How many windows are in your apartment?").

Weiner and Ehrlichman (1976) found significant differences in EMR between the two question types, with verbal questions eliciting significantly more eye movements than the spatial questions. In order to examine the potential impact of length of speech on eye movements, Weiner and Ehrlichman analyzed the rate of eye movements for each question and answer type. They found a significant difference between verbal and spatial questions for one word and extended speech and a trend towards significance for list answers. This suggested that the type of response was not responsible for significant differences in EMR between verbal and spatial questions.

The concept of verbal and spatial questions is broad and has been defined in many ways. Hiscock and Bergstrom (1981) conducted a series of experiments seeking to more precisely determine the tasks that fall under these definitions. They included four types of verbal tasks: word definition, similarities (e.g., In what way are a table and chair alike?), proverb interpretation (e.g., One swallow doesn't make a summer), and miscellaneous verbal questions (e.g., Name a word with three syllables). Spatial questions included visual memory (e.g., How many rows of keys are there on a typewriter keyboard?) and elaborated visuospatial tasks (e.g., If the rising sun is at your back, what direction will you be facing if you turn 90 degrees to your right?). EMR during spatial tasks was significantly lower than during verbal tasks. The verbal tasks varied in terms of their requirements and difficulty levels; however, there was a consistently high rate of eye movements for all four verbal tasks, with no significant inter-task differences. For example, the proverb task was significantly more difficult than the other verbal tasks, based on the percentage of correct answers, but the eye movement rate for the proverb task was equivalent with the other verbal tasks. EMR also did not differ based upon question length or syntax.

Interference Hypothesis

LEM research failed to explain the reason for differences in eye movement behavior associated with different question types. The *interference hypothesis* of ocular motility attempted to fill this theoretical gap (Glenberg et al., 1998; Lawrence, Myerson, Oonk, & Abrams, 2001; Weiner et al., 1976). The hypothesis states that when two tasks share common visual or attentional resources, there will be a reduction in eye movement. With regard to sharing visual processing resources, a spatial question may demand the use of similar resources as does processing of new visual input; therefore, there will be an aversion of gaze to limit that competing stimulus. With regard to attentional resources, questions that demand more attention, usually more difficult questions, would compete for attentional resources with new visual input processing and lead to greater gaze aversion to limit the competition.

This hypothesis assumed the presence of a limited-resource central processor dealing with both external and internal visual stimulation. Glenberg (1997) argued that, normally, individuals are “clamped” to their environment in order to avoid injury. When engaging in challenging cognitive tasks, however, this strong connection may diminish as the processing of external stimuli competes with the primary task. Singer (1978) proposed that the processor needs to “gate out” new visual input. Vying for shared resources may explain lower eye movement rates during spatial tasks, as compared with verbal tasks (Lawrence et al., 2001).

Glenberg, Schroeder, and Robertson (1998) suggested that gaze aversion has functional and practical implications, as the ability to shield one’s eyes from new visual stimulation frees the individual to better consider the problem at hand. Gaze aversion, as explained by the interference hypothesis, is related to lateral eye movement research—both are interested in the presence or absence of an eye movement. Research into the interference hypothesis, however, did not consider the direction of the eye movement and included both horizontal and vertical eye movements, as well as head movements, as demonstrations of gaze aversion (Glenberg et al., 1998).

Beattie (1978) considered the possible relationship between cognitive effort and eye movement behavior in conversation during periods of fluent and hesitant speech. Hesitant speech was assumed to indicate cognitive planning and word finding, and it was associated with more gaze aversion, looking away from the listener, than was fluent speech. Beattie suggested that, when planning speech, individuals look away in order to minimize visual input of a distracting stimulus.

Glenberg et al. (1998) hypothesized that tasks of increasing difficulty would be associated with increased gaze aversion. As difficulty level rises, there should be a greater need to reduce external visual stimulation by shifting gaze away from visually distracting stimuli. In one experiment, the researchers defined difficulty for autobiographical knowledge by the amount of time that had elapsed (e.g., What did you eat today, yesterday, and two days ago?). Gaze aversion was defined by an individual looking away from the question source, either an index card or the researcher. There was a significant increase in the proportion of gaze aversion from easier (present and recent past) to harder (more distant past) questions. In the first study, the rates of looking away were 37% and 40% of the time for the present and recent past conditions, respectively, and 50% for the more distant past condition.

A second study by Glenberg et al. (1998) attempted to replicate these findings using general knowledge questions. This time, in order to minimize the potential for a shift in gaze related to an embarrassing social situation (e.g., if the individual did not know the answer), the session was videotaped and the questions were shown on a computer screen. Glenberg et al. only scored questions that at least 70% of the subjects answered correctly, believing that questions that were too difficult would lead to avoidance and therefore would not be informative regarding the gaze aversion hypothesis. There was a significant negative correlation between question accuracy and gaze aversion; people averted their gaze more for questions answered incorrectly.

While these initial studies focused on correlations between gaze aversion and the difficulty of memory questions, Glenberg et al. (1998) were interested in how performance could be affected by manipulation of the ability to look away. They hypothesized that an inability to avert one's eyes may be associated with a decrease in performance. In order to test this hypothesis, they asked participants to either close their eyes or stare at the experimenter's nose, and found a significant difference in performance between the two conditions, with more correct answers in the eyes closed condition. The authors themselves noted the silliness of the situation and the potential confound of social embarrassment in this study. They conducted another experiment in which they presented participants with words in an episodic memory task and asked participants to fixate on a simple picture or a silent movie during the recall trial. They analyzed the middle five words of each 15-word list, to remove the potential confound of recency and primacy effects, and found a significantly higher percentage of words correctly recalled in the simple picture condition (23% in complex condition and 28% in simple condition). The authors contended that fixating on a complex stimulus, from which an individual would normally look away, led to poorer performance.

Another study that focused on gaze aversion sought to investigate potential differences between older and younger adults (Einstein, Earles, & Collins, 2002). The researchers included a list-learning task and three conditions of visual distractibility: eyes closed, eyes open and fixating on a simple cue, and eyes open and fixating on a complex visual stimulus. In addition, participants were divided into two groups based upon when they were instructed to make saccadic movements: either during the encoding or recall trials. They found that across age groups, difficulty levels of the words, and the stage of memory processing at which the gaze aversion condition occurred (encoding or retrieval), the individuals who closed their eyes recalled more words than those who were fixating on a complex stimulus. However, there was no difference in performance between the simple and complex stimulus fixation groups in the eyes open condition.

The interference hypothesis predicts that more arousing or distracting stimuli should lead to more gaze aversion; if the gaze cannot be averted, facing more distracting stimuli should lead to a decrease in performance, including longer latencies to respond. Ehrlichman (1981) tested this idea by displaying a consistent visual stimulus in front of participants—the experimenter's face (complex) or a gray oval (simple) displayed on a video screen. He asked verbal and spatial questions that were equated for the type of answers to be given: either syntactically complex responses (e.g., asked to speak for at least 20 seconds) or lists of four words. By equating the type of output required for verbal and spatial questions, Ehrlichman sought to make these two types of tasks as similar as possible. Within each condition, participants were either permitted to move their eyes freely or asked to fixate on the stimulus. Ehrlichman found no difference in the quality of responses whether participants fixated on an oval or a face, and response latency was actually shorter for those fixating on a face. In addition, there were no performance differences between the free and fixed gaze conditions.

Ehrlichman (1981) also analyzed the EOG data for eye movement rate over the question presentation, reflection, and response periods in the free eye movement condition. Participants seated in front of a face spent more time fixated on the screen during question presentation (73% of the total time) than during reflection or response (29% of the time). However, individuals seated before the oval showed equivalent high rates of eye movement across all three periods. As an alternative to the interference hypothesis, Ehrlichman suggested that under natural conditions, people would always move their eyes but were suppressing eye movements in the presence of a salient visual stimulus (i.e., the speaker's face). This is supported by the evidence that individuals show reduced eye movements when listening to a question in the presence of a face. Looking during listening may occur because the face provides visual cues to help in the comprehension of the spoken message. Otherwise, the rates of eye movement during listening, thinking, and speaking would all be high, as they were in the oval condition.

Ehrlichman and Barrett (1983) re-analyzed Ehrlichman's (1981) data to assess whether different rates of eye movements occurred for spatial and verbal questions during the reflection and response time periods, under the free eye movement condition. Verbal questions were associated with significantly higher rates of eye movements than spatial questions. There was no difference in EMR, based on the type of visual stimulus presented.

These findings suggest that eye movements occurring during reflection and response are not purely for the purpose of minimizing interference effects of external stimuli. However, it is possible that spatial questions involve processing by similar structures as those used to process new visual input and that a decrease in eye movement rate during spatial tasks would limit the amount of competition for these resources.

Ehrlichman and Barrett (1983) tested this possibility by conducting a second study in which they compared EMR for verbal and spatial questions under both light and dark conditions, using EOG. The interference hypothesis would predict equivalent rates of eye movements between spatial and verbal questions in the dark because there is no visual stimulus to compete for resources during spatial processing. (They also scored a no-task EMR for comparison.) Participants made significantly more eye movements in the light than in the dark, across conditions. Under both light and dark conditions, there was a significant difference between verbal and spatial questions. The no-task comparison eye movement rate fell in between the rates for spatial and verbal questions under lit conditions and at or below the rates for spatial tasks under dark conditions.

The discrepancy in EMR between spatial and verbal questions under dark conditions suggests that the decrease in eye movements associated with spatial questions is not due to a need to reduce visual input. In addition, the interference hypothesis does not explain the higher rates of eye movements associated with verbal tasks, compared to a no-task condition, under light conditions (Bergstrom et al., 1988).

Hiscock and Bergstrom (1981) also tested the notion of competition when they asked participants verbal and spatial questions, and included visual imagery (e.g., imagine a face) and auditory imagery (e.g., imagine the sound of escaping steam) tasks. Hiscock and Bergstrom found that verbal questions were associated with the highest rates of eye movements, followed by spatial questions. Both auditory and visual imagery tasks showed the lowest rates of eye movements, with a negligible difference between them. The low rates of eye movements associated with auditory imagery contradict the assumption of the interference hypothesis that visual imagery would be associated with low eye movement rate due to competition for shared resources. Similarly, other studies have shown that auditory vigilance tasks have low eye movement rates, equivalent to that of visual and auditory imagery (e.g., Antrobus, 1973). The interference hypothesis does not explain the differences in eye movement within a broad range of tasks, nor does it account for the possibility of an increase in eye movement rate associated with verbal tasks after the initial gaze aversion.

Arousal Hypothesis

The *arousal hypothesis* has been used to explain differences in eye movement behavior that other hypotheses could not. The arousal hypothesis predicts that with increased arousal, due to question difficulty or some emotionally arousing quality of the material, comes an increase in eye movement rate (Lorens et al., 1962). Tasks leading to high levels of arousal would have high rates of eye movements, while tasks associated with low levels of arousal would elicit a low EMR.

Antrobus (1973) recorded eye movements of individuals as they engaged in an auditory vigilance task. The task itself was associated with low rates of eye movements. The inter-trial rest periods, however, were notable for a significant increase in eye movement, in addition to an increase in gross body movement. When Antrobus (1973) asked individuals to continue to press keys during the rest period, there was less of an increase in these movements, but the effect still occurred. Eye movement and heart rate both showed a similar pattern of decreasing during vigilance task trials and increasing during inter-trial rest periods, which lent support for the arousal hypothesis.

However, research on arousal and EMR have shown equivocal results. Singer and Antrobus (1965) asked participants to generate or suppress a fantasy and found that suppression was associated with significantly more eye movements than generation, in both an eyes covered and eyes uncovered condition. There was a significant correlation between heart rate and EMR; but no significant correlation between heart rate and the imagine/suppress variable, nor was there a correlation between reported task difficulty and heart rate. This suggests the possibility of a third variable influencing the physiological cues associated with arousal and EMR. Lorens and Darrow (1962) found no significant relationship between EMR and heart rate, conductance level, EEG alpha, or galvanic skin response.

De Gennaro and Violani’s (1988) study of LEM, which included both verbal and spatial questions, found a differential impact of difficulty level on eye movements. There were significantly more eye movements associated with difficult verbal questions versus easier verbal questions. There was no effect of difficulty level on EMR for spatial questions. This suggests that while difficulty may play some role in eye movement frequency, it is moderated by other factors. For example, Bergstrom and Hiscock (1988) compared eye movement rate for verbal and spatial questions, controlling for rated difficulty level, and a significant difference in EMR remained.

Hiscock and Bergstrom (1981) asked participants verbal and spatial questions and instructed them to either provide a verbal response or formulate a response and say, “okay” instead of stating the answer aloud. EMR differences between verbal and spatial tasks remained, but regardless of the question type, EMR was higher when a full response was given. The authors suggested that speaking leads to an increase in arousal and an increase in eye movements, but that arousal cannot fully explain the difference between verbal and spatial questions and may play an independent role in the production of eye movements.

Verbal and Spatial Questions: A False Dichotomy?

The studies mentioned up to this point, consistently revealed higher rates of eye movements for some tasks as compared to others. Up until this point in the discussion, the focus has been on the dichotomy between “verbal” and “spatial” questions. However, those terms are too broad to be meaningful. Verbal tasks associated with high rates of eye movement tap into analogic reasoning, word definitions, interpretation of abstract statements, and syntactic rules. Tasks that reduce eye movements include auditory imagery and vigilance tasks, as well as visual imagery tasks. Difficulty level, the need for verbal production, stimulus complexity and illumination, and the presence or absence of imagery have no systematic impact on EMR. In addition, the use of waiting periods, in which EMR is recorded in the absence of task presentation, has revealed that eye movement at rest tends to be intermediate between these tasks. A comprehensive model of cognitive mode and eye movements is needed to explain why some tasks reduce EMR while other tasks actually increase it. The following is a review of three hypotheses: cognitive change, constraint, and long-term memory retrieval.

The Cognitive Change Hypothesis

Antrobus (1973) introduced the *cognitive change hypothesis*, which states that tasks requiring multiple sequential processes would be associated with increased EMR, while cognitive processes that require few operations would be associated with decreased EMR. The typical imagery tasks used in the body of research described above, such as imagining the Red Cross symbol and counting the number of right angles, require few mental operations, eliciting a low EMR. However, imagery questions that require increased cognitive change would be expected to be associated with higher rates of eye movement. This model can help explain findings by Antrobus et al. (1964). They asked participants to engage in certain tasks, such as generating or suppressing a wish, engaging in passive or active thinking, and imagining static or moving scenes. Active thinking was associated with significantly more eye movements than passive thought. Similarly, Andreassi (1973) found higher rates of eye movement when asking individuals to generate as many words as possible, compared with periods of rest. The findings by Lorens and Darrow (1962), that mathematical operations were associated with high eye movement rates, fit well with this model. Ehrlichman and Barrett (1983) added to that model by suggesting that high rates of sampling of operations or memory locations would lead to high EMR and constrained, or limited, memory search would elicit low rates of eye movement.

The Constraint Hypothesis

Bergstrom and Hiscock (1988) built on the idea of constraint and suggested that eye movement is part of an orienting response, modulated by the specific processing demands of the task presented. They defined constraint in terms of focused attention on a limited or broader amount of information. When attention is focused on a limited amount of information, the eyes move less; in contrast, when the individual searches through more information, eye movements are activated. Bergstrom and Hiscock suggested that these eye movements are an orienting response and not meant to search the physical environment. Most experimental spatial problems require the access of a limited store of information and are therefore associated with low EMR, but verbal questions require the access of information that is varied and inter-connected. A wider database has greater potential for searching through required information, leading to high EMR.

Bergstrom and Hiscock's (1988) study tested this hypothesis by manipulating the levels of constraint and imagery. The researchers sought to determine whether imagery was a necessary factor in low EMR. Bergstrom and Hiscock (1988) divided questions on the basis of imagery level (low, moderate, and high) and asked participants to rate each question for difficulty and imagery. Low imagery questions involved rhyming, moderate imagery questions asked for words that met certain criteria (e.g., contains four letters and starts with an “r”), and high imagery questions required internal visual representation (e.g., name two printed capital letters with two 90 degree angles). In addition, the authors manipulated the level of constraint for each type of problem. Constrained questions necessitated little memory search (e.g., how many vowels are in the word ‘intransigent’?) and unconstrained questions required extended memory search (e.g., name a five-letter word with three consonants and two vowels). In addition, they asked traditional verbal and spatial questions to permit comparison with previous studies.

Bergstrom and Hiscock (1988) found that low imagery questions were associated with significantly more eye movements than moderate and high imagery questions. Unconstrained questions were associated with significantly more eye movements than constrained questions, even after controlling for difficulty and imagery ratings. This strongly suggests that neither difficulty level nor imagery can account for differences in eye movement rates. With regard to interaction effects, in low and moderate imagery categories, unconstrained questions were associated with higher EMR than constrained questions, while constraint did not impact high imagery questions. The authors suggested that it was difficult to develop high imagery tasks that were low in constraint. This finding revealed that constraint is a more relevant factor in EMR than question type.

The constraint hypothesis, and Bergstrom and Hiscock’s (1988) data to support it, can explain much of the varied findings described up to this point. Oculomotor quiescence during imagery tasks is not due to a competition for resources but rather the level of attentional focus involved in the visual imagery tasks included in previous studies. Visuospatial and imagery questions were associated with low rates of eye movements in previous studies because the types of imagery questions required attention to a small amount of information. Verbal questions tended to elicit high rates of eye movements because these questions drew on large amounts of information and required search through a broader database. The constraint hypothesis can explain why auditory vigilance and auditory imagery were also associated with low rates of eye movements, because these tasks require the consideration of only a limited amount of information (Antrobus, 1973; Hiscock & Bergstrom, 1981; Weitzenhoffer & Brockmeier, 1970).

Long Term Memory Hypothesis

Ehrlichman, Micic, Sousa, and Zhu (2007) built upon the concept that search through a larger amount of information leads to higher rates of eye movement. However, Ehrlichman et al. explained that the variations in eye movement is not due to the orientation of attention but on long-term memory retrieval. Ehrlichman et al. based their *long-term memory hypothesis* on Baddeley's (2000) episodic buffer. The buffer is predicted to be a temporary store that integrates working memory and long-term memory retrieval processes. Ehrlichman et al. (2007) suggested that maintenance of information would be associated with visual fixation, i.e. low levels of eye movement, which occurs in tasks such as auditory vigilance. Finding and bringing information from long-term memory into the buffer, however, such as in long-term memory tasks, would be associated with increased eye movements. Tasks requiring a combination of maintenance and retrieval, such as rote memory or working memory tasks, would produce intermediate levels of eye movements. When maintenance fails, or more information is needed to complete the task, new retrieval would elicit higher rates of eye movements.

Ehrlichman et al. (2007) sought to test three hypotheses: the long-term memory hypothesis, by presenting low and high retrieval tasks, the general arousal hypothesis, by looking at difficulty level, and the interference hypothesis, by assessing imagery level. Low retrieval tasks included an auditory vigilance task, in which participants listened for specific patterns of letters within a letter string, and mental manipulation tasks, such as alphabet or number-letter sequencing tasks. The alphabet tasks involved counting all of the letters of the alphabet with specific characteristics, as described below. The high retrieval tasks included general information questions, generating words that rhymed with a target word, listing synonyms of a target word, and naming items that met certain physical characteristics. Participants were asked questions orally while being videotaped.

In order to assess the impact of difficulty on EMR, Ehrlichman et al. (2007) included easy and hard questions within each task. To investigate the impact of imagery, they manipulated visual and auditory imagery in two versions of the alphabet tasks and two versions of the category retrieval tasks, in which all factors other than the type of imagery were held constant. In the *visual* alphabet task, participants were asked to count letters that met visual specifications (e.g., letters with 3 straight lines); in the *auditory* alphabet task, participants were asked to count letters that met auditory specifications (e.g., letters with a long “A” sound). Within the category retrieval tasks, the *visual* object retrieval task required participants to retrieve objects with specific physical characteristics (e.g., objects larger than a credit card); the *auditory* word retrieval task required participants to focus on the sound characteristics of the word (e.g., rhyming). In addition, participants rated each item on difficulty and imagery level.

The difference in EMR between low and high retrieval tasks was significant: among the low retrieval tasks, EMR ranged from .14 (auditory vigilance task) to .67 (number-letter sequencing task); within the high retrieval tasks, EMR ranged from .93 (information questions) to 1.01 (synonyms). There was no significant difference among the tasks grouped as high retrieval, although they differed in task demands and imagery level. The low retrieval tasks, which included mental manipulation, working memory, and auditory vigilance, showed significant differences among tasks. Vigilance tasks elicited the lowest EMR, with a mean of .14. Both alphabet tasks elicited almost identical rates of eye movements, even though they differed significantly in their imagery requirements (M EMR auditory alphabet task = .44; M EMR visual alphabet task = .46). Finally, the number-letter sequencing task elicited the highest rate of eye movements among the low retrieval tasks (M EMR = .67). These findings corroborated the results of Bergstrom and Hiscock (1988) and suggested that imagery per se does not reduce EMR. The specific demands of the task, based on long-term memory retrieval or constraint, appear to be critical factors.

There was one primary difficulty in the first experiment by Ehrlichman et al. (2007). The long-term and working memory tasks differed in ways other than long-term memory search. The working memory tasks required participants to silently maintain their answers in mind until the end of the answer period, while the memory retrieval tasks required verbal responses throughout the answer period. In order to assess EMR and long-term memory retrieval using tasks with equivalent response requirements, a second study was conducted. The auditory vigilance task was altered to include a shadowing component, in which participants repeated each number as it was stated and pressed a clicker when one of the numbers met certain characteristics (e.g., an odd number or a number with curved lines). The alphabet task in this experiment required participants to mentally review the alphabet and state the letters which met certain criteria as they thought of them (e.g., a letter with both straight and curved lines). The memory task was an information retrieval fluency task, in which participants were given a specific category and asked to list as many exemplars as possible within ten seconds (e.g., types of sports). A rote sequencing task, such as reciting the days of the week, was added to assess the impact of automatic memory retrieval on EMR.

High retrieval tasks were associated with significantly higher rates of eye movement compared to low retrieval tasks. The long-term memory retrieval task had the highest rate of eye movements (M EMR = .89). The presence of verbal output throughout the answer period did not significantly change EMR. Reciting overlearned information was associated with a mean EMR of .53; significantly lower than the rate of eye movements during extended memory search. However, this rote memory task showed equivalent rates of eye movements with the vigilance (.38) and mental alphabet tasks (.40). Rote sequencing was rated as the easiest task, but was not significantly different in EMR from tasks rated as more difficult. Working memory and rote sequencing tasks showed a mean EMR of .44, supporting the idea that a task requiring minimal retrieval and maintenance of the information will be associated with an intermediate EMR. Searching long-term memory, however, activates eye movements. This study reinforced the notion of memory search as a primary factor in changes in EMR (De Gennaro et al., 1988).

The studies up to this point investigated semantic memory search, that is, search of general knowledge. In a third experiment, Ehrlichman et al. (2007) sought to extend the findings to autobiographical memory as well. In addition, in order to evaluate the effects of working memory on eye movements, two additional working memory tasks were included. These were a delayed repetition task, in which participants were asked to repeat three or five words after an eight-second delay, and a phrase counting task, in which participants were asked to count the number of letters with specific attributes within a three-word phrase (e.g., the number of vowels). This study replicated the previous ones with its use of low and high retrieval tasks. The low retrieval tasks included a continuous performance (auditory vigilance) task, mental alphabet tasks, and a simple counting task. The high retrieval tasks were the semantic word retrieval task from experiment one and an autobiographical memory task. Rote memory was included as well. Additionally, there were "eyes open" and "eyes closed" conditions to investigate whether the pattern of EMR between low and high retrieval tasks occurs in the absence of visual stimulation.

In the eyes open condition, the semantic and episodic memory tasks, both labeled high retrieval, had almost identical mean EMR (M EMR = 1.40 and 1.41, respectively), and these rates were significantly higher than the low retrieval tasks. The low retrieval tasks did not differ significantly from one another, except for the counting task, which elicited a lower eye movement rate than the delayed repetition task (M counting EMR = .46; M delayed repetition EMR = .89). Within the tasks termed working memory, an increase in difficulty was not associated with a significant increase in EMR. For example, delayed repetition of a five-word phrase was rated as significantly more difficult than the repetition of the three-word phrases, but they had a similar EMR (.92 for 3-word and .84 for 5-word). A no-task waiting period was scored for each participant (M EMR = .95), and this rate fell in between the EMR for high retrieval and low retrieval tasks.

In the eyes closed condition, the inter-rater reliability was low (r = .47), as scoring eye movements that had been videotaped with the participant's eyes closed (i.e., under the eyelids) was a challenging task for the raters. Nevertheless, a significant task effect was found, although the only significant difference between individual tasks was between the counting task (M EMR = .27) and the semantic memory task (M EMR= .45).

Ehrlichman et al. (2007) systematically investigated the potential impact of difficulty and imagery on EMR, but they found no significant relationship. Within and between tasks, difficulty did not play a significant role, and tasks with identical requirements except for the role of imagery did not differ in EMR. The effect sizes found in their studies were very large, with eta squared ranging from .74 to .83. These findings corroborate earlier research suggesting that neither the interference hypothesis nor the arousal hypothesis can adequately explain the full range of findings in EMR research (Bergstrom et al., 1988; Ehrlichman & Barrett, 1983; Weiner et al., 1976). The only consistent factor in EMR was long-term memory retrieval. Ehrlichman et al (2007) proposed a model that links maintenance and retrieval processes with eye movements because searching within memory may use the same neural circuitry as searching for visual information.

Rationale and Goals

The present study built on the long-term memory and constraint hypotheses. In the study conducted by Ehrlichman et al. (2007), three clusters of tasks were found. The top cluster, including tasks with the highest EMR, was comprised of long-term memory retrieval tasks. The middle cluster, including tasks with an intermediate level of EMR, was made up of working memory and rote memory tasks. The lowest cluster, with the lowest EMR, included an auditory vigilance task. The distinction between the rote memory and other long-term memory retrieval tasks seemed arbitrary. Both are essentially long-term memory retrieval tasks. However, rote memory tasks involve almost automatic retrieval of the information, such as the days of the week. In contrast, the other long-term memory tasks included in the study involved more active search processes. That study demonstrated that active and automatic search processes have different impacts on EMR. However, the tasks presented in the Ehrlichman study were very different from each other. The present study sought to determine whether a significant difference in eye movement rate would be found between highly similar tasks in which the one difference was the accessibility of the to-be-retrieved information. More accessible information was expected to be associated with relatively lower rates of eye movement compared to less accessible information. Memory search was predicted to serve as a corollary to visual search. Increased search was expected to lead to higher rates of eye movement, while decreased search was predicted to lead to lower rates of eye movement. No previous research had examined the influence of accessibility within long-term memory retrieval on EMR.

There were two main assumptions made to develop this study. One, long term memory is primarily organized through a series of meaningful connections. A search for information which relied upon these semantic connections was expected to be more easily accessible. In contrast, a search for information based upon more peripheral or superficial elements of the information would be more difficult to access. Two, it is possible to manipulate the encoding of information such that the accessibility of the information at retrieval is impacted.

Based upon the above rationale and assumptions, there were three goals of this research. The first was to explore whether EMR is directly related to ease of access for material stored in long-term memory. The second was to examine whether newly learned information would show high EMR, similar to that found for autobiographical and semantic LTM search. Previous research had focused on previously learned information. A main focus of this study was the impact of an encoding manipulation on subsequent retrieval and therefore on eye movement rate at retrieval. The third was to introduce a working memory task that permitted systematic exploration of EMR at different levels of difficulty. Previous studies did not use a traditional working memory task that allowed a stepwise increase in task difficulty to examine the relationship between difficulty level and EMR within a working memory task.

General Hypotheses

The study hypotheses can be broken down into general and specific hypotheses. There are three general hypotheses. One, both episodic and semantic LTM search would be associated with high EMR compared to working memory and rote memory tasks. The present study sought to confirm previous findings regarding the dichotomy between long-term memory and working memory / rote memory tasks and extend this relationship to newly learned episodic memory tasks. Two, EMR was expected to vary within a long-term memory task as a function of accessibility. This was termed the *accessibility hypothesis*. Greater accessibility of the information within long-term memory was expected to elicit significantly lower EMR compared to lesser accessibility. Accessibility was defined by the type of information to be retrieved or the type of cue used to the retrieve the information. Three, difficulty level should not be significantly related to EMR. The working memory task in this case served as a control for difficulty. The harder working memory condition should not produce significantly higher EMR than the easier working memory condition because difficulty alone should not impact EMR. There needs to be a long-term memory search component for EMR to change.

Task Hypotheses

Levels of Processing. In order to manipulate accessibility of information based on processing during encoding, the *levels of processing* paradigm was used in the present study (Craik & Lockhart, 1972). In this paradigm, semantic processing leads to a retrieval benefit compared to structural encoding. The benefits of semantic processing at the encoding phase may be related to the nature of memory representation (Craik, 2002). Higher level representations of information are more interconnected and networked with basic perceptual information about the word (Schacter, Norman, & Koutstaal, 1998; Schacter et al., 1998; Walla et al., 2001). Greater connectivity may lead to more access routes for retrieval, leading in turn to superior recall. This study utilized this hypothesized relationship between semantic encoding and increased accessibility of the information at retrieval to test whether increased memory accessibility was related to lower rates of eye movements, compared with reduced accessibility.

Information was processed on a shallow level (e.g., phonemic and structural processing, such as, “Are there any r’s in this word?”) or on a deep level (e.g., semantic processing, such as, “Is this word a living thing?”). The nature of the initial processing determines the nature of the encoded trace. Research has consistently found that more words are recalled after deep processing, as compared to shallow processing (Craik, 2002).

The standard levels of processing approach included yes / no responses at encoding, therefore, only EMR at retrieval could be scored. It was hypothesized that information that had been processed on a deep level at encoding would be more accessible at retrieval, leading to relatively lower EMR at retrieval. Information that was processed on a shallow level at encoding was expected to be less accessible at retrieval, leading to relatively higher EMR at retrieval.

One levels of processing paradigm implemented in this study used a generative approach at encoding, that is, the individual was asked to produce a response (e.g., spell the target word or construct a sentence using the target word). In that case, there was the opportunity to score both EMR at encoding and at retrieval. The retrieval hypothesis was the same as above. However, at encoding, it was predicted that deeply encoded words would be associated with significant higher rates of eye movement compared to words encoded on a shallow level. This was expected because accessing semantic memory in order to produce deep encoding requires an active search through memory. In contrast, encoding words on a shallow level, such as spelling, requires almost automatic access of the information, and is a more accessible task.

Fluency Tasks. In order to test the accessibility hypothesis on previously learned information, category and phonemic fluency tasks were used. In fluency tasks, a category (e.g., supermarket items) or phonemic (e.g., words starting with the letter ‘s’) cue is provided and the participant is asked to generate as many words as possible using that cue. It is well established that among non-clinical populations, phonemic cues lead to fewer generated words than semantic cues (Gladsjo et al., 1999; Harrison, Buxton, Husain, & Wise, 2000)**.** Word retrieval using object categories as retrieval cues are likely to activate a semantic system of knowledge about the object. When letters are used as cues, however, the individual must form a novel, non-semantically associated category, and the word generation requires more effort (Martin, Wiggs, Lalonde, & Mack, 1994).

The between task hypothesis expected significantly higher EMR during retrieval based upon a phonemic cue compared to EMR during retrieval using a category cue. Retrieval based upon category information was expected to be more easily accessible than retrieval based upon peripheral cueing. There was an additional within-task hypothesis. Over the 60-second fluency trial, it was expected that as time progressed under both fluency conditions, the task would become steadily less accessible. It was therefore expected that under both conditions, the first 15-second interval would show significantly lower rates of EMR than the last 15-second interval of the fluency tasks.

Working Memory Task. Working memory is the system necessary for the concurrent storage and manipulation of information; it is thought to contain the phonological loop, visuospatial sketchpad, and central executive (Baddeley, 1992). The phonological loop stores acoustic and speech information for one to two seconds and has an articulatory control process akin to self-speech, which helps maintain the information for longer periods of time through repetition (Baddeley, 1992). According to Ragland et al. (2002), the n-back task is a working memory task which has been shown in fMRI studies to be a suitable tool for the detection of working memory load. Within the n-back task, the stimulus presentation at different load levels is constant and the number of items to be kept in mind varies only according to the task instructions, leading to an increase in difficulty level. In the present study, the n-back task served as a control for difficulty. It was hypothesized that as difficulty increased within this working memory task, EMR would remain unchanged.

General Summary and Goals

Building on the long-term memory retrieval and constraint hypotheses, this study sought to investigate the relationship between the extent of memory search and EMR within long-term memory tasks. If, as these hypotheses assert, tasks that require less extensive memory search are associated with lower rates of eye movement than tasks involving more extensive memory search, which elicit higher EMR, then the model should hold true within a long-term memory task. While previous research relied on established information, this study sought to manipulate the accessibility of the information to be recalled by systematically varying the type of processing at encoding, using a levels of processing paradigm (Craik et al., 1972; Craik & Tulving, 1975).

In addition to manipulating the encoding of information, thereby influencing the level of accessibility of the information at recall, this study also included semantic memory tasks. These tasks represent a range on the spectrum of memory accessibility. A category fluency task, for example, which elicits information based upon connectivity of semantic nodes, was expected to be more accessible and, therefore, associated with a lower EMR than a phonemic fluency task. These tasks also provided an opportunity to assess EMR changes over the course of the participants' response within each task. It is hypothesized that as a function of time, increasingly effortful search is required to find more words towards the end of the one-minute period of the fluency task. Therefore, within each fluency task, an increase in EMR from the first 15 seconds to the last 15 seconds of the task was expected. Finally, while difficulty (independent of LTM accessibility) has been repeatedly found not to show any systematic impact on eye movement rate, it has not been adequately assessed within a working memory task. Therefore, an n-back task with increasing difficulty levels was included as a control for difficulty.

Methods

Participants

Forty-five students recruited from introductory psychology courses participated to fulfill a course requirement. Data from six participants were lost for technical reasons. Data from seven participants were not included in the main analyses because they did not meet inclusionary criteria (described below). The final sample of 32 participants consisted of 22 women and 10 men. Ages ranged from 18 to 39, with a mean age of 20.8 years. Table 1 lists demographic variable information. The central premise, that accessibility impacts EMR, was tested using the levels of processing paradigm. Therefore, the presence of a positive level of processing effect, that is, a higher number of deeply encoded words recalled compared to structurally encoded words, was an *a priori* criterion for inclusion in this study. Other inclusion criteria were classification as a native English speaker, ability to complete the tasks, and a minimum of 18 years of age.

Table 1

Demographic Frequencies

		Included Participants	Excluded Participants
N		32	7
Gender			
	Male	10 (31.2%)	4 (57.1%)
	Female	22 (68.8%)	3 (42.9%)
Handedness			
	Right	31 (96.9%)	6 (85.7%)
	Left	1 (3.1%)	1 (14.3%)
Race/Ethnicity			
	Caucasian	22 (68.8%)	3 (42.9%)
	African-American	4 (12.5%)	1 (14.3%)
	Hispanic	3 (9.4%)	0
	Asian	1 (3.1%)	1 (14.3%)
	Other	2 (6.3%)	2 (28.6%)
Bilingual			
	Yes	8 (25%)	unknown
	No	24 (75%)	unknown

Tasks

The current study comprised long-term memory retrieval tasks, including episodic memory and semantic memory tasks, working memory tasks, filler tasks, and a rote sequencing task.

Episodic Memory Task. The episodic memory tasks were two list-learning tasks that used a levels of processing (LOP) paradigm with two levels of processing: deep and shallow. Shallow encoding required the processing of information based upon perceptual features, and deep encoding required the processing of information based upon semantic categories. One list-learning task used a standard procedure for levels of processing studies. In the shallow condition, participants were asked yes/no questions such as, “Are there any r’s in this word?” or “If you imagine the word to be written in lower case, would any of the letters dip below the line?” These questions utilized for shallow encoding used phonemic and imagery information, both of which have been shown to produce superficial encoding. In the deep encoding condition, the yes/no questions were: “Is this word a living thing?” or “Is this word pleasant?” These questions reflected semantically based processing. Four lists of 12 words each were presented in blocks, and the entire block was encoded either at a deep or shallow level. This protocol of presenting words as blocks was found to produce an overall significant levels of processing effect in a pilot study.

The 12-item word lists were drawn from six 80-item word lists developed by Johnson, Kreiter, Russo, and Zhu (1998). The words were four to seven letters in length, and the lists were equivalent in overall word frequency. Within each word list, half of the words were living things, and half were pleasant, in order to meet the needs of the deep processing questions; half of the words contained an “r” and half of the words dipped below the line, in order to meet the shallow encoding question requirements.

The other list-learning task used a novel, generative level of processing paradigm, in which participants were asked to produce more extended answers. This procedure was designed to gather eye movement rate data during encoding as well as retrieval. There were two levels of processing: deep and shallow. In this case, deep processing involved sentence generation and shallow processing involved spelling. Sentence generation has been used in other levels of processing studies to produce a deep level of encoding. Spelling was considered to primarily activate phonemic information and was therefore used as the shallow encoding task. Two lists of 17 words each were presented for processing at a deep or shallow level. These words lists were taken from Ragland et al. (2003) with permission from the authors.

See appendix A for all six word lists.

Semantic Memory. The semantic memory tasks were fluency tasks, which used phonemic or category cueing. Phonemic fluency required participants to generate as many words as possible that started with the letter “s” within 60 seconds, and semantic fluency involved generating supermarket items within 60 seconds. The supermarket fluency task was expected to be relatively accessible because of the strong category cue as well as the constrained nature of the question.

Working Memory Task. The working memory task was an n-back task with two levels: one-back and two-back. Letters were presented over an audiotape at a rate of one letter every 1.9 seconds. The total number of letters in a series was 65 for a total trial time of 125 seconds. In the one-back task, any time a letter was stated twice in a row, the participant was instructed to press on a clicker (e.g., R R). In the two-back task, the participant was instructed to click when a letter was heard twice with only one intervening letter (e.g., B S B). Performance on this task was assessed by calculating a discriminability quotient, which takes into account true positive and false alarm rates (Ragland et al., 2002).

Rote Sequencing. Rote sequencing included overlearned information: counting backward from 20 to one, reciting the alphabet, and listing the days of the week and the months of the year.

Filler Tasks. Filler tasks were used during rest periods between list learning tasks in order to break the uniformity of list learning. The filler tasks included the Digit Span, Information, and Letter-Number Sequencing subtests of the WAIS-III (Wechsler Adult Intelligence Scale – Third Edition). Visual tasks administered during a 10-minute rest period were the Trail Making Tests A and B as well as the Coding and Symbol Search subtests of the WAIS-III.

Procedure

Informed consent was obtained for each participant. To account for the use of video recording, the study was described as an investigation of facial expressions occurring when people are engaged in various tasks. No mention was made of eyes or eye movements. Sample items from the individual tasks were provided for practice. After the participant demonstrated adequate understanding of the tasks, the experiment began. The experiment took 80 minutes to complete and participants were tested individually. The order of the task presentation remained constant. The standard LOP task was partially counterbalanced with a Latin Square such that each list was presented at each of the four positions. In addition, for one half of participants, the first list was processed semantically, and for the other half of participants, the first list was processed structurally. This produced eight cells. The order of the two fluency tasks was counterbalanced, as was the order of the two levels and the two lists within the generative LOP task.

The experiment took place in two adjacent rooms. Participants were videotaped using a camcorder. The video camera captured the participant's face and that image was projected to a monitor in the adjacent room. In the video room, the participant was seated approximately 6 feet from the camcorder in a mostly bare room with the walls draped in white sheets to minimize visual distraction and provide high levels of reflectance. The video camera and speakers were visible to participants. Floor and ceiling lighting were turned on to achieve uniform levels of illumination throughout the room. In order to record eye movements in the absence of changing visual stimulation, all tasks within the video room were presented auditorily.

Task presentation began with a standard LOP list-learning trial (see Table 2). Half the participants began with a deep encoding list and half with a shallow encoding list. The procedure was for the experimenter to ask a question (e.g., "Are there any r's in this word?" or "Is this word pleasant?"), state a word, and wait for the participant to answer yes or no to the question. A question was asked before each word (e.g., "is this word pleasant: needle"). For each block of words, either the two "shallow" questions or the two "deep" questions were asked, as described above. Questions were semi-randomly assigned to the words, such that there was an equivalent number of yes and no responses within a block of trials. Answers were written down by the experimenter and eye movements were recorded by the video camera. Participants were notified before each block of words that there would be a test after the list learning condition.

Table 2

Study Procedure

Task	Order
Levels of Processing List I	1
Digit Span task (WAIS-III)	2
Levels of Processing List II	3
n-back task	4
Levels of Processing List III	5
Information questions (WAIS-III)	6
Levels of Processing List IV	7
10-Minute Break	
Generative Levels of Processing I	8
Letter-Number Sequencing (WAIS-III)	9
Rote Sequencing task	10
Generative Levels of Processing II	11
Verbal Fluency task	12

* The standard LOP lists were counterbalanced using a Latin Square, such that each word list occurred once at each of the four list positions. Also, the level of processing proceeded as: Deep – shallow – deep – shallow or Shallow – deep – shallow – deep.

After the encoding phase of each list, there was a 60-second distracter task (count backward by threes) followed by a free recall test. After each free recall trial, there were five minutes of intervening tasks, followed by another block of 12 words to be processed using the standard LOP procedure. The order of tasks during the five minute periods between word list presentation was standard: Digit Span forward and backward tasks between the first and second lists, the n-back tasks between the second and third lists, and Information questions between the third and fourth lists.

After all four standard levels of processing lists were presented, as well as the tasks included between the lists, the participant was taken out of the video room into a third room for a 10-minute break from the encoding and retrieval trials, during which time visual paper and pencil tasks were administered.

After the 10-minute break, the participant returned to the video room. The two generative LOP lists were presented, with 17 words in each list, to be processed at a shallow (spelling) or deep (generate a sentence) level. After the list encoding was completed, a 60 second distractor task (counting backwards by fours) was administered, followed by a free recall test. The two word lists were separated by five minutes of tasks (Letter-Number Sequencing and Rote Sequencing). After the completion of the free recall trial for the second generative level of processing list, phonemic and category fluency tasks were presented. Answers were manually recorded with notations made at the 15, 30, 45, and 60 second marks. Participants were debriefed at the conclusion of the experiment about its purpose.

Assessing Eye Movement Rate (EMR)

Eye movements were scored using software specifically developed for EMR research. Video mpeg files were loaded into a program that permitted observers to alter the speed and size of the image. In the first phase of scoring, the observer marked the end of the question and answer periods for each item. When participants did not give complete answers, the end of the answer period was determined by other cues (e.g., “I don’t remember”). In the second phase, the program continuously played through the marked segments at one-third to one-half speed, depending on the speed of eye movements by the participants. The size of the participant’s face was increased to between 170% and 250% of its original size in order to achieve an equivalent pupil diameter of 1.2 centimeters for all participants. Whenever an eye movement was detected, the observer pressed a key and the eye movement was marked in a visual display saved in a log file that provided a record of the session. The observer marked only unambiguous saccadic eye movement, that is, eye movements that were at least 3 degrees and which moved the fovea to a new position.

EMR was computed for each trial by dividing the number of eye movements by the number of seconds from the end of the question to the end of the answer period. Reliability was initially examined by correlating EMR scores produced by two independent observers for four randomly selected participants. Correlations were computed over the total set of items resulting in correlations ranging from .85 to .92, with an average $r = .89$.

Data Analysis

Repeated-measures analyses of variance (ANOVA) were conducted using the SPSS-12.0 GLM procedure. These analyses were conducted, instead of an Omnibus MANOVA, because the analyses presented here were hypothesis-driven. The dependent measures were eye movement rate and performance. Frequent violations of the sphericity assumption occurred, therefore, the multivariate approach was used and all *F*-values were based on Pillai's Trace with the effect size expressed as partial η^2. Bonferroni adjusted pairwise comparisons were computed between tasks. Paired t-tests were used to compare overall means for the easier and harder or more accessible and less accessible components of the tasks. Performance on the memory and working memory tasks served as manipulation checks for the LOP and n-back conditions.

Results

Performance

Mean performance and EMR data for all tasks are presented in Table 3.

Table 3

Mean performance, EMR, and time data for all tasks.

Task	Performance (sd)	EMR (sd)	Time in seconds (sd)
Overall EMR		0.98 (0.44)	
LOP: Deep Recall[a]	12.03 (2.67)	1.17 (0.53)	36.21 (12.02)
LOP: Shallow Recall[a]	8.03 (2.85)	1.19 (0.48)	30.61 (12.16)
One-Back[b]	0.90 (0.02)	0.45 (0.45)	38.31 (0.63)
Two-Back[b]	0.82 (0.11)	0.44 (0.42)	38.11 (0.52)
Spelling Encoding		0.64 (0.52)	3.00 (0.76)
Spelling Recall[a]	6.32 (2.21)	1.08 (0.42)	36.85 (14.33)
Sentence Encoding		1.08 (0.42)	5.51 (1.71)
Sentence Recall[a]	5.74 (2.10)	1.10 (0.48)	44.22 (17.87)
ABC		0.61 (0.51)	14.03 (5.44)
Counting Backwards		0.57 (0.53)	13.97 (4.20)
Days of week		0.59 (0.57)	5.11 (1.08)
Months of year		0.65 (0.60)	8.28 (3.09)

Table 3 continued

Task	Performance (sd)	EMR (sd)	Time in seconds (sd)
Letter-Number Sequencing			
First trials		0.69 (0.45)	18.08 (4.17)
Last trials		0.79 (0.55)	47.09 (17.37)
Digit Span Backwards			
First trials		0.67 (0.61)	9.01 (2.31)
Last trials		0.77 (0.51)	31.90 (13.40)
Supermarket Fluency			
Time 1^c	9.91 (2.61)	0.88 (0.59)	15.18 (0.38)
Time 2^c	7.31 (1.57)	0.85 (0.55)	14.63 (0.22)
Time 3^c	5.16 (2.29)	0.92 (0.53)	14.72 (0.28)
Time 4^c	4.50 (2.75)	1.08 (0.62)	14.72 (0.32)
S word Fluency			
Time 1^c	6.91 (1.82)	1.05 (0.62)	15.23 (0.34)
Time 2^c	4.34 (1.82)	1.04 (0.56)	14.67 (0.23)
Time 3^c	3.53 (1.74)	1.10 (0.58)	14.63 (0.28)
Time 4^c	3.31 (1.51)	1.17 (0.63)	14.73 (0.24)

Note. Variables with different superscript letters reflect the following performance data: ^{a} = mean number of items correctly recalled, ^{b} = mean Pr (discriminability score), ^{c} = mean number of words generated.

Level of Processing. Given that only participants who showed an LOP effect were included in the data analyses, it is not surprising that there was a significant effect on performance for the standard LOP task, t (31) = 9.14, $p < .0005$. The dependent variable was the number of words retrieved under each condition of the levels of processing task and the independent measure was the level of processing condition: deep or shallow.

Fluency. Table 4 presents the performance and EMR results for the combined fluency tasks. Performance on the category and phonemic fluency tasks was analyzed using a 2 (Fluency Task) x 4 (15-second time periods) repeated-measures ANOVA. There were significant main effects for Fluency Task: F (1, 31) = 45.44, $p < .0005$, $\eta^2 = .59$ and Time: F (3, 29) = 56.99, $p < .0005$, $\eta^2 = .86$. The dependent variable was the number of words generated and the independent variables were the type of fluency task and four 15-second time intervals. Across fluency task, the number of words generated in the first 15-second quartile was significantly higher than any other quartile and the number of words generated in the second quartile was greater than the last 2 quartiles. There was no difference in performance between the third and fourth quartiles. There was also a significant interaction effect between Fluency Task and Time: F (3, 29) = 5.42, $p < .005$, $\eta^2 = .36$. The significant interaction reveals that the trend for the earlier quartiles to show a significantly greater number of generated words was more pronounced for the category fluency compared to phonemic fluency task.

Table 4

Mean EMR and Performance across task and quartile, with confidence intervals and r values for a partial correlation (controlling for overall mean EMR) between EMR and performance.

Tasks	EMR	95% CI	Performance	95% CI	r
Fluency Task (over time)					
Category Fluency	0.93	0.75 – 1.11	26.88	6.11 – 7.32	r = -.38*
Phonemic Fluency	1.09	0.90 – 1.29	18.09	4.07 – 4.98	r = -.02
Time (over fluency task)					
Quartile 1^{a}	0.96	0.77 – 1.16	8.41	7.75 – 9.06	
Quartile 2^{a}	0.95	0.77 – 1.12	5.83	5.38 – 6.28	
Quartile $3^{a,b}$	1.01	0.83 – 1.18	4.34	3.78 – 4.91	
Quartile $4^{b,c}$	1.13	0.94 – 1.32	3.91	3.32 – 4.50	

Note. Variables with different superscript letters were significantly different at the $p < .05$ level.

* indicates a significant correlation at the $p < .05$ level.

N-back task. Each n-back task presentation was over two minutes in length due to the need to fill a five-minute time gap between lists. However, n-back tasks are often approximately 30-45 seconds in length (Andrews J., Wang L., Czernansky J.G., Gado M.H., & Barch D.M., 2006; Ragland et al., 2002); therefore, the first 38 seconds of the n-back task were scored for performance and EMR. The two-back task was significantly more difficult, evidenced by a lower discriminability (Pr) score, than the one-back task: t (31) = 3.95, $p < .0005$. The dependent measure was the discriminability score, and the independent measure was the n-back condition.

Generative LOP task. A secondary episodic memory task, the generative LOP task, was expected to yield a significant levels of processing effect; however, no significant LOP effect was found: t (31) = -1.31, $p = .20$. The dependent measure was the number of words recalled and the independent measure was the level of processing retrieval condition: deep or shallow.

Eye Movement Rate

Mean EMR across all main task items was .98, with a standard deviation of .44 and a range from .15 to 1.88. The dependent measure in the following section is EMR for all analyses presented.

Extension of previous findings

The first goal was to see whether the long-term memory conditions differed from the working memory condition. A repeated measures ANOVA was conducted to compare the three main tasks: episodic memory (standard LOP), semantic memory (verbal fluency), and working memory (n-back). EMR for the two components of each task was collapsed into one variable per task in order to compare the tasks overall. There was a significant effect of Task, F (2, 30) = 78.03, $p < .0005$, $\eta^2 = .84$. The dependent variable was EMR, and independent variables were the episodic, semantic, and working memory tasks. This pattern and effect size is similar to that found by Ehrlichman et al. (2007). Table 5 presents the tasks in order of EMR. All tasks differed from each other.

Table 5

Mean EMR for the main tasks collapsed over two levels.

Tasks	EMR (sd)	95% Confidence Interval
N-Back	0.44 (0.41)	0.31 – 0.59
Fluency	1.01 (0.47)	0.84 – 1.18
Standard LOP: Recall	1.17 (0.48)	0.97 – 1.34

Note. All tasks differed from each other at the $p < .0005$ level.

Within-task comparisons

The second goal of this study was to test whether systematic variations in accessibility within long-term memory retrieval tasks would be associated with differences in EMR. In contrast, changes in difficulty level in a working memory task were not expected to yield differences in EMR. EMR for the tasks broken down by levels can be seen in Table 3.

EMR for the two levels of the standard LOP task, deep and shallow, was analyzed using a t-test. Contrary to prediction, there was no significant difference in EMR at free recall between the deep and shallow conditions: t (31) = -.84, p = .41.

A t-test was also conducted to compare the two levels of accessibility within the fluency task: category and phonemic fluency. EMR in this analysis was summed over the 60-second time period. There was a significant difference in EMR between less accessible (phonemic fluency generation) and more accessible (category fluency generation) memory retrieval, with phonemic fluency showing significantly higher EMR compared to category fluency: t (31) = -2.05, p < .05.

The n-back working memory task also had two levels, an easier and a harder level. As expected, there was no difference in EMR between the one-back and two-back tasks: t (31) = .21, p = .84.

Time segments for fluency tasks. In addition to an expectation of differences in EMR between the category and phonemic fluency tasks overall, EMR was predicted to increase over time for both tasks. Table 3 shows performance and EMR for fluency tasks over each quartile.

As described above, the number of words generated decreased from the first to the last 15-second quartile, hypothesized to reflect a decrease in accessibility of the information over time. A 2 (fluency task) x 4 (15-second quartiles) repeated measures ANOVA was conducted using EMR as the dependent measure. There was a significant main effect of Fluency Task type, $F\ (1, 31) = 4.20$, $p < .05$, consistent with the t-test described above (see Table 4). There was also a significant main effect of Time, $F\ (3, 29) = 4.86$, $p < .01$. A significant linear trend was found for Time: $F\ (1,31) = 9.02$, $p = .005$, $\eta^2 = .23$. Pairwise comparisons revealed that EMR in the last quartile was significantly higher than that of the first two quartiles, which were equivalent. There was no significant interaction between Fluency Task and Time, $F\ (3, 29) = .26$, $p = .86$.

Between Subjects Analyses Between Fluency Task EMR and Performance

Between subjects analyses were conducted to assess the relationship between EMR and performance over time. To date, there is no empirical support that individual differences in EMR are related to individual differences in performance. Correlations were computed between the participants' average EMR and their average performance for each fluency task.

Using the mean EMR and performance data, between-subjects partial correlations were computed between EMR (controlling for each participant's overall mean EMR) and performance for each fluency task (see table 4). There was a significant negative correlation between EMR and performance for category fluency ($r = -.38$, $p < .05$), such that participants with lower category fluency performance showed higher EMR (when controlling for their mean levels of EMR) than participants with higher category fluency performance. This pattern was not significant for phonemic fluency ($r = -.02$, $p = .90$).

Secondary Hypotheses

Generative levels of processing task. As reported earlier, the encoding manipulations of sentence generation and spelling did not produce a levels of processing effect on performance. However, EMR during the encoding phase of the two types of tasks differed greatly, t (30) = -3.84, $p < .005$. In contrast, EMR during recall did not differ between words that had been encoded either semantically or structurally: t (30) = -.43, $p = .67$. A repeated measures ANOVA was conducted to compare each of the four conditions: spelling encoding, spelling recall, sentence encoding, and sentence recall. EMR associated with spelling words at encoding was significantly lower than that of sentence encoding or the two recall conditions: F (3, 28) = 6.80, $p < .005$, $\eta^2 = .42$.

Initial gaze shifts during LOP list encoding. The standard LOP task used a yes or no question format at encoding, making the use of EMR difficult because of the short latency of the response. In order to look at the role of eye movements during encoding, a lateral eye movement scoring approach was utilized. Whenever the participant was looking straight at the camera during question presentation, any saccadic eye movement away from the camera, in any direction, was noted. A t-test conducted to compare the number of initial eye movements recorded from the deep and shallow encoding conditions was not significant (M deep = 10.19; M shallow = 10.19).

Rote sequencing. Rote sequencing tasks were included in the study to corroborate previous findings that rote sequencing is associated with significantly lower rates of eye movements than long-term retrieval tasks that require extended search. An overall repeated measures ANOVA was conducted with the episodic memory, semantic memory, rote sequencing, and working memory tasks. There was a significant effect of Task, F (3,

29) = 50.56, $p < .0005$, $\eta^2 = .84$. Rote sequencing and the n-back task showed equivalent levels of EMR, both of which were significantly lower than either long-term memory retrieval task (see Table 3).

Digit span backward and letter-number sequencing. Two working memory filler tasks, digit span backward and letter-number sequencing, were analyzed as part of a secondary analysis. In order to divide each task into an easier and a harder condition, mean EMR scores were computed for the first and last four trials of the digit span backward task, and the first and last six trials of the letter-number sequencing task. The number of trials was determined by the structure of the task. In the case of digit span backward, each trial is made up of two turns; in the case of the letter-number sequencing task, each trial is comprised of three turns. The number of digits in the first trials was always two and three digits. The number of digits in the last trials varied based upon the performance of the individual, with a range between four and seven digits. It was expected that the easier and harder conditions would not be significantly different in EMR. Twenty-eight participants completed enough trials of each task to be included in this secondary analysis for letter-number sequencing; all 32 participants were included for digit span backward. A repeated measures ANOVA was conducted including 4 variables (two for digit span and two for letter-number sequencing) to compare the easy and hard components of these tasks. No significant main effect was found: F (3, 25) = .64, $p = .60$. This supports the earlier findings that an increase in difficulty within a working memory task does not lead to an increase in EMR.

*Analyses across all task*s. To compare all tasks, an overall repeated measures ANOVA was conducted. As described above, the two levels of each task (episodic memory, semantic memory, and working memory) were analyzed to determine significant differences. Any tasks in which the two levels did not differ significantly were collapsed into one mean EMR for the task, specifically the n-back, rote sequencing, digit span backward, standard LOP, and generative LOP recall tasks. For tasks in which the two levels were significantly different from each other, each level was included as a separate variable. These tasks were supermarket fluency, s word fluency, spelling encoding, and sentence encoding. (Because letter-number sequencing only had 28 participants, and letter-number sequencing did not differ from digit span backwards in EMR, the letter-number sequencing task was removed from the analysis, leaving 9 variables with 31 participants in the analysis.) The dependent measure was EMR. There was a significant effect of Task, F (8, 23) = 23.55, $p < .0005$, $\eta^2 = .89$. In order to produce clusters of tasks, each task was compared to the task with the next highest EMR. When there was a significant difference between the tasks ordered in sequence according to EMR, a "break" was inserted. In Table 6, these breaks are represented as spaces, resulting in three clusters of tasks. The n-back was associated with the lowest EMR. Rote sequencing, spelling encoding, and digit span backward tasks were associated with intermediate levels of EMR and were not significantly different from one another. The long-term memory retrieval tasks, including sentence encoding, were associated with the highest EMR. Standard LOP recall differed from all other retrieval tasks aside from s word fluency.

Table 6

Mean EMR for 10 variables submitted to an overall repeated measures ANOVA

Tasks	Mean EMR (sd)	n
n-back[a]	0.44 (0.41)	32
Rote Sequencing[b]	0.60 (0.48)	31
Generative LOP: Spelling Encoding[b]	0.64 (0.52)	31
Digit Span Backward[b]	0.72 (0.49)	32
Letter-Number Sequencing[b]	0.74 (0.46)	28
Supermarket Fluency[c]	0.93 (0.50)	32
Generative LOP: Sentence Encoding[c]	1.00 (0.49)	31
Generation LOP: Recall[c]	1.10 (0.43)	31
S Word Fluency[c,d]	1.09 (0.54)	32
Standard LOP: Recall[d]	1.17 (0.48)	32

Note. Variables with different superscripts were significantly different at the $p < .05$ level.

Gender and Bilingualism

The role of gender in EMR for long-term and working memory tasks has not been reported in previous research. Gender influences many aspects of cognition, and it was therefore considered in a secondary analysis. The present study included 10 males and 22 females. The main overall repeated measures ANOVA was conducted a second time using gender as a between subjects factor. The significant main effect of Task remained, F (2, 29) = 63.27, $p < .0005$; $\eta^2 = .81$, but there was no significant main effect for gender and no significant interaction between Task and Gender, F (2, 29) = .26, $p = .77$.

In experiment 3 of Ehrlichman et al. (2007), a sample of bilingual participants seemed to have overall higher EMR than other participants. In order to see if that pattern occurred in the present study, a t-test was conducted to compare overall mean EMR between bilingual and monolingual participants. There was no difference between the groups, t (29) = -.80, $p = .43$.

Discussion

The present study sought to extend previous findings in support of the long-term memory retrieval hypothesis and to test the accessibility hypothesis. The long-term memory retrieval hypothesis states that the retrieval of information from long-term memory is the main factor differentiating non-visual eye movement behavior in a variety of cognitive tasks. Tasks with no long-term memory retrieval requirement, such as auditory vigilance tasks, were expected to be associated with low rates of eye movement. Tasks that involved both retrieval and maintenance, such as working memory tasks, and tasks that involve retrieval of highly accessible material, such as rote memory tasks, were hypothesized to elicit an intermediate level of eye movement. The highest eye movement rate was predicted to occur with long-term memory tasks. The accessibility hypothesis states that within long-term memory retrieval tasks, more accessible information would elicit relatively lower EMR than less accessible information.

The first goal of this study was to extend previous findings of significant differences in EMR between long-term memory and working memory tasks. There were three main types of tasks in the present study: a standard LOP episodic memory task with two levels of accessibility, two semantic memory fluency tasks, and a working memory task with two levels of difficulty, the n-back task. Comparisons between these tasks, collapsed into one episodic, one semantic, and one working memory task, revealed that the working memory task was associated with significantly lower EMR than the semantic memory task, which was also significantly different from the episodic memory task. A significant difference was found between the semantic and episodic memory tasks. This was unexpected and will be discussed below.

The present study extended previous findings of lower EMR for working memory tasks to include the n-back task. In addition, this study extended the findings of high rates of eye movements associated with long-term memory tasks to include newly learned episodic memory tasks. The present study met its first goal, confirming the results of previous studies that LTM tasks elicit higher EMR than working memory tasks. In addition, factors distinguishing the subjects from one another, such as gender and bilingualism, did not play significant roles in the results.

The second goal of this study was to test the accessibility hypothesis. Accessibility was operationally defined by two levels within a standard LOP task and by the type of cue presented to access semantic information in a word fluency task. As a control for difficulty, an n-back task with two levels was also administered.

Results from the standard levels of processing task indicated that words encoded on a deep level were better recalled than those encoded on a shallow level, but there was a negligible difference in EMR. The failure to find differences in EMR is inconsistent with the retrieval accessibility hypothesis and will be discussed within the context of the other findings below.

For the fluency tasks, performance data revealed significantly more words generated using a category cue as compared to a phonemic cue, as expected (Monsch et al., 1992). There was also a significant interaction between fluency task and time, such that a decrease in performance over time was more pronounced for category fluency than phonemic fluency. EMR data supported the prediction of the accessibility hypothesis: phonemic fluency was associated with significantly higher EMR than category fluency. Difficulty per se between the two fluency tasks is not a likely explanation for the EMR differences because performance data on the n-back test confirmed that the two-back task was more difficult than the one-back task, but, consistent with expectations, EMR was equivalent for both tasks.

The effect of difficulty on EMR in working memory tasks was also examined by post-hoc analyses of two additional working memory tasks (digit span backward and letter-number sequencing subtests of the WAIS-III), each of which was divided into easier and harder conditions. There was no difference in EMR between the easier and harder conditions for either the digit span backward or the letter-number sequencing tasks. This lends additional support to the hypothesis that an increase in difficulty per se does not lead to increased EMR; there needs to be a long-term memory component in order for EMR to be affected.

The fluency tasks were subjected to within task analyses as well. The fluency tasks were 60 seconds in length and were divided into 15-second quartiles in order to analyze the effect of time on EMR. In the first analysis, a repeated measures ANOVA, there was a significant linear trend over time, with higher rates of eye movement found for the last quartile compared with the first two quartiles, when time was collapsed across fluency task type.

In addition, the relationship between performance and EMR was supported in a between subjects analysis. While no previous research has found EMR to be related to individual differences, the slopes of EMR and performance over time were computed for each participant and submitted to between subjects analyses. There was a significant negative relationship between EMR and performance for category fluency, such that as EMR increased, performance decreased. Category fluency was hypothesized to be associated with performance because there is inter-item cueing. In contrast, there was no correlation between EMR and performance for fluency, likely because every item retrieved in a phonemically based search reflects a new search.

With regard to secondary tasks, the generative LOP task did not lead to a significant levels of processing effect regarding performance. However, there was a difference in EMR between the encoding trials. Spelling encoding was associated with lower EMR than sentence encoding. An obvious possible explanation would be the difference in response latency between the tasks: spelling led to significantly shorter trial periods than generating sentences. However, Ehrlichman et al. (2007) analyzed the first four seconds of the response period in one of their studies and compared that analysis to data produced from the entire answer period. They found equivalent results (r = .99). Therefore, a short response latency (M spelling response time = 3 seconds) in the present study should not significantly skew the results. In addition, the spelling encoding and sentence encoding trials were collapsed into mean "spelling encoding" and "sentence encoding" trials in order to reduce the potential impact of variability in scoring of trials of very short duration. Therefore, response time is not expected to be the primary difference between spelling and sentence encoding.

One possible explanation for the significant difference between spelling and sentence encoding is that spelling words is very similar to the rote sequencing tasks presented. To successfully spell a common word, the word is accessed as a whole and the subsequent listing of the individual letter information is almost automatic. In that way, spelling is a highly constrained task. In contrast, sentence generation, as well as recall of words from both encoding conditions, requires active long-term memory retrieval and was therefore associated with higher rates of eye movement.

After the initial collapsed analyses of the main tasks and the individual comparisons of the two levels within each task, an overall ANOVA compared all tasks presented. Tasks in which the two levels produced equivalent levels of EMR were entered into the analysis as a collapsed variable, and tasks in which the two levels differed significantly were included as separate variables. Each variable was compared to its next largest neighbor. When there was a break in significance between two neighboring variables, a new cluster was created. This analysis revealed three main clusters of tasks. The first cluster contained the n-back task and was associated with the lowest EMR. The second cluster contained the rote sequencing, spelling encoding condition from the generative LOP, and digit span backward tasks. These tasks did not differ significantly from one another regarding EMR. The third cluster contained the long-term memory retrieval tasks, including supermarket fluency, sentence encoding from generative LOP, collapsed recall conditions from generative LOP, s word fluency, and collapsed standard LOP recall tasks. The degree of overlap among the tasks permitted them to be grouped as one cluster although the standard levels of processing task showed significantly higher EMR than all tasks except for s word fluency.

The results of the overall ANOVA support previous findings of significant differences in EMR based on the tests’ relationship to long-term memory retrieval. The lowest rates of eye movement were associated with tasks requiring attention to externally presented information and online updating and maintenance of that information. Intermediate rates of eye movement were associated with tasks that required some element of retrieval and maintenance. These tasks included the rote sequencing, spelling encoding, and digit span backward tasks. The rote sequencing and spelling encoding tasks are similar, in that both require the accessing of long-term memory and maintenance of the information while it is recited. The digit span backward is a working memory task that required maintaining the initial sequence of numbers presented and manipulating the information in mind.

The highest EMR was associated with tasks that were most involved in long-term memory retrieval. The long-term memory cluster was comprised of a variety of tasks, semantic and episodic, encoding and recall, and tasks with cueing and those without cueing at recall. However, they share a high level of EMR compared to working memory tasks. The presence of these main clusters supports the findings of similar clusters in Ehrlichman et al. (2007) (see table 7).

Table 7

Mean EMR for three task clusters for the present study compared to Ehrlichman et al. (2007).

Task Clusters	Chen	Ehrlichman et al. (2007)
Auditory Tasks (with a Vigilance component)	0.44	0.36
Working and Rote Memory	0.68	0.56
Long-Term Memory Retrieval	1.06	1.08

The difference in EMR between the n-back and the secondary working memory task (digit span backward) bears explanation. The n-back task was designed to test increased working memory load by using a presentation that contained a vigilance component. While a pure auditory vigilance task was not included in this study, it has been found in previous research to inhibit eye movement and has been associated with very low levels of eye movement, as low as .14 in Ehrlichman et al. (2007). In contrast, the digit span backward task did not have a continuous external stimulus. The vigilance component of the n-back task may have led to some eye movement suppression, leading to lower EMR as compared to the other working memory tasks.

With regard to the long-term memory retrieval cluster, sentence encoding was included among the long-term memory retrieval tasks based upon its high EMR. This is likely because generating sentences in response to a target word requires active retrieval of information from long-term memory and is therefore an encoding task with a strong retrieval component. The tasks in this cluster were not significantly different from one another, with the exception of the standard LOP task that differed from all other tasks except phonemic fluency. Supermarket fluency, sentence encoding, generative recall, and s word fluency did not differ significantly from one another. A lack of significant difference in this analysis between the fluency tasks was surprising because it had been significant in an earlier analysis of all 32 participants, but a look at the p value reveals that the difference just missed significance (p = .053).

A significant difference was found between the standard and generative LOP tasks. The range of EMR within the long-term memory cluster was small (.93 – 1.17). The range in EMR between generative and standard LOP was even smaller (1.10 - 1.17) and may not replicate as a significant difference in other studies. Additionally, there are between task differences that may have contributed to the significant difference in EMR between these two LOP tasks. One, there was no significant LOP effect for the generative LOP, while there was a significant LOP effect for the standard LOP task. Two, the generative LOP lists were consistently presented as the fifth and sixth lists of the experiment because the task was added to the protocol in order to look at EMR at encoding, which was seen as a secondary interest. Therefore, list learning fatigue could have played a role both in performance and EMR. Three, the nature of the encoding cues were different. In the generative task, the entire list was processed with the additional cueing of participants speaking the word (i.e., spelling or creating a sentence including the target word), leading to a motor and a second auditory cue. In contrast, the standard LOP required individuals to simply answer yes or no. The suggestion of a "generation effect," that is, improved retrieval due to generation at encoding compared with passive encoding, has face validity (Soraci, Carline, Toglia, Chechile, & Neuschatz, 2003). This improved performance has been linked to an increase in distinctiveness when generation trials are mixed within passive encoding trials; however, this effect has not been found as a between-list phenomenon and is found less in free recall than recognition trials (deWinstanley, Bjork, & Bjork, 1996; Dodson & Schacter, 2001; Kinoshita, 1989). The potential impact of generative encoding on EMR is an argument to be made with caution as there was no significant LOP effect and the generative LOP performance was not higher than the standard LOP performance. Four, the generative LOP task was comprised of only one deep and one shallow list, compared to two of each type of list in the standard LOP task. Five, the generative LOP lists were 17 words each compared to 12 words for each standard LOP word list. Therefore, it is difficult to provide one cause for the significant difference between the standard and generative LOP tasks regarding EMR. Corroboration would be needed in future studies, in which the tasks were more similar, in order for this difference to be considered meaningful.

The results of the overall ANOVA revealed that the standard LOP was not significantly different from the phonemic fluency task but was significantly different from the semantic fluency task. This raises the questions as to why the semantic and phonemic fluency tasks differ in EMR (in an earlier analysis) and why the standard LOP task differs from category fluency and not phonemic fluency? The answer may lie in considering the role of retrieval cues in EMR (Challis, Velichkovsky, & Craik, 1996; Craik, 2002; Eysenck & Eysenck, 1980; Otani, Widner, Whiteman, & St. Louis, 1999). Category fluency provides salient retrieval cues which tap into the semantic memory organizational system of connections between items based upon semantic content. In contrast, the phonemic cue is weaker and requires more searching to arrive at responses (Troyer, 2000; Troyer, Moscovitch, & Winocur, 1997). Likewise, in the standard LOP free recall condition, no retrieval cues are offered; the individual must rely upon the strength of the original encoding. Cueing at retrieval has been studied in the context of LOP research as well as other retrieval tasks, and cued recall or recognition are the most common means of testing the LOP effect (Sauzeon, N'Kaoua, Lespinet, Guillem, & Claverie, 2000). While a levels of processing effect was found for performance for the standard levels of processing task, it is likely that free recall of the information, in the absence of external retrieval cues, required active search for both recall conditions and, therefore, overall high EMR. The possible impact of weak retrieval cues on EMR at retrieval may also explain the significant trend over time for EMR for both fluency tasks. As time went on in both fluency tasks, the retrieval cues became weakened as categories were likely exhausted, requiring more active search in both fluency conditions.

Overall, the present study extended the findings in support of the long-term memory hypothesis to include the n-back task and episodic memory tasks. In addition, the present study analyzed EMR data at encoding and found that even at encoding, tasks that draw upon long-term memory resources are associated with higher EMR than tasks that involve a more rote retrieval and maintenance of the information. This study also revealed a significant relationship between performance and EMR across individuals which had previously not been investigated.

The accessibility hypothesis found equivocal support. The lack of a significant relationship between EMR and accessibility at retrieval for newly learned information suggests the need for an adjustment to the hypothesis as originally stated. There is a possible explanation for the pattern of findings described here: a potential relationship between retrieval cues and EMR. The presence of strong cues to retrieval was associated with lower EMR, while weak retrieval cues were associated with higher EMR.

Saccades and Memory

The above exposition has suggested empirical support for connections between long-term memory retrieval and eye movements. The long-term memory retrieval and accessibility hypotheses are based upon the idea that not all eye movements serve a visual purpose. Then, why do these eye movements occur? It is clear that most of the information individuals encode in memory comes from visual input. Vision and eye movements are important in the search for external information as well as encoding of new information. The eye movements discussed here are not considered necessary to memory retrieval. In fact, if the eye movements were suppressed, there should be no difference in performance. There may be an evolutionary connection between these systems that remains even when visual search is not necessary for retrieval. The following discussion focuses on possible neuroanatomic areas of overlap between the memory and saccadic eye movement systems.

There has been some support in the literature for associating long-term memory retrieval and saccadic eye movements (Christman, Garvey, Propper, & Phaneuf, 2003; Christman & Propper, 2001). Increases in bilateral hemispheric activation, created by saccades, have been associated with increased performance on episodic memory tasks. Christman et al. (2003) conducted their study by asking individuals to make saccadic eye movements, smooth pursuit eye movements, or no eye movements. They found that horizontal saccades were associated with improved episodic memory performance. However, their saccade task required individuals to cross midline. In general, the eye movements made in the present study and in previous studies by Ehrlichman et al. (2007) did not cross midline and were relatively small eye movements. Since eye movements that crossed midline were hypothesized to lead to hemispheric activation in the studies by Christman et al. (Christman et al., 2003; Christman et al., 2001) and the present study did not show those types of eye movements, the current findings are not likely associated with bilateral hemispheric activation.

Sobotka and Ringo (1997) conducted a study of monkeys in which they examined event-related potential information during spontaneous saccadic eye movements under both light and dark conditions. In the dark condition, the potential confound of visual stimulation was absent, and they found that spontaneous saccades activated the medial septum and the anterior and posterior medial temporal lobe. Sobotka and Ringo postulated that these areas are involved in higher-order activity, which is modulated by saccadic eye movement. They suggested that because saccades are the primary means of information input, they may play an important role in modulating memory, even in the absence of visual stimulation. The finding that saccades activate the medial temporal lobes will be explored in greater detail along with other possible neuroanatomical connections between the saccadic eye movement and long-term memory systems.

Episodic buffer

Baddeley (1992) originated the theory of a three-part working memory system. In this system, working memory was considered its own process with a very short temporary store facility and no interaction with long-term memory retrieval. This was largely due to the notion of working memory and long-term memory as neuroanatomically separate because individuals with brain damage (e.g., traumatic brain injury, Alzheimer's dementia, Korsakoff's disease) tended to have deficits in one but not the other. However, research has found that individuals with severe amnesia are able to perform working memory tasks that draw on long-term memory resources, suggesting an area of overlap between the long-term memory and working memory systems (Baddeley, 2000). Baddeley recognized the need for a site of integration between long-term memory retrieval and working memory function. He added a fourth component of his working memory system named the episodic buffer to serve as a longer-term temporary memory store that can accommodate larger chunks of information than the original slave systems (phonological loop and visuospatial sketchpad) and integrate working memory and long-term memory retrieval, both verbal and visual.

Baddeley (2000) noted that the buffer would not be located in only one area of the brain, although the frontal lobes are a likely candidate. Naghavi and Nyberg (2005), in a review of the literature on working memory and episodic memory systems, described two main brain areas found to consistently overlap in activation during these functions: the dorsolateral prefrontal cortex (DLPFC) and the superior and inferior parietal cortex (fusiform gyrus and cuneus near the intraparietal sulcus).

The DLPFC (BA 46 / 9) is important for active maintenance, monitoring, and retrieval of episodic information, as well as increased working memory load (Braver et al., 2001; Buckner & Koutstaal, 1998; Buckner & Wheeler, 2001; Cabeza, Dolcos, Graham, & Nyberg, 2002). It has been implicated in coordinating retrieval strategy, triggering appropriate networks for memory retrieval, and engaging in a continuous assessment of the retrieval process (Buckner et al., 2001; Moscovitch & Winocur, 2002) The superior parietal cortex (BA 7) and the inferior parietal cortex (BA 40), in the area of the intraparietal sulcus, are involved in successful memory retrieval as well as working memory function (Naghavi & Nyberg, 2005). Naghavi and Nyberg (2005) suggested that the connections between the frontal and parietal areas help to integrate the working memory and episodic memory systems.

Another possible area for the episodic buffer is the inferior frontal cortex (BA 45). It is active for both semantic and episodic memory retrieval, as well as during semantic analysis, verbal working memory, and word generation tasks (Buckner, Logan, Donaldson, & Wheeler, 2000; Lepage, Ghaffar, Nyberg, & Tulving, 2000; Martin & Chao, 2001; Ricci et al., 1999).

Brain Areas Associated with Long-Term Memory Retrieval

Memory retrieval relies upon both cortical and subcortical structures. One main area that has been well-studied in lesion and imaging studies is the medial temporal lobe (MTL), including the hippocampus, parahippocampal cortex, and rhinal cortices (perirhinal and entorhinal cortices). Nyberg, Habib, McIntosh, and Tulving (2000) described the medial temporal lobe as an area of integration and association between stimuli from different modalities for the purpose of encoding and retrieval. For example, Schacter and Wagner (1999) found that encoding activated anterior MTL sites and retrieval activated posterior MTL sites, specifically the left parahippocampal cortex.

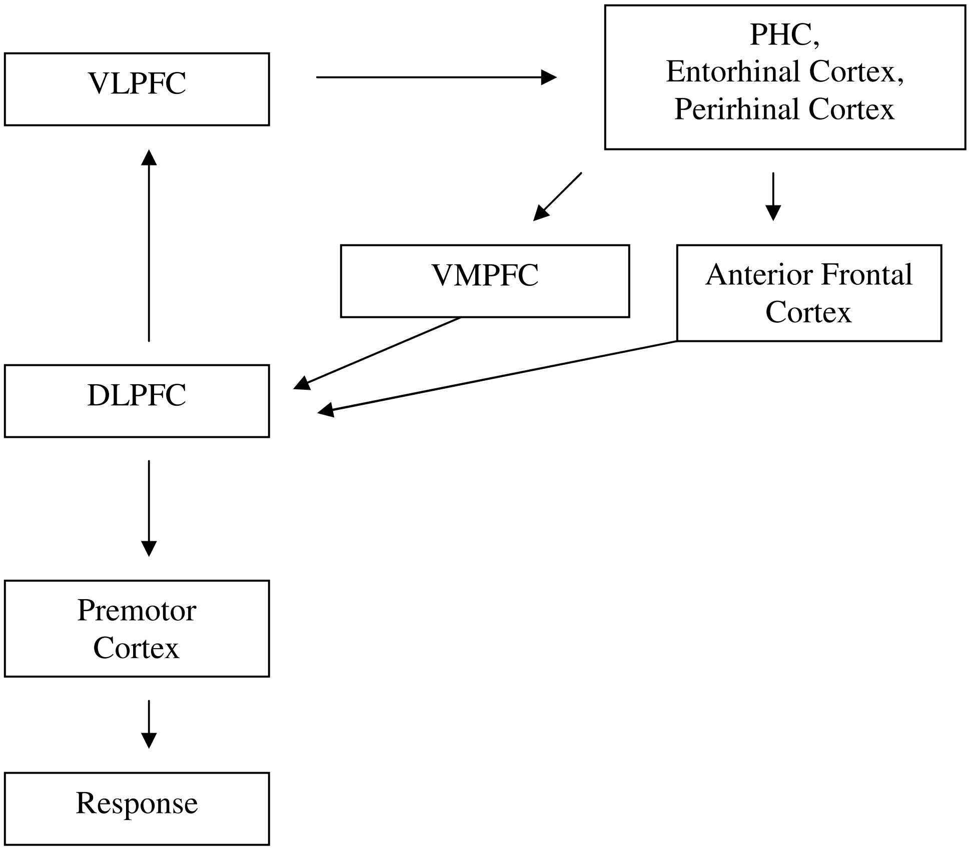
Numerous imaging studies have implicated the prefrontal cortex as a main site of organization, search, and selection for the retrieval of information (Cabeza & Nyberg, 2000; Lepage et al., 2000; Naghavi et al., 2005). These areas include the dorsolateral prefrontal cortex (DLPFC), ventrolateral prefrontal cortex (VLPFC), anterior cingulate cortex, premotor cortex, anterior frontal cortex (fronto-polar cortex), and inferior frontal cortex.

The *DLPFC* (BA 46 / 9) is active for monitoring information in working memory, recognition, and stem completion retrieval tests, including retrieval of words studied in a levels of processing paradigm (Gilboa, 2004; Naghavi et al., 2005). It has also been associated with word generation and semantic processing (Schacter, Alpert, Savage, Rauch, & Albert, 1996). The *VLPFC* (BA 44) is differentially activated during active semantic and episodic memory search, including retrieval of words encoded using a levels of processing paradigm, and its activation depends upon the type of retrieval cue used for that search. The VLPFC is also involved in active maintenance of information (Cabeza et al., 2002; Kapur et al., 1994; Moscovitch et al., 2002). The *anterior cingulate gyrus* (BA 32), which is a ventromedial prefrontal cortical structure, has been implicated as an area of activation for working memory, long-term episodic and semantic memory retrieval, and category fluency tasks; it plays a role in cognitive control and effortful task completion (Hirshorn & Thompson-Schill, 2006; Johnson Jr., Kreiter, Zhu, & Russo, 1998; Lepage et al., 2000; Moscovitch et al., 2002; Nyberg et al., 2003). The *premotor cortex* (BA 6) is important for response selection for retrieval tasks and maintenance of information (Moscovitch et al., 2002). The *anterior frontal cortex* (near BA 10) is active when retrieval is attempted and is important for selecting and maintaining retrieval mode, whether or not the retrieval was successful (Buckner et al., 2001; Cabeza et al., 2002; Miyashita, 2004; Moscovitch et al., 2002). This area is active during retrieval of words which were encoded using a levels of processing paradigm (Kapur et al., 1994). The *inferior frontal cortex* (BA 45), located near the frontal operculum, is important for maintenance, manipulation, and retrieval. This area has been implicated in studies of word retrieval within an LOP paradigm as well as verbal fluency tasks (Gabrieli, Poldrack, & Desmond, 1998; Hirshorn et al., 2006; Johnson Jr. et al., 1998; Klein, Milner, Zatorre, Meyer, & Evans, 1995).

Moscovitch and Winocur (2002) described the role of the frontal cortex in long-term retrieval. To begin the memory search using an indirect external cue, the DLPFC coordinates the retrieval strategy and activates the VLPFC, which readies cues for memory retrieval. The cue provided by the VLPFC activates the hippocampal complex and leads to memory retrieval. Once the information is recovered, the ventromedial prefrontal and anterior prefrontal cortices receive input from the parahippocampal complex in order to determine whether the retrieved information meets the retrieval goals. The two structures project to the DLPFC to verify the memories and then activate the premotor cortex to select among the possible choices for the response (See figure 1).

Figure 1

Interactions between frontal, parietal, and medial temporal cortex in memory retrieval (Buckner et al., 2001; Moscovitch et al., 2002)



Note. VLPFC – Ventrolateral Prefrontal Cortex; PHC – Parahippocampal Cortex; VMPFC – Ventromedial Prefrontal Cortex; DLPFC – Dorsolateral Prefrontal Cortex

Varied verbal tasks, such as free recall and semantic matching tasks, reveal similar areas of activation in the left inferior frontal gyrus (LIFG) in the area of the frontal operculum, and left posterior parahippocampal (BA 36) and fusiform gyri (BA 37). Fernandez and Tendolkar (2001) described pathways connecting the frontal and MTL areas. The parahippocampal cortex receives input from the orbito-frontal cortex, superior temporal sulcus, DLPFC, and posterior parietal cortex. Fernandez and Tendolkar described a lateral path from the lateral prefrontal cortex (PFC) to the parahippocampal cortex through the frontal-occipital fasciculus, and a medial path from the lateral PFC to the presubiculum through the cingulum bundle.

Superior and inferior parietal lobe structures, including the *intraparietal sulcus*, play important roles in memory retrieval. The precuenus (BA 7) is differentially active during successful retrieval of episodic and semantic memory (Naghavi et al., 2005). The superior parietal cortex has been implicated in switching between subcategories during verbal fluency tasks (Gurd et al., 2002). The left inferior parietal cortex (BA 40) may be a passive phonological short-term memory store; and both the superior and inferior parietal lobules are active during the n-back task (Naghavi et al., 2005).

In addition to the cortical structures, subcortical areas, including the cerebellum, thalamic nuclei, and basal ganglia, play an important role in memory retrieval. Gabrieli, Poldrack, and Desmond (1998) conducted a series of studies in which semantic and phonemic information was accessed in verbal encoding and retrieval. Across the studies, they found increased activation of the left prefrontal cortex and cerebellum when semantic information was accessed, regardless of material and modality. Gabrieli et al. described the cerebellum as having close connections to the frontal cortex, such that lesions to the frontal cortex lead to symptoms of cerebellar hypometabolism, and damage to the cerebellum results in signs of frontal lobe damage, such as poor verbal fluency, planning, and associative learning.

Saunders, Mishkin, and Aggleton (2005) reviewed the connections between medial temporal lobe structures and thalamic nuclei. The medial pulvinar nucleus, lateral dorsal nucleus, anterior thalamic nucleus, and nucleus medialis dorsalis receive input from rhinal cortices. The projections can travel along the fornix, external capsule, inferior thalamic peduncle, and temporo-pulvinar bundle. The basal ganglia has been implicated in learning and retrieval of sequential information, encoding and retrieval associated with reward, and implicit learning (Hikosaka, Takikawa, & Kawagoe, 2000). In particular, the caudate nucleus has direct connections with the rhinal cortical structures of the MTL.

Brain Areas Associated with Working Memory Function

Working memory function, both verbal and visual, leads to overlapping areas of activation in the DLPFC, VLPFC, intraparietal sulcus, supramarginal gyrus, and basal ganglia (Naghavi et al., 2005). Specifically, the two-back task activated the DLPFC, VLPFC, anterior PFC, superior parietal lobule, and inferior parietal lobe. Braver et al. (2001) found that the two-back task led to activation of bilateral DLPFC, right anterior PFC, and right supplementary motor area.

Verbal working memory is associated with activity in VLPFC, which, on the left side of the brain, is Broca's areas and is associated with phonological rehearsal. The inferior parietal lobe, an area near the intraparietal sulcus, accesses phonological memory stores (Naghavi et al., 2005; Pochon et al., 2002).

Memory Retrieval and Working Memory: Areas of Overlap

Cabeza and Nyberg (2000) and Naghavi & Nyberg (2005) reviewed the imaging research on areas associated with episodic retrieval and working memory function. These areas of overlap included left DLPFC, bilateral VLPFC, premotor cortex, and anterior cingulate cortex. In addition to these frontal areas, there was bilateral activation of superior temporal cortex (BA 7) associated with attentional resources, bilateral cerebellar activation, and bilateral hippocampal activation. This activation may reflect a need to use medial temporal structures in rehearsing information that requires long retention intervals. The medial thalamus was also implicated in both episodic memory and working memory tasks. Cabeza et al. (2002) compared episodic and working memory activation and found that both led to activation of the left DLPFC. Nyberg et al. (2003) presented the n-back, episodic memory, and semantic memory tasks to participants in a positron emission tomography (PET) study. They found that all tasks activated the anterior cingulate gyrus, left anterior PFC, VLPFC, and DLPFC.

Saccadic Eye Movement System

The areas of the brain associated with saccadic eye movements vary depending on the type of saccadic eye movement being executed. The study of saccadic eye movements and their related brain areas has been conducted with lesion, cytochemistry, and single cell recording studies in animals, as well as fMRI studies in humans. Areas are connected through a complicated series of connections and feedback loops. Excitation, tonic inhibition, enhanced inhibition, and disinhibition all play a role.

The cortical areas involved in saccadic eye movement generation are the frontal eye field (FEF) located in the precentral gyrus, the parietal eye field (PEF) located in the lateral intraparietal sulcus, the supplementary eye field (SEF) located in the medial wall of the frontal lobe, the DLPFC, and the anterior cingulate gyrus (Gaymard, Ploner, Rivaud, Vermersch, & Pierrot-Deseilligny, 1998; Mort et al., 2003; Pierrot-Deseilligny, Muri, Ploner, Gaymard, & Rivaud-Pechoux, 2003).

The frontal eye field is involved in visually and non-visually guided saccades (Gaymard, Lynch, Ploner, Condy, & Rivaud-Pechoux, 2003; Gaymard et al., 1998; Pierrot-Deseilligny et al., 2003). Lesions to the FEF leads to slower saccade implementation and problems with memory-guided saccade generation (Pierrot-Deseilligny et al., 2003). The PEF detects novel, unpredictable targets and is involved in sustaining activation during the delay portion of memory-guided saccades to contralateral space (Pare & Wurtz, 2001). According to Pare and Wurtz (2001), the job of the PEF may be to translate visual information into oculomotor programs, in part due to its physical location between the visual cortex and saccadic centers. PEF sends information to the frontal eye fields and superior colliculus (Edelman & Goldberg, 2001). Both the FEF and PEF appear to be involved in voluntary and reflexive saccades, as there has been evidence to both effects from single cell recording and MRI studies (Mort et al., 2003).

The DLPFC is important for inhibiting reflexive saccades (e.g., in order to execute an antisaccade), as well as maintaining spatial information for memory guided saccades (Gaymard et al., 1998; Pierrot-Deseilligny et al., 2003). The DLPFC also controls the timing of predictive saccades; it decides whether or not to inhibit saccades, facilitates the triggering of a saccade, and helps choose a direction for a forthcoming intentional saccade (Pierrot-Deseilligny et al., 2003). Lesions to this area lead to difficulty with inhibiting reflexive saccades during an anti-saccade task (Munoz, 2002). The anterior cingulate gyrus is involved in memory guided saccades and memorized sequences for visually guided saccades (Berman et al., 1999; Gaymard et al., 1998). Mort (2003) explained that reflexive saccades activate the precuneus, posterior cingulate, and angular cortex.

Subcortical areas involved in saccade generation include the lateral geniculate nucleus of the thalamus, basal ganglia, and cerebellum (Everling, Dorris, & Munoz, 1998; Hikosaka et al., 2000; Munoz, 2002; Petit et al., 2003; Wang, Jin, & Jabri, 2002). These interconnecting areas transmit information to the superior colliculus (SC) (Munoz, 2002). PET and MRI scans reveal activation of the basal ganglia and thalamus during voluntary saccade execution, suggesting that voluntary saccades may use classic motor pathways for their execution (Hikosaka et al., 2000; Petit et al., 2003). Wang, Jin, & Jabri (2002) described the role of the cerebellum in saccade generation. Lesion data suggest that the cerebellum plays a necessary role in saccade accuracy and consistency through its inhibitory transmissions to the SC. The cerebellum has connections to the SC, thalamus, and the brainstem neurons involved in saccade generation and is involved in saccade initiation, modulation, and termination (Enderle, 2002).

The role of the SC is to receive visual, auditory, and tactile information in order to make quick, orienting saccades (Hikosaka et al., 2000). The SC has three main layers: superficial, intermediate, and deep (Hikosaka et al., 2000; Munoz, Dorris, Pare, & Everling, 2000). The superficial layer receives visual information from the retina and other visual areas (Munoz, 2002). The intermediate layer is the motor layer; it sends output signals to the brain stem for saccade stimulation. Cells in this layer fire before and during the saccade (Munoz, 2002). The deep layer receives auditory and somatosensory information. The SC, therefore, is a site of multisensory convergence (Hikosaka et al., 2000; Munoz, 2002).

The brain stem is the final common pathway for saccade generation. This area includes the paramedian pontine reticular formation (PPRF), central mesencephalic reticular formation (cMRF), and rostral interstitial nucleus of the medial longitudinal fasciculus (riMLF). Ipsilateral horizontal saccades are controlled by the PPRF, and vertical saccades are controlled by the riMLF (Hepp, Van Opstal, Straumann, Hess, & Henn, 1993). The cMRF is responsible for triggering saccades through its connection to the SC and PPRF, as well as providing feedback to the SC regarding saccade execution (Chen & May, 2000). The PPRF is involved in horizontal saccade generation, and the riMLF is involved in vertical saccades (Henn & Hepp, 1986).

Several researchers suggest that endogenous saccades follow a pathway from the visual cortex to the PEF (located in the lateral intraparietal sulcus), which projects to the DLPFC. The DLPFC sends information to the frontal eye fields, which send to the caudate nucleus (a basal ganglia structure) and the SC. The caudate nucleus sends inhibitory projections to the substantia nigra pars reticulata (a basal ganglia structure) and thalamus as part of a feedback loop to the FEF and PEF. The FEF connects directly to the SC; the thalamus also projects to the SC, leading to the saccade execution by brainstem neurons (Gaymard et al., 1998; Hikosaka et al., 2000; Munoz, 2002).

Areas of Overlap Between the Two Systems

Moscovitch and Winocur (2002) explained that many areas of the PFC are involved in different types of tasks, such as long-term memory and working memory, because these areas are active when their function is needed, regardless of the task. Therefore, the same areas could be active for memory encoding, retrieval, working memory, or saccadic eye movement tasks if the process requires that area of the prefrontal cortex.

There are areas of the brain that are implicated in long-term retrieval, working memory, and saccadic generation, including the DLPFC, intraparietal sulcus, and anterior cingulate. The cerebellum, thalamus, and basal ganglia are also involved in these functions.

The cerebellum, an area that shares direct connections between primary and association sensory cortices, is important for general motor function as well as saccadic eye movements and has been shown to play a role in memory tasks (Andreasen et al., 1999). According to Andreasen et al. (1999), the cortico-cerebellar loop is linked through the pons, dentate gyrus, red nucleus, thalamus, and basal ganglia. Gabrieli et al. (1998) conducted a study in which they demonstrated a double dissociation between cerebellar and prefrontal function. The cerebellum was differentially activated during a sustained search for information, while left PFC activation was greater when more information required retrieval. The finding that the cerebellum is associated with sustained search when the information is less accessible, and its strong links to the prefrontal lobes and SC, suggests that the cerebellum may play a role in non-visual eye movements. It is also a likely area of connection between saccades, working memory, and long-term memory functions.

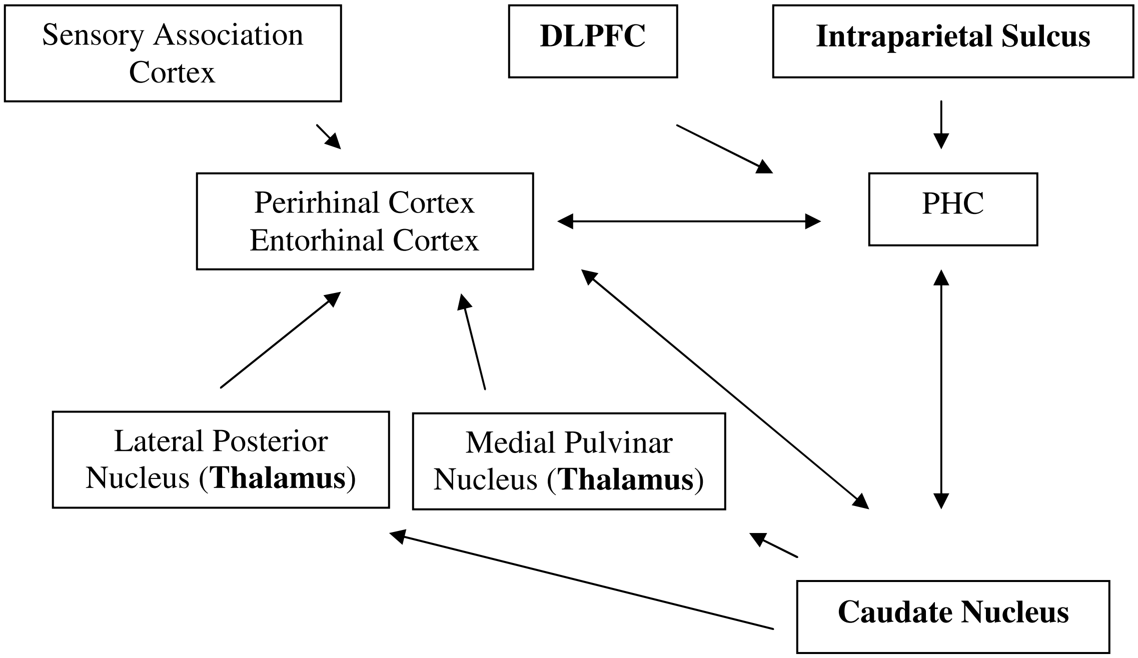
Ehrlichman et al. (2007) described a possible link between memory systems and eye movements through thalamic connections. Thalamic nuclei, specifically the lateral posterior and medial pulvinar nuclei, receive projections from the parahippocampal cortex, as well as the visual layer of the SC. These nuclei transmit information back to the SC. The SC also receives direct projections from the lateral intraparietal sulcus and DLPFC which are suggested as the main sites of Baddeley's episodic buffer (Saunders, Mishkin, & Aggleton, 2005).

The overlap of these areas, as well as connections between them, suggest a neuroanatomical basis for linking saccades, working memory, and memory retrieval functions. Suzuki (1996) described a system of connections between prefrontal, basal ganglia, and medial temporal lobe structures. Many of these areas are involved in memory retrieval, working memory function, and saccadic generation. In saccade generation, the FEF, DLPFC, and lateral intraparietal area PEF activate the caudate nucleus, which transmits information to the substantia nigra pars reticulata and inhibits the SC and thalamus. The caudate nucleus shares direct connections with the medial temporal lobe structures, including the rhinal and parahippocampal cortices; the rhinal and parahippocampal cortices have been implicated in the formation and retrieval of information in long-term memory. The DLPFC is directly and indirectly connected to the parahippocampal cortex through the caudate and thalamus (Suzuki, 1996). Figure 2 demonstrates possible areas of overlap between memory retrieval and eye movements (bolded areas). Table 8 lists brain areas found to be implicated in eye movement, semantic and episodic memory, word generation, and working memory.

In sum, the likely brain structures which underlie saccadic eye movements and long-term memory retrieval are the dorsolateral prefrontal cortex, cerebellum, and basal ganglia. More research is needed in this area to better understand these possible connections, including brain imaging studies.

Figure 2

Cortical and subcortical structures involved in long-term memory retrieval (Suzuki, 1996).



Note. DLPFC – Dorsolateral Prefrontal Cortex; PHC – Parahippocampal Cortex. Bolded names reflect brain areas with overlapping functions in the saccadic eye movement and memory systems.

Table 8

Brain areas and the associated function

Area of the Brain	Semantic Retrieval	Episodic Retrieval	Word Generation	Working Memory
DLPFC (46/9)	x	x	x	x
VLPFC (BA 44)	x	x		x
Anterior Cingulate (BA 32)	x	x		x
Anterior frontal cortex (BA 10)	x	x		x
Inferior Frontal (BA 45)	x	x	x	x
Premotor Cortex (BA 6)	x	x		x
Intraparietal Sulcus (BA 7/39/40)	x	x	x	x
Entorhinal Cortex		x		
Perirhinal Cortex		x		
Parahippocampal Cortex (BA 36)		x		
Cerebellum		x	x	x
Caudate nucleus				x
Thalamus	x	x	x	x

Table 8

Brain areas and the associated function, continued

Area of the Brain	Episodic Buffer	Saccadic Eye Movement
DLPFC (46/9)	x	x
VLPFC (BA 44)		
Anterior Cingulate (BA 32)		x
Anterior frontal cortex (BA 10)		
Inferior Frontal (BA 45)	x	
Premotor Cortex (BA 6)		
Intraparietal Sulcus (BA 7/39/40)	x	x
Entorhinal Cortex		
Perirhinal Cortex		
Parahippocampal Cortex (BA 36)		
Cerebellum		x
Caudate nucleus		x
Thalamus		x

Limitations

As described in detail above, the accessibility hypothesis as postulated received equivocal support. In order to explain the data, a revised accessibility hypothesis was proposed, in which retrieval cues may play an important role in EMR. However, there were some limitations to the present study which may have impacted the results.

First, the standard LOP task included a relatively small number of words -12- per list. Piloting found that when the four lists were comprised of 16 words each, participants became confused by the fourth list and made intrusive errors of words from previous lists. Therefore, the list length was reduced. However, longer word lists may provide more robust levels of processing findings and may lead to differences in EMR between the deep and shallow conditions at recall.

Second, free recall was used for the LOP tasks because of the need to attribute eye movements at retrieval to either deep or shallow processing. However, recognition and cued recall are more commonly used to assess the LOP effect. Free recall lacks retrieval cueing which may impact EMR; cued recall may be a better means of testing the LOP effect. Cued recall would permit the levels of processing task to be presented in semantic and structural blocks, while testing the possibility that the strength of the retrieval cue impacts the efficiency of the memory search and thereby influence EMR.

Third, the generative and standard LOP tasks differed in ways other than simply the type of encoding. For example, the list lengths were different and the generative LOP lists were consistently included as the last two lists in the experiment. The reason for including the generative lists at the end of the experiment was that this task was a late addition to the protocol as a means of evaluating both encoding and retrieval in an unpiloted episodic memory task. Due to these between task differences, the significant difference in EMR between these LOP tasks is not easy to interpret.

Fourth, the semantic memory tasks presented were fluency tasks. Fluency tasks have been well studied in terms of language functioning, word generation, initiation, and efficient search through long-term memory. It requires self-monitoring and switching between subcategories. While there is research to support the use of these verbal fluency tests as semantic memory tasks which differ on accessibility, using tasks which have several possible reasons for differences in performance may weaken the study's findings.

Summary and Future Research

Ultimately, the primary role of saccadic eye movements is to move the fovea from one point of fixation to another for the purpose of visual processing. However, it appears that not all saccades are associated with vision. Increases and decreases in saccadic EMR have been associated with non-visual factors, such as the presence of long-term memory retrieval and working memory (Ehrlichman et al., 2007). The present study extended previous findings associated with the long-term memory hypothesis to an episodic memory task and the n-back task. In addition, this study revealed differences at encoding between tasks with different processing requirements.

The accessibility hypothesis as originally described was not fully supported. There was not the expected strong relationship between performance and EMR across all LTM tasks. However, the presence of differences in EMR between the episodic and semantic tasks, as well as between and within the fluency tasks, suggests that not all long-term memory retrieval impacts EMR in the same way. One possibility is that the presence of retrieval cues during recall, and the strength of those cues, may affect the efficiency of the memory search. Retrieval using strong cues may be associated with lower EMR than retrieval using weak cues.

In order to further research differences between long-term memory retrieval tasks, future studies may focus on manipulating retrieval cues. Manipulating cues at retrieval, perhaps using a cued recall approach to a list learning task, could bring the cueing associated with fluency tasks into the realm of the episodic memory task. In addition, in order to make the semantic and episodic tasks more similar, the semantic task could involve asking participants to study lists of words one week prior to the experiment (Johnson et al., 1998). Comparison between standard and generative LOP protocols would be interesting with a focus on creating two identical tasks that differ only on the nature of the processing. Eye movement at encoding is another promising area of research opened by this study. Further study of eye movement at encoding may help to illuminate the relationship between eye movement and memory processes. Finally, future research would benefit from focusing on areas of overlap in the brain among saccadic eye movement, working memory, and long-term memory retrieval, in imaging studies.

Appendix

Standard Levels of Processing Task Word Lists:

List A	**List B**	**List C**	**List D**
Park	Tiger	Leaf	Supper
Captain	Mayor	Grass	Jail
Alarm	Pencil	Eagle	Parade
Coward	Juice	Cabbage	Spider
Diet	Syrup	Pearl	Glue
Puppy	Hunter	Barber	Pilot
Program	Dime	Frost	Artist
Lion	Tower	Butcher	Ladder
Butter	Doctor	Squirrel	Skunk
Gypsy	Goat	Flag	Robin
Tennis	Snake	Clown	Salt
Oyster	Tooth	Needle	Wolf

Generative Levels of Processing Task Word Lists:

List I	**List II**
Box	Style
Rock	Shadow
Sport	Bag
Talent	Output
Sky	Concept
Culture	Gas
Transfer	Risk
Nut	Tape
Fate	Mistake
Shock	Smoke
Friend	Note
Witness	Fish
Check	Joy
Post	Pot
Bus	Drive
Grain	Bride
Dress	Heat

Reference List

Andreasen, N. C., O'Leary, D. S., Paradiso, S., Cizadlo, T., Arndt, S., Watkins, G. L. et al. (1999). The cerebellum plays a role in conscious episodic memory retrieval. *Human Brain Mapping, 8,* 226-234.

Andreassi, J. L. (1973). Alpha and problem solving: A demonstration. *Perceptual and Motor Skills, 36,* 905-906.

Andrews J., Wang L., Czernansky J.G., Gado M.H., & Barch D.M. (2006). Abnormalities of thalamic activation and cognition in schizophrenia. *The American Journal of Psychiatry, 163,* 463-469.

Antrobus, J. S. (1973). Eye movements and nonvisual cognitive tasks. In V. Zikmund (Ed.), *The oculomotor system and brain functions.* London: Butterworth.

Antrobus, J. S., Antrobus, J. S., & Singer, J. L. (1964). Eye movements accompanying daydreaming, visual imagery, and thought suppression. *Journal of Abnormal and Social Psychology, 69,* 244-252.

Argyle, M. & Cook, M. (1976). *Gaze and mutual gaze.* Cambridge: Cambridge University Press.

Aserinsky, E. & Kleitman, N. (1955). Two types of ocular motility occurring in sleep. *Journal of Applied Physiology, 8,* 1-10.

Baddeley, A. (1992). Working memory. *Science, 255,* 556-559.

Baddeley, A. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences, 4,* 417-423.

Bakan, P. (1969). Hypnotizability, laterality of eye movements and functional brain asymmetry. *Perceptual and Motor Skills, 28,* 927-932.

Bakan, P. & Shotland, R. L. (1969). Lateral eye movement, reading speed, and visual attention. *Psychonomic Science, 15,* 93-94.

Bavelas, J. B., Coates, L., & Johnson, T. (2002). Listener responses as a collaborative process: The role of gaze. *Journal of Communication, 52,* 566-580.

Beattie, G. W. (1978). Sequential temporal patterns of speech and gaze in dialogue. *Semiotica, 23,* 29-52.

Beaumont, J. G., Young, A. W., & McManus, I. C. (1984). Hemisphericity: A critical review. *Cognitive Neuropsychology, 1,* 191-212.

Bergstrom, K. J. & Hiscock, M. (1988). Factors influencing ocular motility during the performance of cognitive tasks. *Canadian Journal of Psychology, 42,* 1-23.

Berman, R. A., Colby, C. L., Genovese, C. R., Voyvodic, J. T., Luna, B., Thulborn, K. R. et al. (1999). Cortical networks subserving pursuit and saccadic eye movements in humans: An FMRI study. *Human Brain Mapping, 8,* 209-225.

Braver, T. S., Barch, D. M., Kelley, W. M., Buckneer, R. L., Cohen, N. J., Miezin, F. M. et al. (2001). Direct comparison of prefrontal cortex regions engaged by working and long-term memory tasks. *NeuroImage, 14,* 48-59.

Buckner, R. L. & Koutstaal, W. (1998). Functional neuroimaging studies of encoding, priming, and explicit memory retrieval. *Proceedings of the National Academy of Sciences USA, 95,* 891-898.

Buckner, R. L., Logan, J., Donaldson, D. I., & Wheeler, M. E. (2000). Cognitive neuroscience of episodic memory encoding. *Acta Psychologica, 105,* 127-139.

Buckner, R. L. & Wheeler, M. E. (2001). The cognitive neuroscience of remembering. *Nature Reviews Neuroscience, 2,* 624-634.

Cabeza, R., Dolcos, F., Graham, R., & Nyberg, L. (2002). Similarities and differences in the neural correlates of episodic memory retrieval and working memory. *NeuroImage, 16,* 317-330.

Cabeza, R. & Nyberg, L. (2000). Imaging cognition II: An empirical review of 275 PET and fMRI studies. *Journal of Cognitive Neuroscience, 12,* 1-47.

Challis, B. H., Velichkovsky, B. M., & Craik, F. I. M. (1996). Levels-of-processing effects on a variety of memory tasks: New findings and theoretical implications. *Consciousness and Cognition, 5,* 142-164.

Chen, B. & May, PJ. (2000). The feedback circuit connecting the superior colliculus and central mesencephalic reticular formation: A direct morphological demonstration. *Experimental Brain Research, 131,* 10-21.

Christman, S. D., Garvey, K. J., Propper, R. E., & Phaneuf, K. A. (2003). Bilateral eye movements enhance the retrieval of episodic memories. *Neuropsychology, 17,* 221-229.

Christman, S. D. & Propper, R. E. (2001). Superior episodic memory is associated with interhemispheric processing. *Neuropsychology, 15,* 607-616.

Cook, M. (1977). Gaze and mutual gaze in social encounters. *American Scientist, 65,* 328-333.

Craik, F. & Lockhart, R. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning & Verbal Behavior, 11,* 671-684.

Craik, F. I. M. (2002). Levels of processing: Past, present ... and future? *Memory, 10,* 305-318.

Craik, F. I. M. & Tulving, E. (1975). Depth of processing and the retention of words in episodic memory. *Journal of Experimental Psychology: General, 104,* 268-294.

Croghan, L. M. & Bullard, P. C. (1975). Conjugate lateral eye movement and latency of verbal response to arithmetic questions. *Perceptual and Motor Skills, 40,* 647-650.

Day, M. E. (1964). An eye movement phenomenon relating to attention, thought and anxiety. *Perceptual and Motor Skills, 19,* 443-446.

Day, M. E. (1967). An eye-movement indicator of individual differences in the physiological organization of attentional processes and anxiety. *The Journal of Psychology, 66,* 51-62.

De Gennaro, L. & Violani, C. (1988). Reflective lateral eye movements: Individual styles, cognitive and lateralization effects. *Neuropsychologia, 26,* 727-736.

Dement, W. & Kleitman, N. (1957a). Cyclic variations in EEG during sleep and their relation to eye movements, body motility and dreaming. *EEG Clinical Neurophysiology, 9,* 673-690.

Dement, W. & Kleitman, N. (1957b). The relation of eye movements during sleep to dream activity: An objective method for the study of dreaming. *Journal of Experimental Psychology, 53,* 339-346.

deWinstanley, P. A., Bjork, E. L., & Bjork, R. A. (1996). Generation effects and the lack thereof: The role of transfer-appropriate processing. *Memory, 4,* 31-48.

Dodson, C. S. & Schacter, D. L. (2001). 'If I said it I would have remembered it': Reducing false memories with a distinctiveness heuristic. *Psychonomic Bulletin & Review, 8,* 155-161.

Doherty-Sneddon, G., Bruce, V., Bonner, L., Longbotham, S., & Doyle, C. (2002). Development of gaze aversion as disengagement from visual information. *Developmental Psychology, 38,* 438-445.

Duke, J. D. (1968). Lateral eye movement behavior. *The Journal of General Psychology, 78,* 189-195.

Edelman, J. A. & Goldberg, M. E. (2001). Dependence of saccade-related activity in the primate superior colliculus on visual target presence. *Journal of Neurophysiology, 86,* 676-691.

Ehrlichman, H. (1981). From gaze aversion to eye-movement suppression: An investigation of the cognitive interference explanation of gaze patterns during conversation. *British Journal of Social Psychology, 20,* 233-241.

Ehrlichman, H. & Barrett, J. (1983). Random saccadic eye movements during verbal-linguistic and visual-imaginal tasks. *Acta Psychologica, 53,* 9-26.

Ehrlichman, H., Micic, D., Sousa, A., & Zhou, J. (2007). Looking for answers: Eye movements in non-visual cognitive tasks. *Memory & Cognition, 64,* 7-20.

Ehrlichman, H. & Weinberger, A. (1978). Lateral eye movements and hemispheric asymmetry: A critical review. *Psychological Bulletin, 85,* 1080-1101.

Ehrlichman, H., Weiner, S. L., & Baker, A. H. (1974). Effects of verbal and spatial questions on initial gaze shifts. *Neuropsychologia, 12,* 265-277.

Einstein, G. O., Earles, J. L., & Collins, H. M. (2002). Gaze aversion: Spared inhibition for visual distraction in older adults. *Journal of Gerontology: Psychological Sciences, 57B,* 65-73.

Enderle, J. D. (2002). Neural control of saccades. *Progress in Brain Research, 140,* 21-49.

Everling, S., Dorris, M. C., & Munoz, D. P. (1998). Reflex suppression in the anti-saccade task is dependent on prestimulus neural processes. *Journal of Neurophysiology, 80,* 1584-1589.

Eysenck, M. W. & Eysenck, M. C. (1980). Effects of processing depth, distinctiveness, and word frequency on retention. *British Journal of Psychology, 71,* 263-274.

Fernandez, G. & Tendolkar, I. (2001). Integrated brain activity in medial temporal and prefrontal areas predicts subsequent memory performance: Human declarative memory formation at the system level. *Brain Research Bulletin, 55,* 1-9.

Gabrieli, J. D. E., Poldrack, R. A., & Desmond, J. E. (1998). The role of left prefrontal cortex in language and memory. *Proceedings of the National Academy of Sciences USA, 95,* 906-913.

Galin, D. & Ornstein, R. (1974). Individual differences in cognitive style-I. Reflective eye movements. *Neuropsychologia, 12,* 367-376.

Galpin, A. J. & Underwood, G. (2005). Eye movements during search and detection in comparative visual search. *Perception & Psychophysics, 67,* 1313-1331.

Ganis, G., Thompson, W. L., & Kosslyn, S. M. (2004). Brain areas underlying visual mental imagery and visual perception: an fMRI study. *Cognitive Brain Research, 20,* 226-241.

Gaymard, B., Lynch, J., Ploner, C. J., Condy, C., & Rivaud-Pechoux, S. (2003). The parieto-collicular pathway: Anatomical location and contribution to saccade generation. *European Journal of Neuroscience, 17,* 1518-1526.

Gaymard, B., Ploner, C. J., Rivaud, S., Vermersch, A. I., & Pierrot-Deseilligny, C. (1998). Cortical control of saccades. *Experimental Brain Research, 123,* 159-163.

Gazzaniga, M. S. (1995). Principles of human brain organization derived from split-brain studies. *Neuron, 14,* 217-228.

Gilboa, A. (2004). Autobiographical and episodic memory-One and the same? Evidence from prefrontal activation in neuroimaging studies. *Neuropsychologia, 42,* 1336-1349.

Gladsjo, J. A., Schuman, C. C., Evans, J. D., Peavy, G. M., Miller, S. W., & Heaton, R. K. (1999). Norms for letter and category fluency: Demographic corrections for age, education, and ethnicity. *Assessment, 6,* 147-178.

Glenberg, A. M. (1997). What memory is for. *Behavioral and Brain Sciences, 20,* 1-55.

Glenberg, A. M., Schroeder, J. L., & Robertson, D. A. (1998). Averting the gaze disengages the environment and facilitates remembering. *Memory & Cognition, 26,* 651-658.

Godijn, R. & Theeuwes, J. (2002). Programming of endogenous and exogenous saccades: Evidence for a competitive integration model. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 1039-1054.

Griffin, Z. M. & Bock, K. (2000). What the eyes say about speaking. *Psychological Science, 11,* 274-279.

Gurd, J. M., Amunts, K., Weiss, P. H., Zafiris, O., Zilles, K., Marshall, J. C. et al. (2002). Posterior parietal cortex is implicated in continuous switching between verbal fluency tasks: An fMRI study with clinical implications. *Brain, 125,* 1024-1038.

Harrison, J. E., Buxton, P., Husain, M., & Wise, R. (2000). Short tests of semantic and phonological fluency: Normal performance, validity and test-retest reliability. *British Journal of Clinical Psychology, 39,* 181-191.

Henderson, J. M. & Hollingworth, A. (1999). High-level scene perception. *Annual Reviews Psychology, 50,* 243-271.

Henn, V. & Hepp, K. (1986). Pathophysiology of rapid eye movement generation in the primate. *Progress in Brain Research, 64,* 303-312.

Hepp, K., Van Opstal, A. J., Straumann, D., Hess, B. J., & Henn, V. (1993). Monkey superior colliculus represents rapid eye movements in a two-dimensional motor map. *Journal of Neurophysiology, 69,* 965-979.

Hikosaka, O., Takikawa, Y., & Kawagoe, R. (2000). Role of the basal ganglia in the control of purposive saccadic eye movements. *Physiological Reviews, 80,* 953-978.

Hirshorn, E. A. & Thompson-Schill, S. L. (2006). Role of the left inferior frontal gyrus in covert word retrieval: Neural correlates of switching during verbal fluency. *Neuropsychologia, 44,* 2547-2557.

Hiscock, M. & Bergstrom, K. J. (1981). Ocular motility as an indicator of verbal and visuospatial processing. *Memory & Cognition, 9,* 332-338.

Jacobs, L., Feldman, M., & Bender, M. B. (1972). Are the eye movements of dreaming sleep related to the visual images of the dreams? *Psychophysiology, 9,* 393-401.

Johnson Jr., R., Kreiter, K., Zhu, J., & Russo, B. (1998). A spatio-temporal comparison of semantic and episodic cued recall and recognition using event-related brain potentials. *Cognitive Brain Research, 7,* 119-136.

Kapur, S., Craik, F. I. M., Tulving, E., Wilson, A. A., Houle, S., & Brown, G. M. (1994). Neuroanatomical correlates of encoding in episodic memory: Levels of processing effect. *Proceedings of the National Academy of Sciences USA, 91,* 2008-2011.

Kendon, A. (1967). Some functions of gaze-direction in social interaction. *Acta Psychologica, 26,* 22-63.

Kinoshita, S. (1989). Generation enhances semantic processing? The role of distinctiveness in the generation effect. *Memory & Cognition, 17,* 563-571.

Kinsbourne, M. (1972). Eye and head turning indicates cerebral localization. *Science, 176,* 539-541.

Klein, D., Milner, B., Zatorre, R. J., Meyer, E., & Evans, A. C. (1995). The neural substrates underlying word generation: A bilingual functional-imaging study. *Proceedings of the National Academy of Sciences USA, 92,* 2899-2903.

Kleinke, C. L. (1986). Gaze and eye contract: A research review. *Psychological Bulletin, 100,* 78-100.

Kocel, K., Galin, D., Ornstein, R., & Merrin, E. L. (1972). Lateral eye movement and cognitive mode. *Psychonomic Science, 27,* 223-224.

Lawrence, B. M., Myerson, J., Oonk, H. M., & Abrams, R. A. (2001). The effects of eye and limb movements on working memory. *Memory, 9,* 433-444.

Lepage, M., Ghaffar, O., Nyberg, L., & Tulving, E. (2000). Prefrontal cortex and episodic memory retrieval mode. *Proceedings of the National Academy of Sciences USA, 97,* 506-511.

Lorens, S. A. & Darrow, C. W. (1962). Eye movements, EEG, GSR and EKG during mental multiplication. *Electroencephalography and Clinical Neurophysiology, 14,* 739-746.

MacDonald, B. H. & Hiscock, M. (1992). Direction of lateral eye movements as an index of cognitive mode and emotion: A reappraisal. *Neuropsychologia, 30,* 753-755.

Martin, A. & Chao, L. I. (2001). Semantic memory and the brain: Structure and processes. *Current Opinion in Neurobiology, 11,* 194-201.

Martin, A., Wiggs, C. L., Lalonde, F., & Mack, C. (1994). Word retrieval to letter and semantic cues: A double dissociation in normal subjects using interference tasks. *Neuropsychologia, 32,* 1487-1494.

Meskin, B. B. & Singer, J. L. (1974). Daydreaming, reflective thought, and laterality of eye movements. *Journal of Personality and Social Psychology, 30,* 64-71.

Milner, B. (1971). Interhemispheric differences in the localization of psychological processes in man. *British Medical Bulletin, 27,* 272-277.

Miyashita, Y. (2004). Cognitive memory: Cellular and network machineries and their top-down control. *Science, 306,* 435-440.

Monsch, A. U., Bondi, M. W., Butters, N., Salmon, D. P., Katzman, R., & Thal, L. J. (1992). Comparisons of verbal fluency in the detection of dementia of the Alzheimer's type. *Archives of Neurology, 49,* 1253-1258.

Mort, D. J., Perry, R. J., Mannan, S. K., Hodgson, T. L., Anderson, E., Quest, R. et al. (2003). Differential cortical activation during voluntary and reflexive saccades in man. *NeuroImage, 18,* 231-246.

Moscovitch, M. & Winocur, G. (2002). The frontal cortex and working with memory. In D.T. Stuss & R.T. Knight (Eds.), *Principles of Frontal Lobe Function.* Oxford: Oxford University Press.

Moskowitz, E. & Berger, R. J. (1969). Rapid eye movements and dream imagery: Are they related? *Nature, 224,* 613-614.

Munoz, D. P. (2002). Commentary: Saccadic eye movements: Overview of neural circuitry. *Progress in Brain Research, 140,* 89-96.

Munoz, D. P., Dorris, M. C., Pare, M., & Everling, S. (2000). On your mark, get set: Brainstem circuitry underlying saccadic initiation. *Canadian Journal of Physiology and Pharmacology, 78,* 934-944.

Naghavi, H. R. & Nyberg, L. (2005). Common fronto-parietal activity in attention, memory, and consciousness: Shared demands on integration? *Consciousness and Cognition, 14,* 390-425.

Nyberg, L., Habib, R., McIntosh, A. R., & Tulving, E. (2000). Reactivation of encoding-related brain activity during memory retrieval. *PNAS, 97,* 11120-11124.

Nyberg, L., Marklund, P., Persson, J., Cabeza, R., Forkstam, C., Petersson, K. M. et al. (2003). Common prefrontal activations during working memory, episodic memory, and semantic memory. *Neuropsychologia, 41,* 371-377.

Otani, H., Widner, R. L., Whiteman, H. L., & St. Louis, J. P. (1999). Hypermnesia: The role of multiple retrieval cues. *Memory & Cognition, 27,* 928-934.

Pare, M. & Wurtz, R. H. (2001). Progression in neuronal processing for saccadic eye movements from parietal cortex area LIP to superior colliculus. *Journal of Neurophysiology, 85,* 2545-2562.

Petit, L., Orssaud, C., Tzourio, N., Salamon, G., Mazoyer, B., & Berthoz, A. (2003). PET study of voluntary saccadic eye movements in humans: Basal ganglia-thalamocortical system and cingulate cortex involvement. *Journal of Neurophysiology, 69,* 1099-1017.

Pierrot-Deseilligny, C., Muri, R. M., Ploner, C. J., Gaymard, B., & Rivaud-Pechoux, S. (2003). Cortical control of ocular saccades in humans: A model for motricity. *Progress in Brain Research, 142,* 3-17.

Pochon, J. B., Levy, R., Fossati, P., Lehericy, S., Poline, J. B., Pillon, B. et al. (2002). The neural system that bridges reward and cognition in humans: An fMRI study. *Neurobiology, 99,* 5669-5674.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32,* 3-25.

Ragland, J. D., Turetsky, B. I., Gur, R. C., Gunning-Dixon, F., Turner, T., Schroeder, L. et al. (2002). Working memory for complex figures: An fMRI comparison of letter and fractal n-back tasks. *Neuropsychology, 16,* 370-379.

Raine, A. (1991). Are lateral eye-movements a valid index of functional hemispheric asymmetries? *British Journal of Psychology, 82,* 129-135.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124,* 372-422.

Ricci, P. T., Zelkowicz, B. J., Nebes, R. D., Meltzer, C. C., Mintun, M. A., & Becker, J. T. (1999). Functional neuroanatomy of semantic memory: Recognition of semantic associations. *NeuroImage, 9,* 88-96.

Roffwarg, H. P., Dement, W. C., & Muzio, J. N. F. C. (1962). Dream imagery: Relationship to rapid eye movements of sleep. *Archives of General Psychiatry, 7,* 235-258.

Saring, W. & von Cramon, D. (1980). Is there an interaction between cognitive activity and lateral eye movements? *Neuropsychologia, 18,* 591-596.

Saunders, R. C., Mishkin, M., & Aggleton, J. P. (2005). Projections from the entorhinal cortex, perirhinal cortex, presubiculum, and to the medial thalamus in macaque monkeys: Identifying different pathways using disconnection techniques. *Experimental Brain Research, 167,* 1-16.

Sauzeon, H., N'Kaoua, B., Lespinet, V., Guillem, F., & Claverie, B. (2000). Age effect in recall performance according to the levels of processing, elaboration, and retrieval cues. *Experimental Aging Research, 26,* 57-73.

Schacter, D. L., Alpert, N. M., Savage, C. R., Rauch, S. L., & Albert, M. S. (1996). Conscious recollection and the human hippocampal formation: Evidence from positron emission tomography. *Proceedings of the National Academy of Sciences USA, 93,* 321-325.

Schacter, D. L., Norman, K. A., & Koutstaal, W. (1998). The cognitive neuroscience of constructive memory. *Annual Review of Psychology, 49,* 289-318.

Schacter, D. L. & Wagner, A. D. (1999). Medial temporal lobe activations in fMRI and PET studies of episodic encoding and retrieval. *Hippocampus, 9,* 7-24.

Singer, J. L. (1978). Experimental studies of the stream of thought. In K. Pope & J.L. Singer (Eds.), *The stream of consciousness.* New York: Plenum Press.

Singer, J. L. & Antrobus, J. S. (1965). Eye movements during fantasies. *Archives of General Psychiatry, 12,* 71-76.

Sobotka, S. & Ringo, J. L. (1997). Saccadic eye movements, even in darkness, generate event-related potentials recorded in medial sputum and medial temporal cortex. *Brain Research, 756,* 168-173.

Soraci, S. A., Carline, M. T., Toglia, M. P., Chechile, R. A., & Neuschatz, J. S. (2003). Generative processing and false memories: When there is no cost. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29,* 511-523.

Spivey, M. J. & Geng, J. J. (2001). Oculomotor mechanisms activated by imagery and memory: Eye movements to absent objects. *Psychological Research, 65,* 235-241.

Suzuki, W. A. (1996). Neuroanatomy of the monkey entorhinal, perirhinal and parahippocampal cortices: Organization of cortical inputs and interconnections with amygdala and striatum. *Seminars in the Neurosciences, 8,* 3-12.

Totten, E. (1935). Eye movement during visual imagery. *Comparative Psychology Monographs*.

Troyer, A. K. (2000). Normative data for clustering and switching on verbal fluency tasks. *Journal of Clinical and Experimental Neuropsychology, 22,* 370-378.

Troyer, A. K., Moscovitch, M., & Winocur, G. (1997). Clustering and switching as two components of verbal fluency: Evidence from younger and older healthy adults. *Neuropsychology, 11,* 138-146.

Walla, P., Hufnagl, B., Lindinger, G., Imhof, H., Deecke, L., & Lang, W. (2001). Left temporal and temporoparietal brain activity depends on depth of word encoding: A magnetoencephalograhic study in healthy young subjects. *NeuroImage, 13,* 402-409.

Wang, X., Jin, J., & Jabri, M. (2002). Neural network models for the gaze shift system in the superior colliculus and cerebellum. *Neural Networks, 15,* 832.

Weiner, S. L. & Ehrlichman, H. (1976). Ocular motility and cognitive process. *Cognition, 4,* 31-43.

Weitzenhoffer, A. M. & Brockmeier, J. D. (1970). Attention and eye movements. *The Journal of Nervous and Mental Disease, 151,* 130-142.