SACCADIC EYE MOVEMENTS IN NON-VISUAL COGNITION: DATA ACQUISITION, RELATIONSHIP WITH MEMORY, AND SENSITIVITY TO PHYSICAL PRESENCE OF AN INTERLOCUTOR

By

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Abstract

Saccadic Eye Movements in Non-visual Cognition: Data Acquisition, Relationship with Memory, and Sensitivity to Physical Presence of an Interlocutor

by

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This study was designed to collect evidence that a subset of the human saccadic eye movement repertoire may be intrinsic to internal cognitive processing and independent from social or perceptual aspects of ongoing cognitive activity. We refer to saccades that accompany processing of internal information as non-visual eye movements (NVEMs) and variations in saccadic activity during different cognitive tasks as non-visual gaze patterns (NVGPs). Because cognitive tasks are typically performed with eyes open, it is of paramount importance for the validity of NVGP research to establish that NVEMs are in fact non-visual. This was the primary goal of Experiment 1 in which data were collected with eyes closed and open using video recordings and electrooculography (EOG). EOG power which integrates frequency and amplitude of EMs was compared to eye-movement rate (EMR) obtained by counting visible EMs from a video record. NVGPs were found with eyes open and closed and EOG power was found to be highly correlated with EMR. Experiment also 1 tested the proposition that NVGPs reflect memory functions, specifically that search through LTM triggers EMs and maintenance of information in WM triggers fixation. While significant effects of LTM search were found both when eyes were open and closed, the effect of maintenance was inconclusive.

A significant effect of LTM search was found using both verbal and non-verbal tasks. Experiment 2 examined the possibility that high EMR is elicited by search for information in LTM. Consistent with this idea, EMR was found to be significantly higher in free recall than in repetition and recognition. EMR was also examined in the presence of social factors. Presence or absence of the experimenter had no effect on the known pattern of NVEMs. In addition, significantly more EMs occurred in high than in low retrieval tasks even when participants were instructed to keep their gaze fixed on the experimenter. Although gaze fixation significantly reduced EMR, spontaneous saccades occurred more often in high than in low-retrieval tasks. Collected evidence strongly attests to the possibility that NVEMs are related to memory as suggested by ample indications of neuroanatomical linkage between oculomotor and memory systems.

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Specific Aims

This study was designed to collect evidence that a subset of human saccadic eye movement repertoire may be intrinsic to internal cognitive processing and independent from social or perceptual aspects of ongoing cognitive activity. Research in our laboratory has reliably related frequency of ocular motility to retrieval requirements of non-visual cognitive tasks. Spontaneous saccades occur at a significantly higher rate in high retrieval tasks (e.g., episodic memory) than in low retrieval tasks (e.g., continuous performance). Spontaneous saccades in such tasks tend to occur in bursts separated by periods of ocular quiescence. In high retrieval tasks, periods of saccadic activity are separated by periods of gaze fixation, while in low-retrieval tasks periods of ocular quiescence tend to be separated by occasional saccades. Patterns of ocular coactivation with processing of information are referred to as non-visual gaze patterns (NVGPs). It is proposed that saccadic eye movements occur in relation to search through long-term memory (LTM) and that gaze fixations reflect maintenance of information in the temporary memory store, mainly the episodic buffer (EB) of working memory (WM). According to this proposal, the difference in eye-movement rate (EMR) in high and low-retrieval tasks is carried by eye movements that occur during periods in which people seem to be searching for relevant information in LTM. Although such a proposal appears to best explain the existing empirical findings, alternative explanations of task-related difference in EMR and the role of external factors in ocular motility must be considered.

With two experiments, the present research attempted to accomplish the following goals:

1. To seek firm evidence that NVGPs are not a result of external visual factors

2. To test the feasibility of EOG power analysis as a means of assessing NVGPs both in eyes open and eyes closed conditions;.

3. To test the LTM-WM hypothesis which states that the rate of eye movements reflects the degree to which processing of cognitive tasks requires searching through LTM and maintenance in WM.

4. To examine whether the LTM-WM hypothesis generalizes to non-verbal material.

5. To explore whether NVGPs found in settings with minimal visual and social stimuli also occur in face-to-face interactions;

6. To examine whether NVGPs can be related to LTM in general or to a specific memory functions such as searching through LTM during recall**.**

Introduction

In accord with their role as gatherers of information from the visual world, saccades are predominantly "exogenous" in nature (i.e., driven by visual stimuli), determined by the visual context and modulated by perceptual goals (Montagnini & Chelazzi, 2005). Whether involuntary (i.e., stimulus driven) or voluntary (i.e., driven by a perceptual goal), they swiftly channel the gaze toward relevant sources of information and in this way enable constant input of visual information (Ross & Ma-Wayatt, 2003). Nevertheless, although the majority of saccades function in the service of vision, both empirical and anecdotal evidence recognize the existence of saccadic eye movements that are not related to external stimuli. These endogenous saccades seem to be related to cognitive (e.g., Antrobus, 1973) and not emotional (Singer & Antrobus, 1965) or sensory (Ehrlichman & Barret, 1983) stimuli. These spontaneous, visual-stimulus-independent eye movements are often psychologically silent in the sense that they are not consciously

monitored, yet are persistent companions of non-visual cognitive processes involved in thinking and memory (e.g., Glenberg, 1997). This thought-related ocular activity does not occur only in experimental or clinical settings but is an easily observed regularity of human gazing behavior that involves only eye movements of the saccadic type.

Saccadic Eye Movements

Saccades are rapid, conjugate eye movements that swiftly shift the gaze among points distributed at the same viewing distance in the visual field (Cumming, 1978). Their high velocity, ballistic nature, and absence of continuous control during movement, make saccades efficient gatherers of information for the fast-processing visual system. Saccades are the only type of eye movements that bring new information onto the fovea; all other eye movements (smooth pursuit, vergence and vestibular) serve to stabilize the image already on the fovea. They are controlled by cortical oculomotor centers (e.g., frontal eye field; parietal eye field) and generated in the brain stem (Munoz, 2002; Pierrot-Deseilligny, Ploner, Muri, Gaymard, & Rivaud-Pechoux, 2002). Their physiological profile (angular displacement, velocity, and acceleration) is a product of the mechanisms used by pretectal structures to control mechanical pointing of the eyes (e.g., inhibition), and of the morphology of the oculomotor muscles that move the eyes.

Saccadic eye movements are accomplished by a set of six extraocular muscles that work in pairs to control angular direction of the eyeball. Each extrinsic ocular muscle has a tonal part that acts like a low frequency mechanical filter and a twitch part that can respond at extremely high frequencies. These muscles are not prone to fatigue (acceleration is directly proportional to the net muscular force of the movement) (Lion & Brockhurst, 1951). Neural signals for saccadic movement are created in pretectum based

on retinal error signals (Cumming, 1978). Saccades can take as short as 100 ms (i.e., express saccades) to initiate in response to a visual stimulus and depending on their magnitude can last between 30and 120ms (Young & Sheena, 1975). However, two consecutive saccades cannot occur in less than 200 ms (Young & Stark, 1963). Saccades are among the fastest movements performed by human muscles with a peak velocity that can be as high as 600°/second (Young & Sheena, 1975). However, the relationship between maximum velocity and amplitude of saccades is nonlinear and the maximum velocity levels of at 600°/second with EMs of 30 degrees (Zuber, Semmlow, & Stark, 1968).

New saccades are triggered in response to peripheral (e.g., extrafoveal) stimuli (Rayner, 1998). In order to be registered, a visual stimulus must last for at least 12.5 msec. The percept of the stimulus persists for 250ms which is equivalent to the average duration of fixation during reading (Yang & McConkie, 2001). Because each eye movement brings new foveal stimulation, this fixation time is necessary to ensure that a stimulus is completely processed and that successive retinal images do not erase the previous ones (Antrobus, 1973). The new stimuli are brought onto the fovea by ether major or minor saccades. The major saccades are associated with the low frequency tonal response of the oculomotor muscles. They include large saccades (greater than 6.2 degrees) and small saccades (1.2-6.2 degrees). The minor saccades are associated with twitch muscles and include minisaccades (amplitude of .033-1.2 degrees; duration 10-20 ms) and microsaccades (0.01 degrees in amplitude; duration less than 10 ms). The minor saccades are essential for the perception and interpretation of visual information: microsaccades contribute to object or character group scanning while minisaccades shift

the line of sight to other features of the same object or to a new character group in reading. Large saccades typically occur within a 3-20 second range, often along with changes in head and body orientation (Cumming, 1978; Zuber, Semmlow, & Stark, 1968). While the minor saccades can only be registered with specialized equipment, major saccades are readily observable and easily studied when eyes are open, covered, closed and in the dark.

Non-visual Saccades

The systematic study of saccades in cognitive processing was pioneered by Yarbus (1967), who studied their role in visual perception and proposed that saccades enable selection of relevant information from visual scenes. However, before Yarbus (1967) demonstrated the role of saccadic eye movements in visual processing, researchers like Ladd, Moore, and Totten observed that saccadic eye movements do not always pertain to visual processing (as cited in Antrobus, 1973). Adding to initial evidence of the existence of non-visual ocular motility, Day (1964) reported that saccadic eye movements tend to occur immediately after a person is asked questions requiring some reflection but not after simple factual questions, and that people have a tendency toward making either leftward or rightward eye movements while answering reflective questions. Day named ocular movement along the horizontal axis following reflective questions the "lateral eye movement" (LEM) phenomenon, and suggested that a systematic relationship exists between attentional processes and the lateral direction of horizontal eye movements.

Following the initial reports of eye movements that did not seem to be involved in acquisition of visual information from the environment, scientific interest in non-visual

ocular motility grew around two main ideas: one, that the phenomenon reflects an interaction of endogenous cognitive activity and visual processing, and the other, that the phenomenon directly reflects the nature of ongoing cognitive activity. Throughout decades of empirical endeavor in delineating this intriguing phenomenon, these two research themes each branched out into several fields of inquiry and for the most part developed in parallel, "scanning" the phenomenon from different perspectives (for detailed description see Micic and Ehrlichman, in press). The interactive approach examined eye movements in the social context focusing on their role in conversation and gaze aversion. In this view, saccadic activity is driven by the interplay between the need to attend to internal thought processes and the need to minimize the potentially distracting effects of the visual presence of another person. Within the cognitive theme, empirical studies followed three different paths of exploration. The quasi-visual approach examined saccadic activity as it pertains to visual aspects of cognition either in terms of visual perception or visual imagery. The activation approach considered saccadic activity a manifestation of either general motoric activation or asymmetrical hemispheric activation. The cognitive processing approach studied ocular activation as a reflection of specific processing requirements of cognitive tasks. Although conceptually different, all three cognitive approaches considered ways in which control of eye movements can be modulated by cognition suggesting that ocular motility may be affected by neural activation responsible for ongoing cognitive processing

The findings of various approaches to the phenomenon converge to show that people make multiple eye movements when responding to cognitive tasks that do not seem to involve visual perception (e.g., Antrobus, 1973; Weiner & Ehrlichman, 1976)

and to suggest that the frequency with which saccadic eye movements occur in those tasks is closely connected to their processing demands (e.g., Antrobus, Antrobus, & Singer, 1964; Bergstrom & Hiscock, 1988; Ehrlichman & Barret, 1983). While some tasks produce high rates of saccadic activity other tasks produce low rates of saccadic eye movements. For example, eyes are almost immobile while a person is engaged in a continuous performance task (Ehrlichman, Micic, Sousa & Zhu, 2007, Experiment 1) but tend to move rapidly when that person attempts to recall information from LTM (Ehrlichman et al., 2007, Experiment 3) both recently learned and long-stored in semantic memory (Micic et al., Experiment 2).

Ocular motility in non-visual tasks involves a wide range of combinations of motionless and moving gaze: single saccades, groups of two or three eye movements, and bursts of saccadic eye movements all of which appear randomly and are separated by time periods of various length in which gaze is stationary. As two mutually exclusive states of ocular activity, eye movement and gaze fixation combine to create patterns of ocular activity that coordinate with requirements of tasks. The task-dependent changes in ocular dynamics are referred to as non-visual gaze patterns (NVGPs), (Micic et al., in press).

Because saccades that occur when people are engaged in cognitive activity that is not primarily visual do not appear to be activated in the service of visual perception they are referred to as non-visual eye movements" (NVEMs). This label is used to differentiate saccadic eye movements relevant to the present research from those that occur in the service of vision. It should not be taken to imply either that no visual

processing is occurring during such eye movements or that visual processing is not related to the presence of these eye movements (Micic & Ehrlichman, in press).

Indisputably, saccadic activation without a need for visual processing is paradoxical. That is one of the reasons that the phenomenon of NVEMs is still underexplored, relatively poorly understood, and often confused with related phenomena such as gaze aversion (Glenberg, 1997). Therefore, before any further theoretical accounts of NVEMs can be considered, it is of paramount importance to empirically validate the phenomenon as a non-visual occurrence. To show that NVEMs are indeed non-visual, it is important to demonstrate that they occur when the eyes are closed. This requirement is directly related to the need to design a measure that can be reliably used to assess EMs when eyes are closed and in darkness. Such a measure must be electrophysiological, must correlate highly with visually obtained measures for trials performed with the eyes open, and be sensitive to the well known effects of tasks. Only strong empirical evidence that NVEMs are indeed non-visual would justify further explorations of their relationship with internal and external factors.

In the present study, NVEMs are hypothesized to be related to both memory processes of search through LTM and maintenance in WM (Micic et al., in press). Originally it was proposed that only LTM search played an active role in the variations in frequency of NVEMs seen across tasks, but the wide range of ocular activation, particularly the presence of long stares in particular, suggested that both LTM search and maintenance in WM may be actively involved in regulating NVGPs. However, the proposal that NVGPs may be a function of dual memory processes is a new idea that

needs to be thoroughly investigated. In addition, alternative routes through which memory can affect frequency of NVEMs must be considered.

For example, it is possible that NVEMs occur at high rates in high retrieval tasks not because of searching for information in LTM but because information searched for is in LTM. This possibility could be examined by comparing frequency of NVEMs during recall and recognition. If NVEMs were a function of the search process, they should occur significantly more during recall than recognition. Another possibility is that NVGPS may reflect not memory processes but requirements for linguistic processing since existent evidence comes only from tasks involving verbal information. Therefore, the notion that NVGPs reflect memory processes independent of verbal task requirements can be asserted only if the same patterns of activation found in verbal tasks are also found in non-verbal versions of those tasks. Additionally, the claim that NVEMs may be intrinsic to memory processes must be based on evidence that NVGPs typical of high and low retrieval tasks are not sensitive to visuo-social stimuli and motor control. The present study attempted to address all these unresolved issues, and thus, delineate the cognitive profile of the phenomenon of NVEMs.

Methods of Registering Eye Movements

Typically, ocular motility in non-visual tasks is assessed in two ways. One involves video recording of participants while they engage in various cognitive tasks and subsequent data collection from the video record by counting the number of visible eye movements. Another is an electrophysiological record of eye movements that occur during tasks. Both techniques provide reliable assessment of EM frequency but the most detailed information about EMs is obtained with eye trackers. Eye tracking instruments

provide information on frequency, direction and magnitude of EMs but that wealth of information is more useful in research areas in which it is important to know the direction of EMs and the position of each EM than for NVEM research which is interested solely in EMR. To our knowledge, eye tracking has not been used in NVEM studies but it is used in the studies of a related phenomenon of memory-guided EMs which direct the gaze toward the location of previously presented items that are no longer there (e.g., Richardson & Spivey, 2000).

Video Recordings

Most NVEM research involves analyses of data collected from video recordings (e.g., Ehrlichman & Barret, 1983; Glenberg, 1997; Bergstrom & Hiscock, 1988) created by the means of analog or digital video cameras. For the purpose of NVEM research, participants are usually recorded while performing non-visual tasks in a visually barren setting and under minimal auditory distractions. Participants are comfortably seated in a chair and asked to be relatively still or lean their head on a chin-rest during the experiment so that their face is always visible on the screen. The camera is positioned at various distances either directly in front of participants, (e.g., Ehrlichman, 1981), above their line of sight (Ehrlichman et al., 2007, Experiment 3) or entirely out of view (e.g. Glenberg, Schroeder, & Robertson, 1998). The reason for placing a camera outside the line of direct sight is the possibility that it could be distracting or could create a situation in which participants feel that they have to look at the camera.

Video recordings as a technique for data collection have a number of limitations. *First*, they require that the participant's head be held steady so that the eyes remain visible. Sometimes this is achieved by using a chin-rest and sometimes by participants'

conscious effort to not move their head while answering questions. *Second*, they cannot be used to assess NVGPs in the dark. Assessing ocular activity in non-visual tasks in darkness is important for testing the role of external visual information in task-related eye movements. *Third*, they may not allow for reliable collection of data in research in which eye movements are studied under closed lids. Assessing EMR from a video recording of tasks performed with closed eyes is difficult due to ocular tremor which occurs when eyes are kept closed voluntary (Singer & Antrobus, 1965). It is also difficult to discriminate between eye movements and blinks or to detect small eye movements. In their Experiment 3, Ehrlichman et al. (2007), detected significantly fewer eye movements under closed lids (the mean EMR across all items was 0.38 with a standard deviation of 0.14 and range from 0.17 to 0.66) then when eyes were open (the mean EMR across all items was 0.93 with a standard deviation of 0.35 and range from 0.31 to 1.68). Inter-judge reliability of that experiment based on the scores of two individual judges was poor: the inter-judge correlations for 15 participants ranged from .13 to .79 with a mean r = .47. Despite an overall decrease in the number of detected EMs, and poor reliability, Ehrlichman et al. found a significant task effect. Because ocular activity under closed lids eliminates possible external influences on NVGPs, it would be important to confirm this finding using a more reliable scoring system. *Fourth*, assessing eye movements from video recordings does not take into account the size of eye shifts.

Electrooculography (EOG)

Some of the limitations of data collection using video recordings can be overcome by using electrophysiological recordings of ocular activity. With electrophysiological recordings, information on ocular activity can be obtained irrespective of the level of

illumination and whether the eyes are open or closed or the head is in motion. The EOG recording is possible because the eye functions as a dipole and as such has a standing electrical potential (sometimes referred to as corneo-fundal potential, Brown, Marmor, Zrenner, Brigell, & Bach, 2006). The main source of this potential is the retinal pigment epithelium which is electrically negative compared to the front of the eye (Brown et al., 2006). The electrical potential that forms between the retina and the cornea projects to the skin and those projections can be picked up by electrodes. To obtain an EOG, five electrodes are attached to the participant's face, two at the outer canthi of the eyes for lateral movements and two above and below one eye for vertical movement. The fifth electrode is fixed at the forehead and serves as the ground. When eyes are still, electrodes register the resting potential of the retina. When eyes are in motion, electrodes register changes in the corneo-fundal potential that occur with each eye movement. On the assumption of an unchanging corneo-fundal potential, the recorded potential corresponds to the size of the eye movement, and indicates the eye position.

The EOG record provides information on the frequency, size (amplitude of the change in potential), and direction of eye movements. However, at this point, NVEM research is only interested in the frequency of eye movements in various cognitive activities. Frequency of eye movements can be determined by measuring the EOG amplitude manually, marking the inclusion criterion of the study on the EOG record, and then simply counting eye movements that meet that criterion. Most studies have based their analyses on eye movements of at least three or four degrees of angular displacement (e.g., Antrobus et al., 1964). However, counting eye movements from an EOG record may not be the most efficient way of assessing EMR since it is sometimes difficult to

discriminate between EMs and blinks or to determine the degree to which some EMs may be meeting the criterion because of their temporal overlap with blinks. Furthermore, counting EMs from an EOG record is a long and tedious process that introduces error due to fatigue during scoring.

Eye Movement Rate (EMR)

Studies of NVEMs report ocular motility either in terms of frequency counts or the number of eye movements divided by the time period within which they were observed (referred to as the eye movement rate or EMR). In our lab, EMR is obtained from video recordings by using software developed by John Zhu which allows the original video mpeg files to be modified in terms of the speed and size of the image. In the process of scoring, the end of the question and answer periods for each item are marked and then each eye movement is entered manually on the time continuum of each marked segment. To allow for precise registration of individual eye movements, the video is played at half the original speed and the image is increased to 160% its original size. For between-subject comparisons, the size of the image of participant's face may be adjusted in order to achieve an equivalent pupil diameter for all participants. Whenever an eye movement is detected, the observer presses a key and the eye movement is marked in a visual display saved in a log file that provides a record of the session. The scorer marks only unambiguous saccadic eye movements; that is, if the scorer is not sure an eye movement has occurred, it is not counted. This approach to scoring has consistently produced highly reliable judgments of eye movements as small as 3 degrees of angular displacement. Reliability has been assessed in a number of previous studies in which the complete video record from several randomly selected participants was scored by two or

three independent judges. EMR was computed for each trial by dividing the number of eye movements by the number of seconds in the answer period of the trial. Correlations were computed over the total set of trials for each participant resulting in a set of correlations between pairs of observers. Interjudge reliability in these studies was found to be very high, mostly over .90. Attempts to reliably measure eye movements under closed eyelids have been much less successful, with average interjudge correlations around .40 (e.g., Ehrlichman et al., 2007).

EMR is obtained from an EOG record manually. The process involves marking the beginning and the ending of a trial, identifying the criterion and counting every EM that is equal to or larger than the criterion irrespective of their direction. The EOG record can be used to validate EMR obtained from video records but manual scoring may lack precision and EOG is prone to blinking artifacts. Since EOG can be used in the full range of eye and lighting conditions and in both clinical and non-clinical settings, finding a way to clear the EOG of blinking artifacts and to produce an automatic, computer based measure of ocular activity is important.

In an EOG, ocular activity is represented in two planes. Upward and downward EMs are captured by the vertical channel which is also very sensitive to blinking, Leftward and rightward Ems, as well as oblique EMs, are captured by the horizontal channel which is less sensitive to blinks. Since the majority of NVEMs occur in the horizontal plane or have a very strong horizontal component registered by the horizontal channel, one way of reducing blinking artifacts from an EOG is to base data collection only on the horizontal channel. Hence, it is essential to establish whether registering

horizontal eye movements can provide a sufficient record of ocular activity, one that is comparable to EMR based on the full range of EMs observed from a video record.

EOG Power

Electrophysiological data in this study was analyzed using software written by John Zhu that utilizes EOG power as a tool of assessing ocular motility. This method of assessing ocular activity is mostly used to remove EOG artifacts from electroencephalographic recordings (e.g., Gasser, Jennen-Steinmetz, & Verleger, 1987), and in sleep research (e.g., Darchia, Campbell, & Feinberg, 2003). To my knowledge, EOG power has never been used to study NVEM patterns. Direct comparison of EMR obtained using video scoring and EOG power is an important step in validating the methodology which may be particularly applicable to assessment of ocular activity in the dark and in eyes closed conditions. In previous research, we attempted to assess NVGPs with eyes closed by observing EMs under the eyelids. Although we found a significant task effect, inter-judge reliability was poor. EOG power might provide a reliable way of testing whether NVGPs occur with eyes closed as well as with eyes open.

In NVGP research, assessing EMR involves counting EMs that satisfy a specified amplitude criterion. Consequently, amplitude of EMs is only considered in reference to the inclusion criterion, and the absolute size of EMs does not influence EMR. Each EM above the criterion is counted and gets equal weight regardless of its magnitude; an EM of 3 degree is “worth” as much as one of 70 degrees. Therefore, EMR is a measure of saccadic frequency rather than a measure of ocular activity in a more inclusive sense.

Because the electrical potential generated during an EM is a measure of ocular displacement, average electrical potential (i.e., power) of a trial is a function of both

frequency and amplitude of EMs that occurred in that trial. Currently, there is no information on how much each of the parameters contributes to EOG power and we do not know how EOG power relates to the EMR acquired by methods in which discrete EMs are counted independent of amplitude. As a result, we do not know whether EOG power will show the same NVGPs that we find in existing EMR research or how closely EOG power will match results found with visual scoring of EM frequency. To the extent that EOG power reflects frequency of EMs rather than amplitude of EMs, correlations between the two methods should be high and power should show the same task-related patterns as visually assessed EMR. This relationship should not be affected due to elimination of the vertical channel because the horizontal channel registers not only leftward and rightward EMs but also the horizontal component of oblique EMs. On the other hand, if amplitude plays a larger role in EOG power, then correlations between the two methods would be attenuated. It is not clear what the task-related effects would be in this case since we do not know whether amplitude is related to tasks or not.

The algorithm for this program involves a series of steps designed to follow the distribution of EMs around the point of primary position (Cook, Stark, & Zuber, 1966). Preliminary analysis of data collected with a series of calibration trials including trials with no EMs and trials with 5, 10 and 15-degree EMs, provided strong evidence that EOG power can be used to assess frequency of EMs. Because the net power of an EM is a sum of two independent powers, the power of baseline and the power of EM and the assumption is that baseline power should be relatively stable for an individual and not vary significantly between trials, once the raw power of eye movement is reduced by the baseline power, the relationship between the frequency of EMs and their power becomes

evident. For example, the power of ten 15-degree EMs (348) is two times larger than the power of five 15-degree EMs (173). This relationship can be mathematically expressed as P10 = 2 x P5. The practical implication of this relationship is that the power can be use to indicate the frequency of EMs in a trial.

The initial analysis using raw power of 5, 10, and 15-degree EMs indicated that by being sensitive to the number of the same-size EMs, the net power of a trial may be a promising novel measure of saccadic frequency. Because empirical analyses based on the total power of EMs include the ever-present noise in the signal, the relationship between EOG power and EMR may be less than perfect. In computations of EOG power, amplitude becomes a concern with large and sweeping EMs that cross the midline but which are not typical constituents of NVGPs. Since they are infrequent but carry a lot of power, they can distort the average power emitted by the majority of NVEMs. Because the objective in using EOG power is to provide information on EM activity comparable to that obtained by visual scoring, the effect of large EMs on total power has to be minimized.

In the absence of empirical evidence of the relationship between EOG power and size of Ems, the criterion for clipping in this study had to be based on the power values of calibration trials and on the fact that NVEMs are mostly small and rarely cross visual midline (Ehrlichman et al., 2007). Based on the available information it appeared that clipping the power of individual trials at 500 mV should clear the record of the effect of large amplitudes without compromising contribution of EM frequency to the measure. Because it is currently not known what portion of EOG power comes from EM frequency, and because of the exploratory nature of this inquiry, power was also clipped

at 1000 mV and 4000 mV which carry less risk for reducing the frequency component of EOG power. Multiple clipping levels allowed for the preliminary assessment of the best method of reducing the amplitude, but not the frequency component, of EOG power through comparison of the average of sets of EMR-EOG correlations using various corrections. Consequently, task effects on NVEMs could be assessed using the EOG power measure that best corresponds to EMR.

NVEMs and Memory

While considering various possible sources of NVEMs (e.g., arousal, mental imagery, interference) several researchers including Antrobus (1973), Ehrlichman and Barrett (1983), and Bergstrom and Hiscock (1988) noticed that frequency of NVEMs may be related to memory. To explore this possibility, Ehrlichman et al. (2007) compared a variety of tasks that differed in their requirements for retrieval of information from LTM. Low retrieval tasks included vigilance tasks, tasks requiring rote memory (e.g., reciting the alphabet), and tasks requiring maintenance (e.g., delayed word repetition) and manipulation (e.g., reporting the number of vowels in three words) of information in temporary memory while high-retrieval tasks involved episodic recall (e.g., recalling a list of words), semantic fluency (e.g., reporting three synonyms of a given word) and autobiographical memory (e.g., recalling a past personal event).

Ehrlichman et al. (2007) considered the memory hypothesis alongside the alternative explanations that NVGPs are a function of difficultly, mental imagery (Experiment 1), arousal (Experiment 2) and visual interference (Experiment 3). In all three experiments, the mean EMR of high-retrieval tasks was significantly higher than the mean EMR of the low-retrieval tasks and effect sizes measured with *eta-squared*

were very large ranging from 0.74 to 0.96. There was no evidence that difficulty or imagery had an effect on EMR in low and high retrieval tasks. The question of the role of difficulty is important to NVEM research because there is evidence that it can affect EMR (Lorens & Darrow, 1962) and rate of gaze aversion (Glenberg eta l., 1998) and, consequently, it was addressed in all three experiments. However, all experiments reported that between- tasks differences in EMR could be attributed to retrieval requirements, not to difficulty.

The Ehrlichman et al. (2007) study provided strong evidence that ocular activity in non-visual cognitive tasks may be best understood in terms of the degree to which tasks require retrieval from LTM. The only factor consistently influencing the rate of eye movements was LTM retrieval; neither visual imagery, nor difficulty, nor requirements for overt verbal responding were related to between-task differences in EMR. Overall, the EMR of relatively high-retrieval tasks (mean = 1.08) was twice that of the EMR of relatively low-retrieval tasks (mean = 0.52) with very large effect sizes (mean d = 2.21; mean η^2 = .89). In addition, the EMR of a baseline, no-task condition fell midway between the EMR for high and low retrieval tasks. Importantly, different versions of tasks that evoked high or low amounts of visual imagery (as indicated by participants' ratings) revealed no effect of imagery on EMR, thus replicating the findings of Bergstrom and Hiscock (1988). These findings support the idea that gaze patterns in non-visual tasks with various requirements for retrieval of information may be related to memory operations activated in order to perform those tasks. According to the memory hypothesis, the difference in saccadic frequency is a direct consequence of searching through LTM in high retrieval tasks which is absent in low retrieval tasks.

The claim that changes in the gaze patterns found in tasks that do not involve external or memory-based visual information may reflect processes performed within the milieu of memory functions was further tested in three experiments conducted by Micic et al (in press). Their study examined whether or not spontaneous saccadic eye movements are related to LTM retrieval (Experiment 1), addressed the possibility that saccadic frequency reflects the degree of accessibility of items stored in LTM (Experiment 2), and assessed whether or not saccadic eye movements have a functional role in retrieval from LTM (Experiment 3).

By using structurally comparable tasks with different retrieval demands, Experiment 1 of Micic et al. (in press) provided substantial support for the LTM hypothesis. Tasks which shared basic task structure but differed in requirements for LTM search were found to differ dramatically in EMR, while tasks that differed in basic task structure but required LTM search produced virtually identical EMRs. This was an important finding because in the studies that provided initial evidence of the involvement of memory related functions in NVGPs (Bergstrom & Hiscock, 1988; Ehrlichman et al. 2007), low- and high-retrieval tasks also differed in other respects. For example, in the Ehrlichman et al. (2007) study, all of the high retrieval tasks required participants to answer questions concerning general knowledge or autobiographical information (e.g., naming modes of transportation; recalling number of movies seen in the last two weeks). In contrast, the low retrieval tasks included a variety of continuous performance and working memory tasks, some of which involved presentation of external auditory stimuli and required motor responses (e.g., clicking when a specified pattern was heard in a list of spoken letters). Therefore, in order to uphold the LTM hypothesis, it was necessary to

rule out the possibility that task-related changes in EMR may not be a result of retrieval requirements but an artifact of extraneous factors. While Experiment 1 found strong support that EMR increases in tasks requiring LTM search, Experiment 2 found no evidence that accessibility of items in LTM had an effect on the pattern of saccadic activity in these tasks. That any type of LTM tasks other than rote overlearned retrieval elicits high EMR was further confirmed in Experiment 3 which found no evidence that high EMR of high-retrieval tasks affects performance.

Micic et al. (in press) confirmed that NVGPs accompany retrieval and maintenance of internal information in a reliable and predictable way: tasks relying on retrieval of information from LTM consistently and independently of voluntary oculomotor control are associated with significantly more saccades than tasks that do not require access to LTM. The study demonstrated that the tendency to produce multiple saccades in high retrieval tasks is very strong and neither easily nor completely suppressed by voluntary gaze fixation but is absent in low retrieval tasks. According to the LTM model of NVGPs (Ehrlichman et al., 2007), the strong tendency toward generation of saccades is triggered by search through distributed networks of LTM while the tendency to suppress saccadic activity occurs when information needed for further processing is readily available in the episodic buffer, the interface between WM and LTM (Baddeley, 2000). In the lack of evidence that high EMR of high-retrieval tasks is functionally significant, this study concluded that NVGPs may be an epiphenomenon of activated memory functions of search and maintenance.

In contrast to studies of NVGPs, evidence that eye movements may play a functional role in memory comes from the study of phenomena such as gaze aversion

(e.g., Glenberg et al., 1998) and memory-guided saccades (Richardson & Spivey, 2000). Research on gaze aversion provides ample evidence that while answering difficult questions both adults and children tend to shift their gaze away from visual displays (Glenberg et al., 1998), and from the questioner both in face-to face (Doherty-Sneddon, Bruce, Bonner, Longbotham, & Doyle, 2002; Glenberg, 1997) and in live video link situations (Doherty-Sneddon & Phelps, 2005), and that repositioning of the gaze improves performance (e.g., Doherty-Sneddon, Riby, Calderwood, & Ainsworth, 2009).

According to the 'looking at nothing' phenomenon (Ferreira, Apel, & Henderson, 2008), spontaneous saccadic eye movements that occur in recall are related to memory (e.g., Richardson, Altmann, Spivey, & Hoover, 2009) and indicate auditory, visual and spatial features of a previously experienced stimulus (Richardson & Kirkham, 2004; Richardson & Spivey, 2000). Evidence shows that eye movements to empty spatial locations accompany recall of visual information *(*Laeng & Teodorescu, 2002), processing of relevant spoken information (Altmann, 2004; Altmann & Kamide, 2004), and recall of spoken semantic information (Richardson & Kirkham, 2004; Richardson & Spivey, 2000). However, *w*hether or not "looking at "objects that are no longer there" (Richardson & Spivey, 2000) is functionally significant for retrieval is yet to be determined (e.g., Ferreira et al., 2008; Hoover, & Richardson, 2008).

The relationship between eye movements and memory and the potential functionality of saccadic activity in retrieval of information is also suggested by researchers interested in the effect of bilateral horizontal eye movements on episodic retrieval (e.g., Christman & Propper, 2001). Several studies report facilitatory effects of voluntary bilateral saccades on episodic recognition and retrieval (e.g., Christman,

Garvey, Propper, & Phaneuf, 2003; Parker, Relph, & Dagnall, 2008). This effect is specific to saccadic eye movements and does not occur after smooth pursuit or fixation. Saccades elicited in these studies are large (27°), and typically cross the midline. It is proposed that eye movements improve retrieval from episodic memory by increasing interhemispheric activation (Christman et al., 2003).

Eye movements detected in NVEM research are generally smaller than the voluntary saccades elicited in the bilateral eye movement studies (< 15°), are not voluntary and do not seem to improve performance on tasks involving retrieval of episodic and semantic information (Ehrlichman et al., 2007).. Most of the time people are not aware that they start moving their eyes at some point while trying to recall information from LTM. These eye movements occur spontaneously and occur at a variable rate and in random directions during a task. While there is no doubt that the direction of eye movements may be related to spatial aspects of the 'episodic trace' of information (Altmann, 2004; Altmann & Kamide, 2007), research on NVEMs presents compelling evidence that ocular behavior may also be related to cognitive processes that do not reference contextual (e.g., spatial, temporal, sensory modality) aspects of information. While lateral eye movement (LEM) research did not find consistent evidence linking the direction of eye movements to type of information being retrieved, a growing body of evidence collected within the cognitive approach to NVEMs suggests that the frequency with which NVEMs occur may indicate the type of memory function activated: when information is retrieved from LTM, saccadic frequency is found to be high and when information is to be maintained or manipulated in WM, saccadic frequency is low (e.g., Micic et al., in press).

Maintenance in Working Memory

The abilities to maintain and manipulate information relevant for the subsequent behavior but no longer available in the environment are essential for successful processing within WM. The ability to maintain information is studied with experimental paradigms designed to isolate component processes of WM by introducing a delay between stimulus presentation and response production (e.g., delayed match-to-sample tasks). In this paradigm, subjects are presented with a cue stimulus, asked to maintain information about that stimulus during a brief delay in which stimulus is removed from the environment, and finally, to respond to a probe stimulus so that it can be determined whether information about the cue stimulus was successfully retained. Although the delay between presentation and testing serves as the means of examining the ability to retain information over brief periods of time, multiple processes are active during the delay. Alongside efforts to maintain information (e.g., rehearsal), subjects may engage in suppression of distraction, mental timing, expectancy, preparation of motor response, monitoring of internal and external states, and preservation of alertness (Gazzaley, Rissman, & D'Esposito, 2004).

Dual Task. Although co-occurrence of multiple processes may not be entirely avoided in experimentation, the uncertainty about processes activated alongside maintenance during a delay in which there is no task to be performed may be significantly reduced by introducing maintenance as a secondary task in a dual task paradigm. Typically, in a dual task paradigm, subjects are required to perform two tasks simultaneously and performance on those tasks is compared to single-task conditions to examine whether or not processes required by two tasks draw on the same pool of

processing resources. For example, having to say ‘the” selectively affects performance on a verbal but not on a visuo-spatial task (Baddeley & Hitch, 1974), while performing a spatial tacking task affects performance on a visual imagery but on a verbal task (Baddeley, Grant, Wight, & Thomson, 1973).

For cognitive processes that can be conducted in parallel, a secondary process may serve as the means of controlling the occurrence of various internal processes often activated during thinking. On the assumption that there is a strong tendency to monitor our output and especially when undergoing a test, it can be expected that maintenance of a specified aspect of an answer should not interfere with the ability to perform the primary task. In this scenario, if subjects are asked to report the number of instances in which a specific type of item occurred, the set of accompanying processing would be highly predictable: subjects would have to monitor items for the specified quality, select those that satisfy the requirement and maintain the mental tally of targets. When the distribution of items is completely random, no expectancies should form, and because of the demands of a dual tasks situation, the need to reduce internal distraction or to preserve alertness should be minimal if not completely absent.

In accord with the proposition that WM involves contributions of multiple subcomponent processes (Baddeley, 2000) multiple brain regions associated with basic operations of WM have been detected, some of them in the prefrontal cortex (PFC). Event-related functional magnetic resonance imaging of human brain during spatial memory task associated selection with activation of Brodmann area (BA) 46 of the dorso-lateral prefrontal cortex (DLPFC)and maintenance with activation of BA 8 and the intraparietal cortex (Rowe, Toni, Josephs, Frackowiak, & Passingham, 2000). However,

neurophysiological experiments with monkeys indicate that WM maintenance is a process supported by a widely distributed network whose functional connectivity enables integration of information processed by the PFC, the parietal cortex, and posterior unimodal association areas. There is evidence that the neural network mediating on-line maintenance of faces includes DLPFC and ventro-lateral PFC (VLPPFC), the premotor cortex, the intraparietal sulcus, the caudate nucleus, the thalamus, the hippocampus, and occipitotemporal regions (Gazzaley, et al., 2004).

Retrieval from Long-term Memory

Memories stored in LTM can be accessed through semantic and episodic retrieval (Tulving, 1986). Semantic retrieval involves retrieval of information that constitutes general knowledge of the world such as vocabulary, public events and personalities, and personal facts (Tulving, 1994; Tulving, 2002). Information stored in semantic memory is devoid of temporal and spatial context in which it was acquired which is contrary to the way information is stored in episodic memory (Tulving, 1983). Episodic memory encodes, stores, and makes available for retrieval memories of personally experienced events (Tulving, 1983). Retrieval of such memories involves content of an event, individual perspective of the person recalling an event, and information about temporal and spatial parameters of the event is more complex than retrieval of semantic memories (Tulving, 1983). The ability to retrieve information from episodic and semantic memory can be assessed using direct tests of memory such as recall and recognition.

Free Recall. In recall, an attempt is made to access events or information stored in LTM and to bring them to conscious awareness. This can take a form of free recall, cued recall, and serial recall. Free recall, as a basic experimental paradigm, involves a

list of items, a study session with a specified number of trials, and a test session of specified duration. After the study session, participants are prompted to recall as many items from the list as possible and in any order. Items used in free recall are traditionally words, randomly selected from a larger set, although any type of material that can be named or reproduced is appropriate. At study, items are presented one at the time and presentation rate varies between 20 ms (McDermott & Watson, 2001) and five seconds (Johnston & Jenkins, 1971; McDermott & Watson, 2001). Recall sessions can start immediately after the last trial as is the case in immediate free recall, or after a delay which is often filled with distracter tasks, as in delayed free recall. Recall can last from 30 seconds to few minutes and involve either spoken or written presentation of retrieved information.

Performance on free recall can be measured by the number of words recalled which can depend on factors such as familiarity, frequency and length of words, the type of material, the list length, and the task used to process the material (e.g. repetition). In the multi-trial version of free recall performance is measured by a number of trials needed to learn a specified proportion of items. Because there are no instructions on how to retrieve information, free recall is a fruitful paradigm for the study of principles of memory organization such as the serial position effect (Murdock, 1962) in which probability of recall is much greater for initial and terminal items (primacy and recency effect, respectfully) than items located in the middle of the list, the tendency to report terminal items from the study list first during free recall (Hogan, 1975), lag-recency effects which is the tendency to report neighboring items from the study list in succession (Kahana, 1996), and subjective organization of the list in which on multiple recall trials

words recalled successively in initial recall trials tend to be recalled in the same manner in later recall trials (Tulving, 1968).

Verbal Fluency. In addition to studying memory for test study items, retrieval from LTM can be studied by testing recall of already stored information such as semantic knowledge. This is accomplished with verbal fluency tests which require retrieval of words stored in the mental lexicon. Two commonly used versions of verbal retrieval tasks are semantic fluency and phonemic fluency (Azuma, 2004). In semantic fluency, participants are asked to recall words from a specific semantic category (e.g., colors) and in phonemic fluency, participants report words staring with a specific letter (e.g., words beginning with letter 'p'). Early reports of retrieval from semantic memory used unconstrained free recall or a free emission paradigm in which an individual names over a period of several minutes as many members of a large category (e.g., animals) as possible. Commonly used versions of the phonemic fluency tasks are "FAS" and "CFL" fluency (Lacy et al., 1996). The variant of the phonemic fluency that is used the most is the controlled oral word association task (COWAT) (Loonstra, Tarlow, Sellers, 2001). Word retrieval is typically timed at 60 seconds. Both tests of verbal fluency are used as standard methods of neuropsychological assessment (Harrison, Buxton, Hisain, & Wise, 2000).

Performance on verbal fluency tasks is typically assessed with the total number of words reported. Other performance measures include number and length of clusters of words from the same semantic or phonetic subcategory, number of switches between categories (Troyer, Moscovitch, & Winocur, 1997), and number of repetitions. During retrieval, items tend to be produced in bursts of either semantically or phonetically related

words (e.g., Troster et al., 1998). In semantic fluency, typical category exemplars are reported more than less typical ones, earlier in the list and with higher frequency (e.g., Kail, & Nippod, 1984). The rate of production of new items declines hyperbolically over the duration of the task (e.g., Gruenwald, & Lockhead, 1980). These characteristics are consistent findings of research with adults and with children (Henley, 1969; Kail, & Nippod, 1984). Performance on semantic fluency tasks tends to be better than on phonemic fluency tasks (Gladsjo et al., 1999; Harrison et al., 2000) possibly due to activation of the semantic system of knowledge about an object in semantic fluency which does not occur in phonological fluency. In contrast to retrieval guided by a semantic category, letter-guided retrieval requires forming of a non-semantically associated category, and generation of words that belong to that category is more effortful (Martin, Wiggs, Lalonde, & Mack, 1994). According to neuropsychological evidence, verbal fluency tasks activate frontal and temporal lobe but frontal activation is more prominent in phonemic fluency and temporal activation is higher in semantic fluency tasks (Baldo, Schwartz, Wilkins, & Dronkers, 2006).

Recognition. Recognition allows us to correctly remember previously encountered items by matching a given environmental content with a content stored in memory. This type of retrieval is considered to involve two components: recollection (i.e., remembering) and familiarity (i.e., knowing) (Yonelinas, 1994). Familiarity is context-independent since it only requires knowledge of the stimulus features, while recollection requires that stimulus features are remembered together with the context in which the stimulus was previously experienced and is, as such, context-dependent.

While recollection requires conscious effort, familiarity tends to be an unconscious and automatic process (Jacoby, 1991).

Recognition memory can be assessed with several methods. One of the simplest forms of testing recognition is the old-new paradigm in which participants have to decide whether an item presented at testing was presented during study The response involves a 'yes" for old items and 'no' for new items. Another method of testing recognition is forced choice recognition. Participants are presented with several items, usually 2-4, one of which is a target and the rest act as distracters and has to decide which one is a previously experienced item. Yet another approach to studying recognition involves measuring response time. The main idea of mental chronometry is that speed of the response reflects complexity of an underlying physiological process, with slow reaction time occurring in complex and fast reaction time accompanying simpler processing. Response time is typically measured in milliseconds and seconds. , Recognition studies cover a wide span of materials including words (e.g., Nobre, Allison, & McCarthy, 2002) sentences (e.g., Tulving et al., 1994) faces (e.g., Haxby et al., 1996) objects (e.g., Hofer et al., 2007; Schacter, et al., 1997) actions (e.g., Decety et al., 1997) and visual scenes (e.g., Montaldi et al., 1998). Both visual (e.g., Montaldi et al., 1998) and auditory (e.g., Tulving et al., 1994) materials are used.

Gaze and Language

Looking behavior is never random. During social interaction more eye movements occur while speaking than while listening (Argyle & Cook, 1976; Ehrlichman, 1981; Exline, Jones, & Maciorowski, 1977). Eye movement studies of language production indicate that even in the visual world, once speaking begins, the

timing and sequence of fixations is controlled by the utterance and not by the perceptual properties of the visual stimulus (Bock, Irwin, Davidson & Levelt, 2003). Evidence of the anatomical overlap of language and memory functions in the left prefrontal cortex (e.g., Desmond et al., 1995) and posterior parietal cortex (e.g., Gurd et al, 2002), and of the fundamentally linguistic nature of memory processes such as conceptual priming, semantic analysis, and episodic memory (Gabrieli, Poldrack & Desmond, 1998) opens a possibility that oculomotor control and planning could be modulated by language related processing.

Functional MRI shows that language and saccades share a cortical area in the posterior parietal lobule (Simon, Mangin, Cohen, Le Bihan, & Dehaene, 2002), thus offering one possible answer to the question of a possible relationship between eye movements and language. In line with the general role of the parietal lobe in sensorimotor conversion operations, the inferior parietal lobule is the auditory-motor interface of language processing that connects temporal area of phonological speech analysis and frontal area of articulatory speech production (Hickok & Poeppel, 2000). The area around and near the left posterior segment of the inferior parietal sulcus (IPS) beneath the left angular gyrus shows activation in response to three different tasks involving either saccades directed to visual stimuli, phonological encoding (i.e., phoneme detection), or calculation (i.e., subtraction). This activation may have been the source of the high EMR found in tasks involving hard mental multiplication problems (Amadeo & Shagass, 1963; Lorens & Darrow, 1962) and tasks involving mental solving of anagrams (Andreassi, 1973).

Although this functional overlap is to a degree a product of inter-subject averaging and smoothing of inter-individual variability, the existence of functional overlap between language-related and saccade-related cortical areas is evident with language functions being left lateralized and saccadic function causing bilateral activation. Single-subject analysis reveal that the pattern of overlap varies within the full range across subjects from no overlap, to marginal and complete overlap between language, calculation and saccade-related posterior parietal areas (Simon et al., 2002) providing biological bases for understanding of individual differences typically found in studies of NVEMs. Over various fluency tasks used in Ehrlichman et al. (2007) study, individuals' mean EMR ranged from 0.01 to 2.97 in Experiment 1; from 0.12 to 2.04, in Experiment 2, and from 0.02 to 2.39 in the free eye conditions and 0.00 to 1.74 in fixed gaze condition for all 66 participants in Experiment 3. We do not know if the same area of the IPS is activated with spontaneous non-visual saccades, but the variability in the overlap of cortical areas related to saccades, language and calculation may explain the consistent finding that correspondence between eye movements and thought is optional not obligatory (Kaplan & Schoenfeld, 1966) as well as our finding that performance on phonemic fluency tasks is not dependent on concurrent saccadic activity.

The anatomical overlap found by Simon et al. (2002) does not imply functional relevance of saccades in phonological detection and mathematical operations but it reduces the likelihood of saccadic activation being a physiological epiphenomenon based on the increase in general arousal (Antrobus, 1973) or the spread of activation (Amadeo & Shagass, 1963) within motor and premotor cortices activated during programming of a verbal response. That the difference in saccadic frequency is indeed an effect of the

question and not an artifact of differences in response requirements is well documented in literature. Whether the answer involves complex syntax or just listing of four words (Ehrlichman & Barrett, 1983), a full overt answer or just a one word acknowledgment ('okay') that the answer had been formed covertly (Hiscock & Bergstrom, 1981) does not factor into the difference in EMR found between verbal and imagery tasks. In agreement with the behavioral evidence, the finding of anatomically overlapping saccadic and phonological areas indicates that if there is a relationship between saccadic generation and language, it is based not on speech production but on the more fundamental operations necessary for thought (e.g., answer) formation such as retrieval and phonological decoding of memorial (e.g., semantic) traces. That eye movements are more related to memory processes such as LTM search than language is indicated by the findings of studies in which subjects were required to retrieve a memory of a melody and just hum a portion of it. Humming of melodies from LTM was found to produce high EMR, comparable to that of verbal-linguistic tasks (Bergstrom & Hiscock, 1988; Ehrlichman, Weiner & Baker, 1974).

Rationale for the Current Studies

Study 1: Saccadic Frequency and Memory Functions: EMR and EOG Measures

The first aim of Experiment 1 was to examine whether EOG power can be used as a measure of oculomotor activity that is equivalent to measures of ocular activity collected from a video record. To our knowledge, EOG power has never been used to study eye movement patterns. This experiment directly compared results obtained from video scoring and EOG power in order to validate the use of the new methodology for data collection in eyes closed conditions.

The second aim of this experiment was to determine whether spontaneous saccadic activation and gaze fixation can be related to memory functions of searching through LTM and maintenance of information in WM memory as proposed by the LTM-WM hypothesis. The LTM-WM hypothesis is that search through LTM triggers eye movements (EMs) but maintenance of information in WM triggers fixation. To the extent that a task requires LTM search, the task will produce high EMRs. To the extent that a task requires maintenance of information in WM, the task will produce low EMRs. Four predictions followed from these two premises:

1. EMRs are low in tasks in which all of the information necessary to complete the task can be maintained in WM without further accessing of LTM have. For example, in a two-back task, all information is held in WM while participants are responding to a particular pattern of stimuli.

2. EMRs are low to moderate in tasks where the information from LTM is highly structured. (e.g., describing one's kitchen) or involves over-learned sequences (such as the alphabet) and which do not require maintenance of information in WM (e.g., reciting the months of the year).

3. EMRs are moderate to high in tasks that require some access of information from LTM but also require maintenance of information in WM depending on how often LTM search is activated. For example, in monitored retrieval tasks, participants must keep track of features of retrieved material (e.g., the number of words in a fluency task that contain a long *e* sound).

4. EMRs are high in tasks which require extensive and repeated LTM search but do not require maintenance of information in WM (e.g., recalling information from semantic memory).

The third aim of this experiment was to examine whether NVGPs occur with non-verbal material. Previous research did not address the possibility that NVGPs may be specifically related to language; tasks used in previous research were mostly verbal and required a spoken answer: verbal-linguistic tasks such as interpretation of proverbs (e.g., Weiner & Ehrlichman, 1976), reporting of factual information (e.g., Meskin & Singer, 1974), phonological encoding of numbers and letters (e.g., Ehrlichman et al., 2007), semantic fluency (e.g., Ehrlichman et al., 2007) etc. Non-verbal tasks such as musical questions requiring humming were seldom used to asses EMR (Ehrlichman et al., 1974, Experiment1, Bergstrom & Hiscock, 1988, Experiment1) and LEMs (Kocel, Galin, & Ornstein, 1972).

The existing evidence suggests that it is not speech but active accessing of linguistic information that may act as a factor in ocular motility (Hiscock & Bergstrom, 1981, Experiment 3) but cannot separate contributions of language and memory to EMR. To examine whether NVEMs occur due to searching for information stored in LTM or due to the nature of information being accessed (verbal-linguistic, non-verbal), this study will include non-verbal LTM and WM tasks comparable to the verbal variants of such tasks typically used in NVEM research. The prediction is that, like in the case of verbal material, the EMR will respond to the nature of memory processes and not to the nature of information. I expected the EMR to be significantly higher in high than in low retrieval non-verbal tasks.

Study 2: Saccadic Frequency and Social Factors

The primary purpose of Experiment 2 is to examine the effect of the physical presence of another person on the known pattern of NVGPs. This experiment will attempt to answer the question of whether NVGPs observed during tasks varying in the degree of retrieval requirements are evident despite the gaze tendencies that might be expected to occur when another person is physically present. The effect of social factors on NVGPs has not been addressed in previous research on NVEMs but there is a wealth of data on gaze tendencies in social dyads and while answering questions. Studies of ocular behavior in social situations report that people tend to look at the interlocutor in conversation and suggest that this tendency may reflect the need for feedback, speech synchronization and maintenance of affiliative balance (Argyle, Lalljee, & Cook, 1968). Gaze aversion studies report that people look away from another person's face and from a visually engaging stimulus while performing difficult verbal tasks (Glenberg et al., 1998) and propose that people avert their gaze to prevent visual interference and cognitive overload (Doherty-Sneddon & Phelps, 2005; Glenberg et al., 1998).

In contrast to social and gaze aversion explanations of ocular behavior in dialogues and non-visual cognitive tasks, the memory hypothesis proposes that NVGPs involve changes in ocular activity more related to the cognitive processes activated by tasks than to social context and sensory load. This proposal is supported by the fact that NVGPs found in non-visual cognitive tasks performed with open eyes also occur when such tasks are performed with closed eyes (Ehrlichman et al., 2007) and in complete darkness (Ehrlichman & Barrett, 1983). It is probable that performing tasks in the presence of an experimenter may reduce EMR observed when such tasks are performed

in non-social setting (i.e., participant alone) due to tendencies to look at or away from interlocutor. However, if NVEMs reflect some aspect of cognitive tasks, it is highly likely that patterns of saccadic activation observed in tasks with different retrieval requirements in various non-social settings will not be affected by the presence of another person. The number of eye movements should remain higher in tasks requiring search through LTM than in tasks requiring maintenance of information in WM irrespective of the presence or absence of the experimenter.

This prediction was based on existing evidence that physical presence of another person does not affect ocular activity typically observed in non-visual tasks. For example, Ehrlichman, Weiner and Baker (1974) used a face-to-face condition in their study of the effects of verbal and spatial questions on initial gaze shifts to ensure that gaze was centered at the end of the question and found no effect of a face or a camera on gaze patterns: there were significantly more stares in spatial than in verbal questions whether participants were facing an experimenter or a camera. Studies of gaze aversion also report that the face of an experimenter does not affect gaze aversion differently than a complex visual display (e.g., Doherty-Sneddon et al., 2002; Doherty-Sneddon & Phelps, 2005; Glenberg et al., 1998). Evidence collected through various approaches to studying ocular activation in non-visual tasks converge to suggest that although EMs in general may be modulated by external factors, those that occur in connection with non-visual cognitive tasks seem to be essentially related to ongoing cognitive activity.

Additionally supporting the proposal that NVEMs may be yoked to cognitive processing was the finding that maintaining fixation of a simple visual target may be quite effortful while performing tasks which typically tend to be accompanied with high

EMR such as high retrieval tasks (Micic et al, under review). Although a serendipitous finding of Micic et al., this is a very important finding since it suggests that the bond between EMs and cognitive processes may be automatic and prepotent and as such resistant to alteration. In order to examine the extent to which NVEMs are sensitive to social factors such as the physical presence of another person or to instructed control of gaze, this experiment will attempt to replicate the finding of Micic et al. and extend it to fixation of a human face in a face-to-face experimental situation. It is expected that the tendency for frequent EMs in high-retrieval tasks will not be eliminated by instructions to fixate a target. It is expected that more EMs will occur in high retrieval tasks than in low-retrieval tasks in both gaze conditions (fixed gaze, free gaze), despite the instructions to keep the gaze on the target, and irrespective of the fixation target (experimenter's face or a gray oval).

The existing evidence that NVGPs are associated with specific cognitive tasks is currently best explained by the memory hypothesis according to which NVGPs can be used as a motor index of active memory functions, searching for information in LTM or maintenance of information in temporary buffers of WM. However, using NVGPs as an index of memory functions may be premature as existing research has not investigated alternative sources of saccadic facilitation within the domain of memory. Specifically, the possibility that NVEMs may reflect a type of memory and not memory functions has not been examined. The memory hypothesis holds that NVGPs are process-specific relating them to processes of searching through LTM and of maintenance of information in WM. According to this view, high EMR reflects the search function and low EMR reflects the maintenance function. In contrast, domain specificity would mean that EMs

reflect the source of information operated on - LTM or WM. Consequently, according to the domain specificity view, high EMR would be related to LTM and low EMR to WM.

The attempt to parse out the contribution of memory function and type of memory to spontaneous saccadic activity was the secondary aim of this experiment. While previous research (Ehrlichman et al., 2007) and Experiment 1 address the differential contribution of search and maintenance to NVGPs, this experiment examined the possibility that NVGPs may be domain specific. If NVGPs are domain specific, they should not be sensitive to processes performed within the domain. In the domain of LTM, two processes can be directly compared as information stored in it can be retrieved in two ways, through recognition and recall. If ocular activity is domain specific eyes should move at a similar rate while recalling and recognizing verbal information. If EMR increases because the tasks require retrieval of information from LTM, saccades should occur at a high rate when attempting to retrieve information using both recall and recognition. However, if saccadic frequency reflects the memory functions of search and maintenance, EMR should be different in recall than in recognition. Because recall involves searching for information in LTM and recognition requires matching of information in LTM with a stimulus, EMR should be higher in recall than in recognition.

To summarize, the predictions of this experiment were that: 1, EMR is higher in high retrieval tasks than in low retrieval tasks irrespective of the social condition 2, EMR is higher in high retrieval tasks than in low retrieval tasks irrespective of the gaze condition and, 3, eyes move more frequently during recall than during recognition of verbal information. *In toto,* this set of findings would suggest that the phenomenon of spontaneous saccadic activation in non-visual task is 1, a cognitively based phenomenon

2, robust under social and non-social situations and gaze instructions and 3, related to memory functions recruited by tasks.

Study 1: Saccadic Frequency and Memory Functions: EMR and EOG Measures

Method

General procedure. The procedures common to both experiments are outlined here and procedures specific to each individual experiment are presented in the method section of each experiment. Participants were run in the study individually. They reported to the lab at the scheduled time, the nature of their participation was explained, and written informed consent was obtained. 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 cognitive tasks. This deception was necessary because there is strong evidence that when people are aware that their eye movements are being studied, they cease to be entirely spontaneous. Therefore, in order to prevent contamination, eye movements were not mentioned. Head movements were not restrained but participants were asked to sit as still as possible during the experiment so that their head would always be in the camera's view.

The experiment was conducted in a mostly bare room (180 cm x 300 cm) with the walls painted white to minimize visual distraction and provide high levels of reflectance. To further minimize visual distraction, the video camera was be placed 27 cm from the ceiling so that it was not in participants' direct line of sight. The view of camera-related equipment (e.g. tripod) was blocked with a plastic white sheet hung at the distance of 160 cm from the chair in which participants were seated. The distance between the camera lens and participants' eyes was approximately 195 cm. To prevent loss of data,

participants were instructed not to look at the camera or to lean forward and look at the floor.

Participants were familiarized with tasks before trials begin. Task instructions (read by the experimenter) and prerecorded tasks (n-back) were presented through an audio system. Response period for each task lasted 30 seconds following participants' statement of readiness. The camcorder transmitted the image of participants' faces to a computer in the adjacent control room. Eye movements were also recorded for two waiting periods: one before and one after the tasks trials. Eye movements were scored visually offline using software specifically developed for EMR research. Calibration checks were performed to indicate that eye movements of 3 degrees and higher will be readily detected. Debriefing was included in the video record.

Participants and recruitment.

Twenty-one Queens College students (10 men and 11 women) participated in this study either in partial fulfillment of the research requirement of an Introductory Psychology course or as paid volunteers. Seven students were reimbursed for their participation and 14 received research credit. Information about the study was available to students registered for Psychology 101on the research website and to paid volunteers on a flier distributed around the college campus. Data from five participants were not included in the main analyses. The final sample of 16 participants consisted of eight men and eight women. Ages ranged from 18 – 35, with a mean of 20.9.

Materials.

Verbal tasks. Four categories of tasks differing in their requirements for LTM search and maintenance of information in WM were used to test WM-LTM Model.

Combining high or low retrieval requirements with high or low maintenance requirements resulted in the following categories of tasks: low retrieval-high maintenance (LRHM), low retrieval-low maintenance (LRLM), high retrieval-high maintenance (HRHM) and high retrieval-low maintenance (HRLM). Each category was represented with four tasks lasting thirty seconds each.

The LRHM category consisted of four 2-back tasks. In these tasks, participants needed to respond by clicking with a hand-held clicker whenever they heard a stimulus that repeated the item right before the immediately preceding stimulus (x, z, x). Four lists of 25 letters each were prerecorded in a male voice. The inter-stimulus interval (ISI) was 1.2 seconds. In one version of the task, targets were letters with a long "e" sound (e.g., b) and in another, targets were letters with a short 'e' sound (e.g., "m") in them. There were 10 targets and 15 filler items in each list. Letters that occur in consecutive order in the alphabet never occurred in sequence in any of the lists. In order to create a high maintenance requirement in this task, in addition to responding to targets, participants had to keep mental count of the number of times they made an overt response. Participants were instructed to count all their responses regardless of accuracy and to report that number immediately after the list stopped playing.

The LRLM category included four 0-back tasks. In these tasks, participants needed to respond by clicking as soon as they heard a stimulus with a specific phonemic quality. Two tasks required participants to click every time they heard a letter with a long "e" and two tasks required clicking to letters with a short 'e' sound. Four lists of 25 letters each were prerecorded in a male voice. The inter-stimulus interval (ISI) was 1.2

seconds. Each task included 10 targets and 15 filler items. These tasks did not require mental counting.

The HRHM category of tasks involved four monitored retrieval tasks. Participants were asked to report as many members of a specified semantic category as possible in the given amount of time. In addition to reporting items from a given category, they had to mentally count the words they reported that satisfied a linguistic criterion – a specified number of syllables Semantic categories used in these tasks included colors, fruits and vegetables, domestic animals, and musical instruments. Participants were to keep mental count of either one-syllable or two-syllable words. Recalling colors and musical instruments was associated with counting two-syllable words, while recalling fruits and vegetables and domestic animals was associated with counting one-syllable words.

The HRLM category involved four semantic fluency tasks. In these tasks, participants simply had to report words from a specified category. There was no mental counting requirement in these tasks. Semantic categories for these tasks included occupations, sports, academic disciplines, and modes of transportation. In both versions of the HS tasks, participants reported their answers at a self-paced rate (i.e., as soon as they come up with a word).

Non-verbal tasks. There were two types of non-verbal tasks. They could be classified as tasks with low- or high retrieval requirements. The low-retrieval tasks were 2-back tasks. In this task, a sequence of 25 high and low pitched tones was played on the desktop computer. The lists were prerecorded and tones were generated using MIDI input from a keyboard played in time with a metronome. The ISI was 1.2 s. Like in its verbal

analog of this task, participants were required to respond by clicking to a tone that had the same pitch as a tone that was heard immediately before the preceding tone (i.e., high, low, high). There were two versions of this task. Each version lasted 30 s and required 10 responses. The third version was used to train participants on the task. The two versions of the tasks used for the experimental session were performed one preceding and one following the retrieval task. Each trial lasted 30 seconds. The high retrieval non-verbal task required participants to retrieve tunes from LTM. There were no restrictions in terms of the type of melodies to be retrieved - jingles from advertisements, songs with and without lyrics, movie music, or any other source of melodies could be retrieved. Participants were to hum a brief, two-to-three second long section from a melody and then try to hum another tune. In the instructions, participants were encouraged to hum as many melodies as possible. This task lasted 60 seconds.

Design. This experiment employed a within subject blocked design (see Figure 1). Two sets of matched tasks were performed, one with eyes open and one with eyes closed. One half of the participants first performed tasks with their eyes open and one half first performed tasks with their eyes closed.

The order of tasks within each block was determined with a Latin square. The order of tasks was different in the two blocks within each eye condition and tasks from the same category were never performed in sequence. The order of blocks of tasks and tasks within blocks was constant in the two eye-conditions.

Table 1

Example of the order of matched pairs of tasks in Experiment 1

Eyes open	**Eyes closed**
Block 1	**Block 3**
2-back (long ‘e’)	2-back (long ‘e’)
0-back (short ‘e‘)	0-back (short ‘e’)
Musical instruments/2-syllable words	Colors/2-syllable words
Academic disciplines	Modes of transportation
Block 2	**Block 4**
0-back (long ‘e’)	0-back (long ‘e’)
Sports	Occupations
2-back (short ‘e’)	2-back (short ‘e’)
Fruits and vegetables/1-syllable words	Animals/1-syllable words

Apparatus and procedure. Prior to the experiment, the experimenter explained the experimental setup, the rules and requirements that need to be observed by both the experimenter and the participant in order to run the experiment, and application of electrodes. Procedure involving application of electrodes was explained both on the research website and again before obtaining the signed consent form. The skin was cleaned of oils with a disposable alcohol swab and small amount of skin preparation gel (Nuprep) was applied to reduce skin impedance at area of contact. Pre-gelled silver/silver chloride disposable electrodes (Unitrace, manufactured by United Medical Supply Corp.) were used; two were applied to temporal canthal region of each eye and

one to the center of the forehead to serve as a ground electrode. Electrical signals from electrodes were transmitted to the computer using one channel of a bioamplifier (Coulbourn Instruments) with the following set of parameters: gain set at 10,000, high band cut off at 40 Hz and low band cut off at 1 Hz, percent of gain of 35, and coupling at 1 Hz. Impedance of applied electrodes was kept as low as possible, preferably below 10 kOhms. Recordings were obtained with a time constant of 10. A set of six ceiling lamps and two floor lamps were used to create a uniformly lighted field of vision. EOG data acquisition involved software designed for this study. EOG and video recording were synchronized and monitored on the same computer. Prerecorded n-back tasks were presented from a separate computer. The experimenter was located in a control room during testing and communicated with participants via an audiovisual system.

Data Analysis. Data were collected from video recordings according to the standard procedure described in the Introduction. The analysis was based on data from 16 participants. Data from two participants were lost for technical reasons, data from two participants could not be used due their eyes not being fully visible during all tasks, and data from one participant could not be used because the participant did not follow task instructions. For the remaining 16 participants, analysis was based on 21 trials. Trials included two baselines, 16 trials using verbal material, and three trials using non-verbal material. Starting and ending time for each task were determined from the video record and statistical analyses were based on ocular activity registered within 30 seconds for each trial. An example of order of tasks and trial time stems can be found in Table 1.

Table 2

Example of Task/Eye-Condition Configuration and Time Record

Trial #	Task	Eyes	Start	Stop	Time
1	baseline 1	o	0:16	0:47	31
2	maintain 1 (instruments - 2s)	c	3:53	4.26	33
3	retrieve 1 (academic disciplines)	c	4.59	5:32	33
4	n-back maintain 1 (L)	c	6:14	6.46	32
5	n-back 1 (L)	c	7:38	8:09	32
6	maintain 2 (animals - 1s)	c	8:46	9:18	33
7	retrieve 2 (modes of transportation)	c	9:56	10:26	30
8	n-back maintain 2 (S)	c	11:04	11:36	32
9	n-back 2 (S)	c	12:28	13:00	32
10	maintain 3 (colors- 2s)	o	13:41	14:12	31
11	retrieve 3 (occupations)	o	14:37	15:09	32
12	n-back maintain 3 (L)	o	15:43	16:14	31
13	n-back 3 (L)	o	16:57	17:28	31
14	maintain 4 (fruits & vegetables - 1s)	o	17.59	18:31	32
15	retrieve 4 (sports)	o	19:01	19:33	32
16	n-back maintain 4 (S)	o	20:06	20:37	31
17	n-back 4 (S)	o	21:16	21:47	31
18	baseline 2	o	22:20	22:50	30
19	tones	o	24:51	25:22	31
20	humming	o	26:49	27:50	31
21	tones	o	28:22	28:53	31

Note 1: 1-s: one-syllable words; 2-s: - two-syllable words; (L) - long ‘e’ sound; (S) - short ‘e’ sound, o - eyes open, c: -eyes closed; 1-4: block number .
Note 2: Trial start and end times are in minutes and seconds. Time is in seconds.

Video and EOG recordings were synchronized by starting EOG recording with a 5-second delay and activating video recording at the zero point. Synchronization of the starting time for the EOG and video record ensured that temporal discrepancy in visual and EOG data points due to differences in signal conduction times from the amplifier and the camera would be negligible. This allowed us to base the analysis of both the EMR and EOG data on the starting times of individual trials determined from the video record.

EOG data were collected only from the horizontal channel. This approach reduced the time needed for application of electrodes.

The electrical signal was communicated to the bioamplifier via a nine-foot long 3-lead Bio Amp cable and lead wires. The cable has a yoke with three sockets for the lead wires. The lead wires click into place in the cable yoke, and have snap connectors at the other end to connect to typical EKG electrodes. The average impedance was 8.9 kOhms. Signal form the amplifier was conducted through a three-foot long cable connected to the desktop computer.

Data analysis of EOG power involved two measurement units. At acquisition, the EOG was measured in mV. That data was entered in the calculation of EOG power. The power for a given set of N measurements was calculated according to the following formula: $P = (V_1^2 + V_2^2 + ... + V_N^2) / N$ ($Vi^2$is the square of i^{th} measurement, P is power, N is the number of measurements). Because power is the mean of the squared measurements, its unit of measurement is a square mV. The results of this formula were very large numbers, so to simplify further calculations they were divided by 1000. Therefore, EOG power of, for example 295, really meant 295,000 mV^2. These calculations were done on the full range of the raw EOG data.[1]

Saccadic activity was analyzed for eyes open and eyes closed conditions. In the eyes open condition, EMs were assessed using the video and EOG records. In the eyes closed condition, EMs were assessed from the EOG record only. Effects of non-verbal tasks were assessed only with eyes open. EMR and EOG data were analyzed with repeated measures analysis of variance (ANOVA) using SPSS-12.0 GLM procedure. The multivariate approach was used. All F values were based on Pillai's trace with effect

size expressed as partial η^2 Average correlations between EMR and EOG were based on eight trials performed with eyes open and computed using Pearson's *r***.** All statistical analyses were performed at the alpha level of .05.

Results

Correlational analysis. The first order of business in this experiment was to establish whether EOG power can be used as a measure comparable to EMR scored from video recordings. For this purpose, we assessed EOG-EMR correlations across all eyes-open trials for each subject. To compute within-subject correlations, each of the eight 30 sec trials was divided in half, resulting in 16 paired EMR-EOG data points for each participant. The average correlations between EMR and each of the EOG measures were then calculated for each participant.

Table 3

Profile of the Sets of Correlations of EMR and Variants of EOG Power

	EOG Raw Pearson's r	EOG Raw Spearman rho	SQRT Raw Pearson's r	EOG (500) Pearson's r	EOG (1000) Pearson's r
Average r	.76	.80	.82	.86	.84
Lowest r	.37	.36	.38	.37	.37
Highest r	.90	.96	.97	.98	.95
Percent r ≥.9	.31	.44	.50	.62	.50
Percent r ≥.8	.31	.25	.25	.19	.37
Percent r ≥.7	.12	.06	.06	.06	x
Percent r ≥.6	.06	.12	x	.06	x
Percent r ≥.5	.12	.06	.06	x	.06
Percent r ≥.4	.06	.06	.06	x	x
Percent r ≥.3	.06	.06	.06	.06	.06

Note: P- power; SQRT - square root transformation of EOG data

We compared EMR with raw EOG power using Pearson's *r*, and Spearman's rho, with EOG power after square root transformation and with raw EOG power clipped at 500 mV and at 1000mV. [2] As can be seen in row 1 of Table 2 all five comparisons yielded high average correlations ranging from .76 to .86. Of the five methods of determining EOG power, the method that clipped power at 500mV appears to have the strongest relationship to EMR, with 93 % of individual correlations greater than $r = .60$.

To compensate for underestimation of the average of a set of correlations, we submitted the correlations with EOG (500) P to Fisher's *z* transformation. Although the resulting average of *r*-to-*z'* transformation is an overestimate of the population value of *z*, which is opposite to the underestimation that occurs because the sampling distribution of the correlation coefficient is skewed, there is evidence that the positive bias of average *z* back-transformed to *r* is less than the negative bias of the average *r* and the use of z transformation is recommended when averaging correlation coefficients of small samples (Silver, & Dunlap, 1987). *Z*-transformation improved the average correlation for EMR and EOG (500) power from .86 to .91.

It is important to note that these average correlations are computed across tasks within subjects. The fact that EOG power closely tracks EMR in a within-subjects analysis does not imply that it does so in a between-subjects analysis. Indeed, as can be seen in Table 3, the relationship between EOG power and EMR from subject to subject is highly variable. This result is not unexpected and reflects the fact that individuals differ in the size of their eye movements across all tasks, and while EOG power is affected by the size of eye movements, EMR is not. For the purposes of assessing task effects on saccadic activity in within-subjects analyses, these convergent validity correlations are

impressively high and provide a clear rationale for utilizing EOG power in studies of NVGPs when video recording is not feasible.

Table 4

Participants' minimal and maximal EMR and EOG (not clipped)

Participant	Minimal EMR	Maximal EMR	Minimal EOG	Maximal EOG
2	0.13	1.33	10	295
3	0	2.07	8	889
4	0	1.47	2	302
5	0	1.67	2	177
6	0	0.53	7	500
8	0	0.60	1	136
9	0	2.73	1	204
10	0	1.33	2	70
11	0	0.33	3	15
13	0.2	2.53	29	422
14	0	2.53	2	829
15	0	2.33	4	210
17	0	0.53	3	27
18	0	1.07	7	222
20	0	1.13	3	219

Task Effects.

Video record analysis of verbal tasks.

Retrieval: Consistent with the existing body of evidence, the main effect of retrieval requirement was significant: F (1, 15) = 31.33, $p < .01$, $\eta^2 = 0.68$. The mean EMR of tasks with high retrieval requirements (M = 1.02, SE = 0.16) was significantly greater than in tasks with low retrieval requirements (M = 0.19, SE = 0.06).

Maintenance: It was expected that maintenance manipulation would affect EMR in such a way that increased maintenance requirement would reduce EMR. Although the

means for high and low maintenance tasks were in the predicted direction (0.57 for high maintenance, 0.64 for low maintenance), these differences were not significant ($F < 1.0$). The interaction between retrieval and maintenance was also not significant ($F < 1.0$).

Table 5

Mean EMR for Verbal Tasks Performed with Eyes Open

Tasks	EMR	SD
Low retrieval, high maintenance	0.15	0.19
Low retrieval, low maintenance	0.24	0.32
High retrieval, high maintenance	0.99	0.70
High retrieval, low maintenance	1.05	0.65
Baseline	0.72	0.42

Video record analysis of non-verbal tasks. Two non-verbal tasks differed in their retrieval requirement: a humming task was considered a high retrieval task and a task requiring responding to a series of tones was considered a low retrieval task. As predicted, the mean EMR of Humming ($M = 1.11$, $SD = 0.69$) was significantly higher than the mean EMR of Tones ($M = 0.21$, $SD = 0.25$).

EOG Power Analysis. Because EOG (500) had the highest average correlations with EMR, EOG (500) power was used to analyze NVGPs. EOG (500) power was assessed separately for trials performed with eyes open and with eyes closed. Results of the analyses of verbal tasks are presented in Tables 5 and 6.

Table 6

Mean Raw EOG (500) Power for Verbal Tasks Performed with Eyes Open

Tasks	Power	SD
Low retrieval, high maintenance	12.78	11.62
Low retrieval, low maintenance	14.53	17.65
High retrieval, high maintenance	43.91	32.84
High retrieval, low maintenance	47.84	27.57

Table 7

Mean Raw EOG Power for Verbal Tasks Performed with Eyes Closed

Tasks	Power	SD
Low retrieval, high maintenance	16.40	11.31
Low retrieval, low maintenance	14.25	18.17
High retrieval, high maintenance	26.43	18.72
High retrieval, low maintenance	28.09	14.46

Retrieval: As in the video record analysis, a significant main effect of retrieval requirement was found. This effect was found both in the eyes open: F (1, 15) = 14.35, p <.001, η^2 = 0.66 and eyes closed conditions, F (1, 15) = 13.99, p = .002, η^2 = 0.48. The mean power of tasks with high retrieval requirements (M eyes open = 45.88, SE = 7.31, M eyes closed = 27.26, SE = 3.92) was significantly greater than in tasks with low retrieval requirements (M eyes open = 13.66, SE = 3.51, M eyes closed = 15.33, SE = 3.18).

Maintenance: Consistent with the video record analysis, the means for high and low maintenance were in the predicted direction in the eyes open condition; however, this pattern was not found in the eyes closed condition. In neither condition were the means

statistically significant, nor was there a significant interaction between retrieval and maintenance.

Experiment 2: Effects of Social Factors

Method

Participants and recruitment. Participants in this experiment were 21 women (average age of 21.8) taking the Introductory Psychology course at Queens College. Participation was limited to women because the experiment was run by a woman and previous research showed effects of gender on the pattern of looking behavior in face-to-face situations (Argyle, Lalljee, & Cook, 1968). Information about the study was available on the Psychology 101 research website.

Materials. The effect of recognition on EMR was tested with two lists of 14 abstract nouns. At the learning phase, participants heard the following words: advice, blessing, concept, insight, denial, feeling, opinion, passion, respect, wisdom, spirit, talent, honor, effect. At test, participants heard the following words: content, denial, attitude, belief, opinion, patience, respect, spirit, theory, insight, honesty, wisdom, feeling, effort. The words were read at a rate of two words per second for the total task time of 30 seconds.

The effect of retrieval on EMR was tested with a set of high retrieval tasks and a set of low retrieval tasks. High retrieval tasks (i.e., high search – low maintenance) required participants to report as many members as possible of the following categories: musical instruments, modes of transportation, occupations, college majors, fruits and vegetables, colors, sports, and domestic animals. The low retrieval tasks (i.e., low search

– high maintenance) involved eight series of 25 letters. The lists were prerecorded with an ISI of 1.2 seconds. In one half of the tasks, targets were letters with a short ‘e’ sound and in the other two, targets were letters with a long ‘e’ sound. High and low retrieval tasks were timed at 30 seconds.

Design. This experiment used a 2 (experimenter presence) x 2 (gaze conditions) within-subjects design. To examine whether NVGPs are sensitive to social factors such as the physical presence of another person, two matching sets of tasks (total of 16 tasks) were created, one to be performed with experimenter present and one with experimenter absent. Category fluency tasks were grouped in the following way: musical instruments, sports, colors, fruits and vegetables and modes of transportation, occupations, college majors, farm and pet animals. N-back tasks were grouped in four pairs each comprised of one short ‘e’ and one long ‘e’ sound as targets. The order of sessions (experimenter absent or present) was counterbalanced across subjects.

Each category of task was represented with four pairs of tasks. Each pair was performed under different gaze condition, and matching pairs were performed in different sessions (social conditions). The order of tasks within each block (gaze and social condition) was determined by Latin square. Within each session, one set of tasks was performed with free gaze, and one was performed with the fixed gaze, but the free gaze condition always preceded the fixed gaze condition. The order of gaze blocks and the order of tasks within each block were constant for the two sessions.

The list of abstract nouns used for the recognition test was always presented at the beginning of the experimenter-absent condition ostensibly as a means of testing the sound system. Participants were asked to repeat each word to ensure that both participant and

the experimenter can hear and understand each other. Recognition test was given after the last task of the experimenter-absent condition and was followed by free recall. Both tests were performed with free gaze.

Procedure. The experimental manipulation was presented as a need to ensure that the experiment can be run equally well using a desktop and a laptop computer so that future studies may be conducted outside the laboratory. For one half of the subjects the experiment begun with the experimenter present session and for the other half of the subjects, the experiment will begin with the experimenter absent session. In the experimenter absent session, tasks were presented using a desktop computer. In the experimenter present condition, tasks were presented using a laptop computer. When in the same room, the experimenter was seated about 3 feet away from the participant and did not maintain eye contact with the participant. This was necessary because of possible confounding of the effect of physical presence of another person with the effect of eye contact. Participants were told that experimenter has to look at the computer screen to read instructions and ensure that the video record is satisfactory.

In the experimenter absent condition, a grey oval the size of the experimenter's head was affixed to the curtain blocking the view of the camera at the same position the experimenter's head was at in the experimenter present condition. Participants were in the experimental room while the experimenter made changes needed for the second session: to connect or disconnect video camera, speakers and the laptop, and to attach or remove the grey oval. The experimenter's chair remained in the experimental room during both conditions. In the experimenter absent condition, the laptop was placed

behind the curtain so that participants cannot see it. The experimenter's appearance was informal (a black outfit, hair held in a ponytail and minimal makeup).

In gaze fixation blocks, participants fixated their gaze on a gray oval the in experimenter-absent condition and on the experimenter's nose in the experimenter-present condition. Using a nose as a fixation point seemed appropriate because nose is the most prominent facial feature when the head and the eyes of an experimenter are turned slightly downward in an effort to avoid eye contact. The nose was used as a fixation point in studies interested in functionality of gaze aversion (Glenberg et al., 1998). In the experimenter–present condition, the experimenter sat as still as possible and tried not to move her head at all while participants were fixating on her nose. Trials in which either the experimenter's head was moving or participants failed to follow instructions were repeated.

Before they are asked to perform recognition test, participants will be reminded of the list of words they were introduced to at the beginning of the study. They will be given the instructions to say "yes" whenever they hear a word they were certain was on the original list, "no" whenever they hear a word they were certain was not on the original list, and to repeat the words for which they were not sure if they herd them on the first reading. Free recall was performed about one minute after recognition.

Data analysis. Data were collected from video recordings according to the standard procedure described in the Introduction. The analysis was based on data from 17 participants. Data from one participant could not be used because the eyes were not fully visible during all tasks and the participant did not maintain fixation. For the remaining 17 participants, analysis was based on 16 trials involving semantic fluency and

n-back task (trials 3 – 10 and 15 – 22) and on trials involving repetition, recognition and recall. An example of the protocol can be found in Table 7. Multivariate tests examined the main effects and interactions of the following factors: task (n-back/fluency), gaze (fixed/free), and experimenter (present/absent). Separate analyses were conducted for the effects of repetition, recognition and free recall on EMR. All statistical tests were performed at the alpha level of .05.

Table 8

Example of the Protocol for Experiment 2

Trial Condition	Task	Gaze
Session 1: Experimenter absent		
1	Repetition	free
2	Baseline 1	free
3	2-back with maintenance L	free
4	Semantic fluency (musical instruments)	free
5	Semantic fluency (sports)	free
6	2-back with maintenance S	free
7	Semantic fluency (fruits and vegetables)	fixed
8	Semantic fluency (colors)	fixed
9	2-back with maintenance L	fixed
10	2-back with maintenance L	fixed
11	Baseline 2	free
12	Recognition	free
13	Recall	free
Session 2: Experimenter present		
14	Baseline 3	free
15	2-back with maintenance L	free
16	Semantic fluency (modes of transportation)	free
17	Semantic fluency (occupations)	free
18	2-back with maintenance S	free
19	Semantic fluency (animals)	fixed
20	Semantic fluency (college majors)	fixed
21	2-back with maintenance L	fixed
22	2-back with maintenance L	fixed
23	Baseline 4	free

Note: L - long; S - short

Results

Tasks: There was a significant effect of tasks on EMR: F (1, 16) = 32.69, $p < .01$, $\eta^2 = .67$. EMR was higher in fluency tasks than in n-back tasks.

Gaze: The effect of gaze on EMR was significant F (1, 16) = 21.78, $p < .01$, $\eta^2 = .58$. As expected, more EMs occurred when gaze was free than when gaze was fixed.

Task x Gaze: There was an interaction of gaze and tasks F (1, 16) = 11.94, $p = .003$, $\eta^2 = .43$. Although fixation reduced EMR of both tasks, that reduction was greater for fluency than for n-back tasks. The difference in EMR between high and low retrieval tasks was greater when gaze was free than when it was fixed.

Table 9

Mean EMR for all tasks and conditions

Conditions	Tasks	EMR	SD
Experimenter absent/Gaze free	n-back	0.26	0.52
Experimenter absent/Gaze free	fluency	0.94	0.67
Experimenter absent/Gaze fixed	n-back	0.04	0.09
Experimenter absent/Gaze fixed	fluency	0.28	0.19
Experimenter present/Gaze free	n-back	0.40	0.50
Experimenter present/Gaze free	fluency	0.94	0.63
Experimenter present /Gaze fixed	n-back	0.07	0.16
Experimenter present/Gaze fixed	fluency	0.33	0.24

Experimenter: There was no overall main effect of the experimenter. Presence or absence of the experimenter had no effect on the rate at which EMs occurred in tasks.

This factor did not interact either with tasks or with gaze and there was no triple interaction among tasks, gaze and experimenter.

Repetition, recognition, and recall.

Tasks: Repetition, recognition, and recall were performed in the absence of the experimenter and with free gaze only. As expected, a significant effect of tasks was found: F (2, 16) = 7.98, p = .004, η^2 =.52. Although existing research does not offer any information on EMR for recognition in non-visual tasks, based on the evidence of lower EMR in repetition (Micic et al., in press, Experiment 1, M = .76) and higher EMR in episodic recall (Ehrlichman et al. 2007, Experiment 3, M = 1.41), we expected the EMR of episodic recall to be higher than the EMR of both repetition and recognition because those two tasks should not require as much searching through LTM.

Table 10

Mean EMR of Repetition, Recognition and Recall

Task	EMR	SD
Repetition	0.51	0.40
Recognition	0.66	0.53
Recall	0.94	0.47

Pairwise comparisons revealed that the average EMR of recall (M = .94, SD = .47) was significantly higher than the average EMR of repetition (M = .51, SD = .40) and the average EMR of recognition (M = .66, SD = .53). The average EMR of repetition and recognition were not significantly different (p = .21).

Performance. Fluency tasks involved reporting members of a semantic category in a given amount of time, thus performance on those tasks was assessed with a total number of words reported excluding repetitions. There were no intrusions. The total number of words reported was not significantly affected by the presence or absence of experimenter or by the gaze condition, and there was no evidence of an interaction between the two factors ($M_{\text{absent-free}}$ = 11.5, SD = 2.9; $M_{\text{absent-fixed}}$ = 11.1, SD = 3.44; $M_{\text{present-free}}$ = 12.5, SD = 3.07; $M_{\text{present-fixed}}$ = 11.4, SD = 2.71).

The n-back trial involved dual-task situations and as such required two responses. One was to detect a target (i.e., click) according to the 2-back rule and the other was to mentally count the number of clicks irrespective of whether or not they were correct and report that number. Performance was measured on both responses. Performance on the detection task was assessed with number of correct detections (hits), errors of omissions (miss), and of commission (false alarms). Because the number of false alarms was negligible, analysis was performed on the number of total hits. The total number of hits did not show independent effects of gaze and experimenter but there was a significant interaction F (1, 17) = 5.59, p =.030, η^2 =.25. Performance was best when experimenter was absent and gaze was fixed on the gray oval ($M_{\text{absent-free}}$ = 16.28, SD = 3.27; $M_{\text{absent-fixed}}$ = 17.28, SD = 3.03; $M_{\text{present-free}}$ = 16.0, SD = 3.66; $M_{\text{present-fixed}}$ = 15.94, SD = 3.24).

The absolute difference between the actual and reported number of clicks showed a very similar pattern ($M_{\text{absent-free}}$ = 1.72, SD = 1.93; $M_{\text{absent-fixed}}$ = 0.67, SD = 1.08; $M_{\text{present-free}}$ = 1.39, SD = 1.58; $M_{\text{present-fixed}}$ = 1.56, SD = 1.29). It did not change significantly due to the presence or absence of the experimenter or the gaze condition but there was a marginally significant interaction between experimenter and gaze F (1, 17) = 3.84, p

=.064, η^2 =.18. The reported count of clicks was most accurate when gaze was fixed on a gray oval.

In the recognition task, participants were required to detect words that were presented to them at study. Study session was an instance of incidental learning and involved a list of 14 words. To ensure that each word was adequately processed, participants repeated each word after it was read to them. Therefore, performance at study was 100 %. For the recognition task, participants heard a list of 14 words, seven old words, chosen from the middle of the original list, and seven new words. Performance at recognition was measured using correct acceptance (old word), correct rejection (new word) and instances when a decision could not be made. Individual performance based on correct acceptances and rejections ranged from 7 – 13 words (50 – 92.8 % correct). On average, participants made 10 correct decisions in recognition (71.85 % correct). Decisions were incorrect 22.27 % of the time, and could not be made only in 5.88 % of the cases.

Performance at recall was assessed with the total number of words recalled from the study list. It ranged from 2 – 6 words (14 – 43 %). On average, participants recalled 4.11 words (29 %) processed at study. Average recall also included 1.59 words (11 %) heard during recognition (i.e., new words). Out of the total number of words recalled, 75 % was from the study list. There were only three intrusions.

Discussion

Experiment 1

The primary goal of Experiment 1 was to examine the possibility of finding a measure of ocular activity that could be used to assess NVGPs as reliably as with the

EMR but in a wider range of conditions. Specifically, the experiment was geared toward finding a measure that would correspond to a measure of saccadic frequency and could be used when EMR could not be reliably assessed from a video record, such as in darkness and with eyes closed. Finding such a measure is important because the identity of NVGPs as a non-visual, cognitively grounded phenomenon is still under scrutiny and the phenomenon is in need of clear differentiation from related phenomena which are more dependent on external stimuli, mainly looking at nothing phenomenon and gaze aversion. For this purpose, EMR and EOG power were assessed simultaneously while participants engaged in tasks with empirically well established NVGPs. This allowed us to compare EMR and EOG power on a trial by trial basis through correlational analysis as well as to assess whether the two indicators provided comparable evidence of task effects. In addition, by recording EOG power with eyes closed, we were able to see whether previous evidence of NVGPs using video records would also be found using EOG power measurements.

Before discussing the results of the analysis it is important to note that neither EMR nor EOG power are completely reliable methods for quantitative measurement of EM activity. EMR is based on observable behavioral data, and is a somewhat subjective measure because it depends on the ability of the scorer to detect EMs from a visual record (Ehrlichman et al., 2007). Although this method has excellent reliability (in the .90 range) with eyes open, it is only marginally reliable with eyes closed (in the .40 range). In contrast, EOG power is an objective measure based on electrophysiological record of ocular activity but it is susceptible to effects of various sources of variability. For example, the EOG signal can change when there is no EM, it can be affected by dark

adaptation, metabolic changes in the eye, the state of the contact between the electrodes and the skin, the velocity of an EM, and it is known to be prone to drift and generation of spurious signals (Carpenter, 1988).

In the present experiment, EOG power was computed according to the algorithm explained earlier in the text and was treated in several different ways in order to find the variant that is best correlated with EMR. Overall, correlational analysis found a very strong relationship between EMR and EOG power measures including raw EOG power, Square Root of EOG power, and power clipped at 500 and 1000mV. As previously explained, EOG power was clipped in an attempt to reduce the impact of very large EMs on EOG measurements. The best EMR-EOG relationship was found when EOG power was clipped at 500 mV. This adjustment to EOG power yielded an average validity correlation of .91 (using Fisher's z transformation). This is a very high correlation, possibly as high as could be expected given the inherent lack of reliability of both measures. According to the high correlations found in the present study, EMR and EOG measures are closely related even though EMR measures only frequency of EMs while EOG power integrates both frequency and amplitude of EMs.

That EOG power may be very closely related to EM frequency is also reported in a sleep study of eye movement density (EMD) in normal elderly (Darchia, Campbell, & Feinberg, 2003). The incidence of EMs in this study was assessed from EOG record using computer software (PASS PLUS) and with visual scoring. EM incidence was determined by counting the number of half waves for each 20-second epoch of visually defined artifact-free stage REM and also by determining the rate of EMS (number of half waves per 20 seconds). Amplitude of EMs was determined by summing up peak-trough

distances in the average half wave (curve length) and also by dividing curve length by the number of half waves. Period-amplitude analysis, which can distinguish between the effects of incidence and amplitude on EOG power, demonstrated that reduced EOG power in elderly was almost entirely due to reduced frequency of EOG potential. Computer measures were cross validated with visual scoring. Visually scored EMD was found to be highly correlated with computer measures ($r = .96$).

Findings of Darchia et al. (2003) provide strong evidence that EOG power mainly reflects frequency of EMs. This is an important finding because if EOG was not found to be related to incidence of EM potentials, changes in its value would not be easily explainable since they could come from the reduction of EM velocity, from degradation of the corneo-retinal difference, or both (Tursky, & O'Connell, 1966). Finding that the incidence of EM potentials is reduced in the elderly and that this change is reflected in reduction of EOG power and in visually determined EMD, suggests that EOG power can be used to identify frequency of EMs. It seems that EOG measures can be used with confidence to assess saccadic activity in conditions involving closed eyes and eyes open in complete darkness in which EMR does not seem to be a sufficiently accurate measure. Data from these conditions are important as they may be indispensable in delineating the NVGPs phenomenon, in determining its practical applications, and in further testing of the WM-LTM hypothesis.

The LTM-WM hypothesis was partially supported in the present experiment. The distribution of the mean EMR found for the four combinations of two levels of retrieval and two levels of maintenance was consistent with that proposed in the hypothesis: average EMR was lowest in low retrieval – high maintenance tasks (2-back with

maintenance), higher in low retrieval –low maintenance task (0-back, no maintenance), it increased further in high retrieval-high maintenance tasks (semantic fluency with maintenance) and was highest in high retrieval-low maintenance tasks (semantic fluency without maintenance). As evident from Table 4, average EMRs of task groups were within the expected ranges: low for LRHM tasks (M = 0.15), low to moderate for LRLM tasks (M = 0.24), moderate to high for HRHM tasks (M = 0.99), and high for HRLM tasks (M = 1.05). Although the distribution of means is in the predicted direction, we cannot conclude that such a distribution is a function of both LTM search and maintenance, since the effect of maintenance was not found to be significant.

Findings of this experiment indicate that patterns of ocular activation may be related to memory functions. Consistent with previous literature (e.g., Ehrlichman et al., 2007), this experiment found that the number of spontaneous saccades significantly increases with activation of the search function. That maintenance of information can reduce the number of spontaneous EMs cannot be concluded based on available evidence. Maintenance reduced EMR when eyes were open but not significantly. EMRs of both high and low retrieval tasks were reduced when those tasks were performed with what was considered high maintenance requirement. However, that reduction was minimal where it was expected to be highest, in HRHM tasks. There are several possible reasons why maintenance did not reduce EMR.

The high maintenance requirement was always secondary to the retrieval requirement. That means that participants were instructed to perform either a high or low retrieval task, and do the best they can on the secondary task. One possibility is that the high maintenance requirement was not high enough to cause a significant change in gaze

pattern. For example, having to count the number of responses made in the continuous performance task clearly requires maintenance of information as the last number has to be remembered in order to continue counting. However, this maintenance involved simply counting up to 10. In high retrieval tasks, counting of two-syllable words that were generated in semantic fluency may have not been much different than the counting of one-syllable words. There were also instances in which none of the generated words satisfied the syllable requirement and therefore, there was no count to be maintained. Furthermore, some participants may have not been fully engaged in this aspect of the tasks because they could not perform it. This is more likely to be the case in semantic fluency in which words had to be analyzed for the number of syllables. Participants were trained on this task but because we did not ask them to report the words that satisfied the criterion, it was not possible to assess what the reported numbers really reflected. Although it is not clear to what extent the maintenance component of tasks was successfully performed, it is evident that participants did attempt to perform it and that attempt was reflected in saccadic frequency. The fact that maintenance component did change EMR in the expected direction even under these circumstances is encouraging as it suggest that with better designed maintenance tasks, the effect of maintenance may be as robust as the effect of retrieval requirements on EMR and thus, should be examined further.

The finding that both requirements for retrieval and maintenance of information can affect the rate at which eyes move in non-visual tasks is an important confirmation that spontaneous saccadic activation and gaze fixation can be related to memory functions of searching through LTM and maintenance of information in WM memory.

This is an important improvement in the ability of the memory hypothesis to support its proposed explanation of the relationship between NVGPs and memory with empirical evidence. Ehrlichman et al. (2007) proposed that spontaneous gaze changes are related to memory and suggested that high EMR reflects searching through LTM. They substantiated this proposal with anatomical evidence of neural connections between brain structures and areas involved in oculomotor control and memory. Their interpretation of the interplay between activation and inhibition of saccadic EMs was based on the analogy of memory functions of search and maintenance with functional differentiation between saccadic and fixation portions of the superior colliculus, respectively. The proposal that gaze fixation reflects maintenance of information, and that saccadic EMs reflect search for information was explicitly stated in the WM –LTM hypothesis

In order to test the possibility that NVGPs may reflect searching for verbal information stored in LTM and not just the search function as proposed by the memory hypothesis, this experiment explored the patterns of EM activity in non-verbal tasks with low and high retrieval requirements. Non-verbal tasks were created to be analogous to verbal tasks typically used in NVGP research in terms of task structure, type of response, and retrieval requirements. The low retrieval task (Tones) was a continuous performance task of a 2-back type using a series of high and low tones instead of letters but requiring the same type of a response. The high retrieval task (Humming) involved humming of a portion of melodies from LTM. This information is retrieved by accessing its acoustically coded memory trace. Although acoustic information may be retrieved along with the corresponding verbal information, this may not be a rule. It therefore appears

that we can conclude that our findings support the proposition that saccadic activation seen in NVGPs is related to activation of the LTM search function.

Existing literature reports moderately high EMR in tasks requiring humming of familiar tunes (Bergstrom & Hiscock, 1988, Experiment 1). We note that mean EMR of the present humming task (M = 1.11) is almost two times greater than the mean EMR of the humming task from the Bergstrom and Hiscock study (M = 0.69) but similar to the mean EMR of the verbal high retrieval – low maintenance task from the present study (M = 1.05). Although the humming task of the present study and that employed in Bergstrom and Hiscock study both asked for retrieval of acoustic information stored in LTM, their EMRs are very different. This observation may be explained by the fact that in the present study, participants had to search for tunes to hum while in the Bergstrom and Hiscock experiment, participants were instructed on what tune to hum. Therefore, it is possible that two tasks differ in their search requirement and that the Bergstrom and Hiscock's humming task may have required much less of a search since participants were told what tune to recall. This explanation is further supported by the fact that although geared toward accessing different types of information (verbal and acoustic), both verbal and non-verbal tasks in the present study required searching for information stored in LTM. This comparison of verbal and non-verbal task effects seems to suggest that EMR of high retrieval tasks reflects activation of the LTM search function and not the type of information being retrieved. However, because it is possible that tune-related verbal information was accessed together with non-verbal information, this is not a definitive conclusion and the impact of non-verbal tasks on E MR should be further examined using tasks that could reduce or control contribution of language to processes of retrieval.

Experiment 2

This experiment tested the claim that NVGPs are essentially a cognitively based phenomenon independent from sensory and social influences. For this purpose, ocular activity was observed while participants engaged in tasks that typically produce either high or low EMR in the presence or the absence of the experimenter. In agreement with the hypothesis, the data indicated that the presence of another person does not influence the rate at which saccadic eye movements occur in these two types of tasks. Whether or not the experimenter was physically present, eye movements occurred at a higher rate in high retrieval tasks than in low retrieval tasks. Similar findings are reported in the literature on gaze aversion where gaze patterns are found not to be differentially affected by the human face and a complex visual stimulus (e.g., Doherty-Sneddon et al., 2002; Doherty-Sneddon & Phelps, 2005; Glenberg et al., 1998).

Additionally, this experiment like Experiment 3 of Micic et al (in press), found evidence that the tendency toward specific patterns of saccadic activation in non-visual tasks is very strong. The known pattern of NVGPs was found both when tasks were performed in the presence or in the absence of the interlocutor and both in fixed and free gaze conditions. Although participants were able to reduce eye movements under fixation instructions, EMR was never reduced to zero, and in the high retrieval tasks eye movements continued to occur at a higher rate than in the low retrieval tasks. Under instructions to maintain fixation of a target, the average EMR of low retrieval tasks was extremely low and in high retrieval tasks it was reduced to 0.30, which is very close to average EMR of low retrieval tasks under free gaze condition. (M = 0.33). This is very strong evidence that NVGPs are inherent to non-visual cognitive activity and represent

prepotent motor activity that is not easily modified by voluntary control, especially when tasks require retrieval from LTM. According to the performance data, high retrieval tasks can be performed equally well when gaze is fixed or free, and in the presence or absence of another person. For tasks with low retrieval but high maintenance requirement, voluntary control of gaze seems more feasible and can affect performance.

The aspect of non-visual cognitive activity thought to be responsible for NVGPs is activation of the LTM search function (Ehrlichman et al., 2007) and there is ample evidence that this may as well be the case. NVGP studies consistently report high EMR in tasks with high retrieval requirements and low EMR in tasks with low retrieval requirements (Bergstrom & Hiscock, 1988; Ehrlichman et al., 2007; Micic, Ehrlichman, & Chen, in press). However, in order to be able to relate NVGPs to search-related process the possibility that spontaneous EMs occur because cognitive activity requires using information from LTM or WM must be considered. This previously unexplored possibility was examined in this experiment by comparing EMR during immediate repetition, delayed recognition and free recall of a list of abstract words.

To assess whether changes in ocular motility depend on the source of information or on the process performed on that information, we manipulated both utilization of memory stores and processing requirements of tasks. We compared EMR in a repetition task which required simple repetition of information that entered temporary store of WM, in recognition task which requires comparison of information stored in LTM against information in WM memory, and in free recall which requires retrieval from LTM. Performance data indicated that participants performed the recognition task successfully categorizing 71% of the words. In free recall, 75% of the words retrieved were from the

study list. Having to recall information from LTM was accompanied by an EMR that was significantly higher (M = 0.94) than the EMR of both recognition (M = 0.66) and repetition (M = 0.51). These findings are consistent with findings of NVGP studies which utilize high retrieval tasks requiring recall and as such, provide important support for the suggestion that high rate of EMs in those tasks is the function of searching for information in LTM. Since both recognition and recall involve information stored in LTM, the difference in EMR in these two tasks cannot be related to memory store from which information is being used.

Pairwise comparisons revealed that EMR of recognition and repetition were not significantly different. The EMR of these tasks is comparable to EMR of tasks such as number-letter sequencing (M = 0.67), chain retrieval (M= 0.53), and mental alphabet (M = 0.68) (Ehrlichman et al., 2007, experiments 1, 2, and 3, respectively). It is about twice as high as the EMR of the n-back task performed with free gaze in this study (M = 0.33). While this difference may indicate that having to produce a spoken answer may to some degree influence the rate of EMs, it is well documented that overt verbal activity does not explain the difference in EMRs of various tasks (Ehrlichman & Barret, 1983). It seems that the difference in EMR of these tasks can be better understood in terms of cognitive processing than in terms of speech production. What this set of task effects seems to suggest is that EMR in tasks that do not require pure recall of information from LTM reflects processing within different buffers thought to exist in WM. Because recognition, repetition, number-letter sequencing, chain retrieval and mental alphabet all involve contacting information in LTM, it seems that EMR of these tasks reflects processes performed within the episodic buffer of WM. In contrast, n-back tasks do not tap into

LTM and EMR in those tasks may reflect operations performed in the phonological store of WM (Baddeley 1986, 1992). WM processes possibly reflected in NVGPs will be considered in detail in the general discussion.

We note that the EMR of free recall remained high although the recognition task always preceded recall and thus, participants heard half of the original list for the second time shortly before (one minute) having to recall the words. It seems that although memory traces of items to be recalled were activated in the preceding task, participants had to search through LTM in order to perform free recall. This finding is consistent with the finding of Micic et al. (in press), who report in their Experiment 2 that accessibility of items in LTM does not influence the rate at which eyes move during free recall. Therefore, it seems that the significant increase in EMR seen in recall trials as compared to recognition trials can be attributed to activation of LTM search function.

Since the EMR of episodic recall is somewhat lower than the EMR reported for episodic tasks in other studies (e.g., Ehrlichman et al., 2007, Experiment 3, $M = 1.41$; Micic et al., in press, $M = 1.13$), we briefly consider possible methodological and theoretical sources of that difference. It is possible that ITI between recognition and retrieval was too short, so that a portion of information might have stayed within the WM buffers and was, therefore, more readily available for retrieval which could reduce EMR. Perhaps if two retrieval trials were separated by a larger interval, the EMR of recall would be greater. It is also possible that EMR of free recall may have been somehow affected by the 50% increase in the number of words in recognition. These possibilities could be addressed in future research by introducing two recall trials, one to be

performed before and one after the recognition task, and by increasing and filling ITI with distracter tasks.

Because recognition involves a feeling of familiarity which is unconscious and context independent and remembering, which is conscious and context dependent, EMR may be affected by the inconsistencies that occur in live audio presentation. To ensure that the EMR in recognition does not change due to factors other than recognition of words per se, the list of words should be prerecorded making sure that they are pronounced evenly and without enunciation of either new or old items. From a more theoretical perspective, a question that might be relevant here is the one of the degree to which LTM search function might be activated during recognition and counteracted by processes involved in matching with an external stimulus. One way of assessing activation of the search function could involve testing whether EMR is sensitive to the proportion of new items in the probe list. If the search function plays a major role in recognition, we could expect the EMR to increase with the increase in the number of old items. Further inquiry into the relationship between spontaneous EMs and recognition may be important since there is evidence that a brief session of bilateral saccades improves performance on both episodic recall and recognition (Christman, Garvey, & Propper, 2003).

Taken together, the findings of Experiment 2 attest to the robustness of the NVGP phenomenon and provide strong evidence that the phenomenon is rooted in cognitive activity. The finding that NVGPs remains unchanged in the presence of another person is important because it helps in delineating the phenomenon and defining its place in the world of related phenomena such as gaze aversion (Glenberg, 1997) and looking at

nothing (Richardson, Altmann, Spivey, & Hoover, 2009). By examining saccadic behavior in non-visual tasks in the presence of various visual stimuli (e.g., chair, laptop and an interlocutor), this experiment complements the finding that examined the phenomenon in a visually impoverished environment (Ehrlichman et al., 2007) in complete darkness (Ehrlichman & Barret, 1983) and with eyes closed (Ehrlichman et al., 2007, experiment 3) thus allowing us to conclude that NVGPs may be a purely cognitively based phenomenon that is independent from external (visual or social) influences. The fact that the tendencies toward task-specific activations cannot be entirely eliminated by voluntary control further attests to the robustness of the effect of cognitive processes on EMR. Being fully in line with the existing empirical evidence, our findings that people spontaneously move their significantly more while engaged in recall than in recognition, strongly support the idea that NVGPs reflect memory functions needed to gain access to information in LTM and operate on information in WM.

General Discussion and Theoretical Significance

The findings in this research that saccadic patterns that occur when people retrieve information from LTM through recognition and when people perform non-visual tasks in the presence of another person are consistent with the existing body of evidence relating changes in gaze patterns to memory functions activated by various non-visual tasks. With the evidence on the rate of saccadic activation in recognition, a more complete pattern of task-dependent changes in ocular activation begins to emerge as EMR consistently shows dependence on the retrieval requirements of tasks. The fact that both across and within studies, similar EMRs occur in specific groups of tasks, allows us

to consider the ways in which cognitive functions can be reflected in oculomotor functions.

In general, when eye movements are scored from a video record and the minimum eye movement detectable is three degrees of angular displacement, the average eyes-open EMR for groups of participants spans a very large range (.10-1.41) that can be roughly divided in three zones: low (0.10-.50), moderate (0.51 - 0.90) and high (0.91 -1.40). Low EMR typically occurs in tasks with minimal or no retrieval requirements such as auditory vigilance tasks and tasks requiring participants to mentally go through the alphabet and count letters according to a specific visual or phonological attribute (Ehrlichman et al., 2007). In auditory vigilance with shadowing the average EMR is 0.38 (Ehrlichman et al., 2007, Experiment 2). EMR in mental alphabet tasks ranges from 0.40 to 0.46 when letters are counted based on acoustic or visual attributes (Ehrlichman et al., 2007, Experiments 1 and 2). Saccadic frequency of all n-back tasks used in the present study also falls within the low EMR zone. Average EMR was lowest in 2-back tasks in which participant took mental count of their responses ($M_{\text{2-back with counting}} = 0.15$) and somewhat higher in n-back tasks that did not involve counting ($M_{\text{0-back}} = 0.24$, Experiment 1; $M_{\text{2-back}} = 0.33$, Experiment 2). What is common to all tasks linked with low saccadic frequency is that they require continuous attention to a series of either externally presented or internally generated stimuli.

In a striking contrast to low EMR tasks, the average EMR of high retrieval tasks (e.g., fluency) is 2.5- 3 times greater than the average EMR of the low retrieval tasks (e.g., n-back) (Micic et al., in press). High EMR typically occurs in tasks that rely on accessing information stored in LTM such as verbal fluency, remote associates, and

episodic recall. In these tasks, average EMR is very high (Micic et al., in press, Experiment 1, $M_{\text{remote associates}} = 1.38$, $M_{\text{verbal fluency}} = 1.41$, Experiment 2, $M_{\text{episodic recall}} = 1.12$). Average EMRs of well over one eye movement per second in tasks requiring retrieval of information from LTM are consistently reported in NVGPs research (e.g., Bergstrom & Hiscock, 1988; Ehrlichman et al., 2007; the present study). Because processing requirements of high-retrieval tasks vary greatly in terms of the content to be retrieved, it seems that the only commonality among the tasks involves the need to search through LTM in order to provide the answer irrespective whether it involves words, events or non-verbal content.

Moderate EMR occurs in tasks such as delayed repetition (Ehrlichman et al., 2007, Experiment3, $M = 0.89$; Micic et al., in press, Experiment 1, $M = 0.76$), number-letter sequencing (Ehrlichman et al., 2007, Experiment 1, $M = 0.67$), and chain retrieval and phrase-letter counting (Ehrlichman et al., 2007, Experiment 3, $M = 0.7$, $M = 0.79$, respectively). According to the present study, EMR of recognition ($M = 0.66$) also belongs to this category. Because of the likely involvement of information from LTM, cognitive operations performed in these tasks are most likely to take place in the EB of WM. Although we originally considered that the main operation of that short-term memory store would be maintenance of information, evidence gathered in the present and other studies suggests that although maintenance may play a role in WM processing other operations might also be involved and perhaps be even more important for successful performance.[3]

Some clues as to the type of processes that may occur within the EB come from the only exception to the alignment between the EMR zones and the level of retrieval

inherent to tasks, and that is the retrieval of overlearned sequences. Although information retrieved in such tasks has undoubtedly been stored in LTM, their EMR is more akin to the EMR of WM tasks than to the EMR of tasks probing LTM (Ehrlichman et al., 2007). Moderate EMR in these tasks suggests that the likelihood of activating the search function might be low in retrieval of over-practiced information. If retrieval requirements of tasks are contingent on the degree of activation of the search function, then overlearned sequences may be classified as a moderate retrieval task despite the fact that overlearned information is stored in LTM. There are two reasons that this may well be the case. First, retrieval of overlearned sequences may not trigger the search function as much as less-practiced information stored in LTM since each word may serve as a very strong cue for the next word, thereby making it more readily available in the episodic buffer. Second, due to the highly associative and ordered relations of over-practiced sequences, reporting it in a proper temporal order may activate both gaze fixation and eye movements. One possibility is that fixation occurs due to low level of activation of the search function. If so, this would not qualify as activating gaze fixation – it would just mean that the saccadic function was *not* activated while eye movements occur in relation to the retrieval of information that is lost due to failure of maintenance (i.e., as people lose track of their current position in the sequence, Ehrlichman et al., 2007).

Nevertheless, while there is no evidence of a direct relationship between the number of EMs and task performance, this study suggests that under some circumstances, fixation may be beneficial for performance and especially for low retrieval tasks. Experiment 2 found that performance is significantly better when gaze is fixed on a gray

oval than when gaze is fixed on experimenter's nose or is free to move in the presence of an oval or the experimenter. This improvement in performance compared to fixation of experimenter's nose cannot be explained by proposing distracting effect of the face since there is no difference in performance while looking at the nose and without gaze restriction. A possible explanation is that fixating on the oval was less restricting that fixating the nose because the oval was the size of the head but lacking a specific location to be fixated. Therefore, such fixation may have been easier to accomplish thus improving performance. Another possibility is that oval did not have any details on it that may have been distracting. It is also possible that while gray oval was perfectly stationary, the experimenter's head was not to the same degree. These possibilities should be examined in future research.

The actual mechanisms behind gaze patterns of overlearned sequences and other tasks from the moderate EMR cluster are subject to further investigation. However, uncovering mechanisms of gaze patterns associated with the moderate EMR task cluster may be instrumental for description and explanation of the systematic relationship between EMR and task requirements since they suggest that operations performed on information (e.g., search, maintenance) may be more important than the source of information (e.g., LTM) for formation of patterns of saccadic activation. This suggestion is supported by our findings that the difference in EMR of recognition and recall may be better understood in terms of processes than the source of information (memory store). While EMR in recall may predominantly reflect activation of the LTM search function, EMR of recognition may involve a combination of search and output planning mechanism. The proposed distinction between EMR associated with the episodic buffer

and the phonological store may also be more adequately defined in terms of processes performed on information than the store *per se*. Consider that while the main actions of the EB reflected in moderate EMRs may be sequence production and coordination of operations of LTM search and output planning, processes reflected in low EMRs may involve a combination of perceptual processing and output planning. Exploring key elements of WM (phonological store, EB) from a process-oriented approach and not as functionally distinct storage entities (Jones, Macken, & Nicholls, 2004) and considering search through LTM a function of WM might provide a fertile ground for explaining the link between spontaneous gaze shifts and various memory functions suggested by NVGPs, memory-guided EMs of the looking at nothing phenomenon and, by evidence that saccadic EMs can improve retrieval from LTM.

To explain the effect of retrieval requirements on NVEMs, Ehrlichman et al. (2007) proposed the existence of an isomorphism between processes involved in visual perception and memory (i.e., search and maintenance). According to this view, as visually guided saccades reflect searching for information in the visual field and fixations reflect maintenance of information in a temporary store of visual WM, non-visual saccades reflect accessing information in LTM and fixations reflect maintenance of information in a temporary memory store such as the episodic buffer (Baddeley, 2000).

Ehrlichman et al. (2007) proposed that the link between memory functions and spontaneous saccadic eye movements developed in evolutionary history in which the existing neural milieu of an older system was functionally adapted and modified to accommodate development of a new system. Findings of the present study that memory functions of search and maintenance can modulate ocular motility independently from

visual and social influences provide compelling empirical bases for speculations about neuroanatomy of linkage between oculomotor and memory systems. The neuroanatomical model of NVGPs first proposed by Ehrlichman et al. (2007) and further developed by Micic (in preparation) is outlined in the Appendix.

Future Directions: Theoretical Implications and Practical Applications

If memory and oculomotor systems are indeed linked in the way suggested by the LTM-WM model, the shifts of gaze people make when they search their memories may provide clues to how this (possibly unique) human ability emerged from earlier perceptual systems (cf. Jonides, Lacey, & Nee, 2005). Therefore, one use of NVGPs would be to provide valuable insight into evolutionary development of the human brain and of cognitive functions. Yet more importantly, due to its cognitive underpinnings and large individual differences, this easily accessible epiphenomenon of ongoing cognition may have an explanatory and diagnostic potential superior to that of functional behaviors which seldom have more than a single purpose. The profound effect of non-visual cognitive tasks on the rate of eye movements raises the possibility of several practical applications.

For example, NVGPs may be relevant to the inquiry of the causes of driving accidents. Studies of driving attribute impaired visual scanning of the environment (Recarte & Nunes, 2000) and decreased processing capacity (Recarte & Nunes, 2003) as the major causes of accidents to spatial gaze concentration (i.e., long fixations) and reduced inspection frequency of mirrors and speedometer (Recarte & Nunes, 2000) that occur when drivers engage in spatial-imagery, generation of words (Recarte & Nunes, 2000) and casual conversations (McCarley, Vais, Pringle, Kramer, Irwin, &

Strayer,2001). However, as suggested by Micic et al (in press, Experiment 3), while talking, people experience difficulties maintaining fixation and tend to make numerous unintentional eye movements they are not aware of.

Studies of NVEMs suggest that being actively engaged in verbal thinking may be hazardous simply because seemingly random saccades, which tend to occur in large numbers while speaking, may direct the gaze toward various points in the visual field that may not be relevant to driving. Although this repositioning of the gaze may resemble saccadic activity typical of scene evaluation, it may not provide for adequate foveation and efficient visual processing of the circumstantially captured stimuli since it is not exogenously driven. There is strong evidence that vision can be affected both when there is endogenous saccadic activity (e.g., Wallis & Bulthoff, 2000) and when eyes are predominantly still (e.g., Craver-Lemley, & Reeves, 1992). Therefore from the perspective of a modern, fast-paced lifestyle in which a great deal of thinking and communication occurs while driving, study of NVGPs offers a fertile ground for the inquiry and development of safe driving practices.

Perhaps a little more speculative at this time is a proposal that NVGPs can have some role in the medical field where, in conjunction with other clinical measures, they could be used to identify the presence of cognitive function that cannot be communicated. The current methods of assessing the level and content of consciousness lead to erroneous evaluations, misdiagnosis, and mistreatment of 40% of patients with altered states of consciousness (e.g., Andrews, Murphy, Munday, & Littlewood, 1996; Childs & Mercer, 1996). Therefore, improving assessment of cognitive function and thus prognosis and treatment of patients with severe brain damage is of paramount

importance. The systematic relationship between NVGPs and mental activity suggests a possibility that electrooculographic evidence of saccadic eye movements under closed lids in response to either external or endogenous stimuli could be an important, easily obtainable, objective sign of cognitive function. Accordingly, further inquiry of NVGPs in both clinical and non-clinical settings may be instrumental to obtaining a novel, valid, reliable, and affordable indicator of cognitive function in altered states of consciousness.

Future inquiry of NVGPs should examine individual differences, hemisphericity, and functional significance of both eye movements and gaze fixation. The question of functionality remains important since there is no simple explanation as to why in the course of evolution a non-functional behavior (NVEMs) would intermittently be given precedence over functional behavior (visual eye movements) despite possibly detrimental effects of such an arrangement on sensory processing and the apparent lack of the benefit for cognitive processing. One possibility is that the cost of shared pathways that was negligent at the point in history in which coupling between oculomotor and memory related areas developed could be efficiently reduced by the means of a controlling mechanism (e.g., attention). A yet unexplored alternative is that the link between two systems does not reflect phylogenic development in which sharing of the circuitry occurs due to isomorphism of processes used by two systems (memory search and visual search, respectively) but due to actual functional significance of the processes of the older system (visual processing) for the processes of the younger system (e.g., creation, storage and retrieval of memory traces) in which case, future explorations of NVGPs might uncover additional ways in which eye movements could reveal the inner workings and organization of the mind.

Footnotes

[1] EOG data were also analyzed using Root Mean Square (RMS); however, the results from RMS were identical to those for power and, therefore, are not further discussed.

[2] EOG power clipped at 4000mV did not differ from EOG power clipped at 1000mV and was therefore, not used in statistical analysis.

[3] No-tasks baselines also fall in the moderate EMR range. However, because in the baseline condition some eye movements are clearly visual (i.e., participants are looking around the room), the rate of eye movements that can be considered NVEMs is probably closer to the low range.

Appendix

Neuroanatomy of NVGP: The WM-LTM Model

Ehrlichman et al. (2007) proposed that oculomotor and memory systems communicate through a neuroanatomical link formed in the course of evolution of neural circuits that support active memory search. Their anatomical model of NVGPs shows how the saccadic portion of the oculomotor system and LTM system can interact via striatal pathways and transmodal thalamic nuclei. At the center of their model is the superior colliculus, a mesencephalic convergence center which in its intermediate layer harbors tonic fixation neurons and saccadic burst neurons (Munoz & Everling, 2004), and which relates information about where and when saccades should occur (Munoz, 2002) to the brain-stem gaze circuitry (Sparks, 2002). Frontal, parietal and temporal memory-related cortices can affect temporal distribution and frequency of saccadic generation via direct and indirect neural connections with the superior colliculus.

Essential to the LTM claim of NVGPs is the evidence that cortical regions involved in retrieval from LTM, mainly the medial temporal lobe (Schacter & Wagner, 1999), may affect saccadic frequency through direct and indirect (via transmodal thalamic nuclei) connections with the portions of the prefrontal cortex involved in oculomotor control such as the dorso-lateral prefrontal cortex (Cabeza, Dolcos, Graham, & Nyberg, 2002; Kapur Craik, Tulving, Wilson, Houle, & Brown, 1994; Moscovitch & Winocur, 2002). Indication that brain regions involved in memory can communicate with the superior colliculus together with functional specialization within the superior colliculus substantiated the idea that activation of the collicular saccadic zone and the resultant high saccadic frequency may be related to searching for information through

LTM, and that activation of the collicular fixation zone and the resultant low saccadic frequency may be related to maintenance of information in WM.

The neuroanatomical model of Ehrlichman et al. (2007) provided a biological anchor for the behavioral evidence that some saccadic eye movements may not be related to processing of visual information but to processing of information within the memory system. However, this model did not present mechanisms through which brain regions of LTM could influence the superior colliculus to create combinations of saccadic eye movements and intervals of ocular quiescence (i.e., NVGPs) typical of WM and LTM tasks. To explain how retrieval requirements of tasks may result in either saccadic eye movements or in gaze fixation, and to account for the variability in gaze patterns across tasks, we propose that memory functions occur within a dynamic equilibrium in which a change in activation of one memory function (e.g., maintenance) is accompanied with an opposite change in activation of a complementary function (e.g., search). The hypothesized principle of functional interaction within the memory system and the evidence of linkage between the memory and the oculomotor system seem to converge on a plausible neural mechanism behind task-specific NVGPs.

The LTM-WM model introduced here proposes that in a single-task situation levels of activation of the neural circuitry supporting complementary memory functions are integrated into a single motor command to either initiate a saccadic eye movement or render the eyes immobile. According to this idea, the intervals of gaze fixations and of saccadic eye movements found within NVGPs represent fluctuations in the levels of activation of memory functions recruited while performing a task. Although NVGPs comprise both saccadic eye movements and gaze fixations, one of these ocular behaviors

will tend to dominate the gaze pattern indicating greater activation of the memory function intrinsic to the task. For example, eye movements dominate the NVGPs of tasks which require searching through long-term storage of information (e.g., fluency task) while gaze is mostly stationary in WM tasks (e.g., n-back task) in which a small number of eye movements is likely to be a sign of updating the temporary memory store.

The fact that NVGPs involve successive periods of saccadic activity and gaze fixation, and dramatically differ in WM and LTM tasks, strongly suggests that the key link between the oculomotor and memory systems may be a neural system capable of communicating activation of assorted memory functions to the neural centers of gaze control. The only neural system with the capacity to connect WM and LTM systems with the common saccadic effector system in the upper and lower brain stem, and to give rise to both eye movements and gaze fixations, is the basal ganglia. Basal ganglia output can modify saccadic frequency bidirectionally by inhibiting and disinhibiting the saccadic portion of the superior colliculi via one of the three known parallel pathways of control: the direct pathways from caudate nucleus to substantia nigra pars reticulata, the indirect pathway connecting caudate nucleus and substantia nigra pars reticulata via globus pallidus pars externa and/or the subthalamic nucleus, and the hyper-direct pathway from the subthalamic nucleus to substantia nigra pars reticulata (Hicosaka, 2007).

That NVGPs as a motor outcome of the basal ganglia output to the superior colliculus may be a sign of memory functions such as search through LTM and maintenance in the episodic buffer becomes plausible with the anatomical evidence that neural projections from cortical regions implicated in both WM and LTM converge on the striatum (nucleus caudatus and globus pallidus (Figure 2). The striatum receives

direct projections from areas implicated in WM such as the dorso-lateral prefrontal cortex and ventro-lateral prefrontal cortex (Finch, 1996; Postuma & Dagher, 2006) and areas involved in LTM retrieval including entorhinal cortex, perirhinal cortex and parahippocampal cortex (Finch, 1996; Postuma & Dagher, 2006; Suzuki, 1996). Additionally, cortical regions involved in WM and LTM seem well interconnected (Takahashi, Ohki, & Kim, 2007). Both direct (e.g., Goldman-Rakic, Selemon, & Schwartz, 1984) and indirect (e.g., Fernandez & Tendolkar, 2001) connections exist between dorso-lateral prefrontal cortex and parahippocampal cortex with reciprocal connections between the two running through the caudate nucleus (Poldrack, & Packard, 2003) and thalamic nuclei (Suzuki, 1996). Furthermore, reciprocal connections run between the parahippocampal cortex and the posterior parietal cortex (Moscovitch & Winocur, 2002) which projects directly to the superior colliculus (Goldman & Nauta, 1976; Pierrot-Deseilligny, Muri, Ploner, Gaymard, & Rivaud-Pechoux, 2003; Gaymard, Ploner, Rivaud, Vermersch, & Pierrot-Deseilligny, 1998) and together with the dorso-lateral prefrontal cortex and the inferior frontal cortex is currently considered the neural substrate of the episodic buffer (Naghavi & Nyberg, 2005).

Consistent with the anatomical support of the idea that neural output of the LTM and WM circuitry can be translated into gaze patterns comprised of saccadic eye movements and fixations, physiological evidence indicates that saccades may be related to mnemonic processes (e.g., Sobotka, Zuo, & Ringo, 2000) and that the relationship between portions of the medial temporal lobe and the striatum may be competitive (e.g., Moody, Bookheimer, Vanek, & Knowlton, 2004). In the rat brain, stimulation of the entorhinal neurons (Finch, Gigg, Tan, & Kosoyan, 1995) has an inhibitory effect on the

striatum while striatal activation leads to hippocampal inhibition and vice versa (Gabrieli, Brewer, & Poldrack, 1998; Poldrack, & Packard, 2003). The competitive connection between LTM brain regions and the basal ganglia substantiates the idea that search and maintenance of information are complementary functions and that the dominant gaze pattern may be indicative of the degree of task-induced activation of the search function neurally expressed by the extent of the medial temporal lobe activation.

The competitive relationship between brain regions of LTM and the striatum provides for a simple explanation of the NVGPs occurring in LTM and WM tasks. High EMR occurs during high retrieval tasks because activation of the medial temporal lobe for the purpose of searching through LTM leads to inhibition of the striatum and the resultant disinhibition of the saccadic neurons in the superior colliculus. Ocular quiescence in WM tasks occurs because inactivity of the medial temporal lobe in those tasks leads to activation of the striatal inhibition of the saccadic neurons in superior colliculus. In the system in which saccadic generation depends on the net excitatory signal from the memory related brain regions, it is essential that activation of the cortices involved in the search functions are coordinated with activation of the brain regions involved in functions other than searching through LTM. Implicit to this observation is the idea that the basal ganglia may perform a sequence of operations while regulating the oculomotor outcome: 1) coordination of activation of relevant brain regions through competitive (medial temporal lobe) and non-competitive (prefrontal cortex) connections, 2) integration of feedback from the memory related brain regions and 3) transmission of the net effect of feedback integration to the intermediate layer of the superior colliculi.

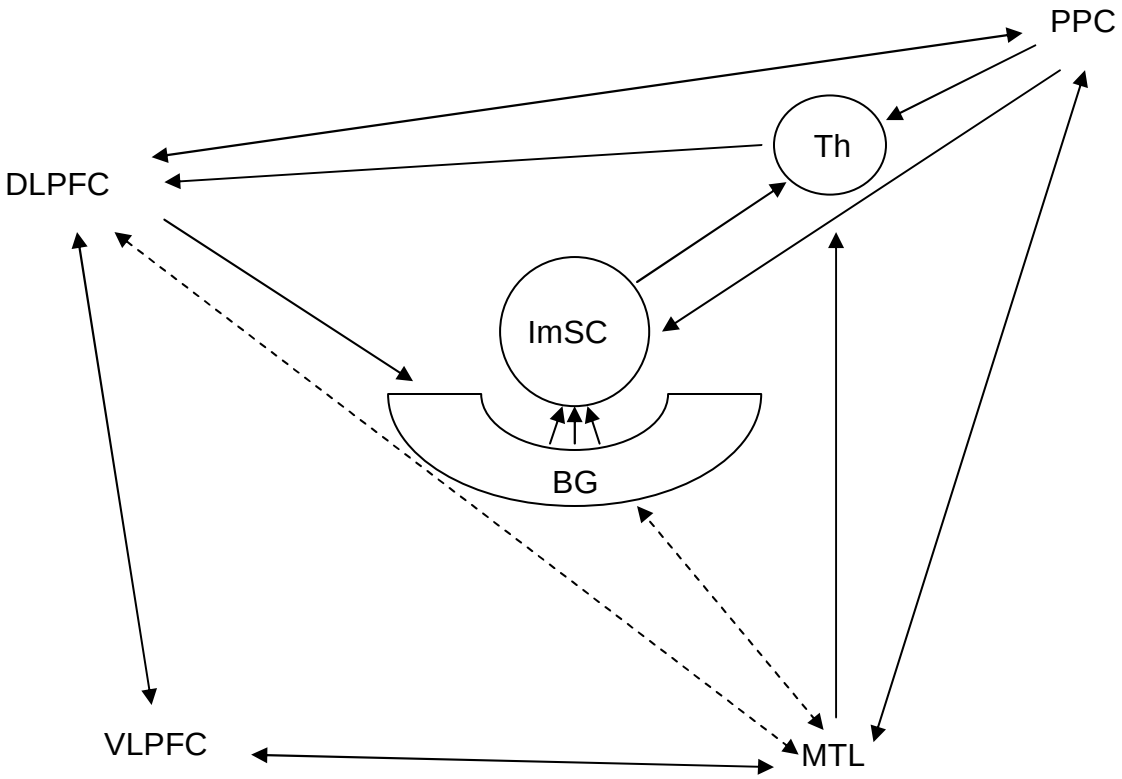
Anatomical, physiological and morphological evidence converge to show that the basal ganglia is equipped with neural circuitry capable of coordinating widely distributed cortical areas, integrating multiple neural inputs and modulating the oculomotor output. Basal ganglia harbors memory-guided saccadic neurons, neurons related to cognitive functions (Hikosaka, Takikawa, & Kawagoe, 2000; Merker, 2007), and neurons sensitive to reinforcement and reward (Nakamura & Hikosaka, 2006). Electrical stimulation studies suggest that in the monkey brain, substantia nigra pars reticulata preferentially influences memory-guided (i.e., non-visually guided) saccades (Basso & Liu, 2007). In accord with the behavioral findings of saccadic facilitation in tasks requiring retrieval of information from LTM, physiological evidence indicates that saccadic facilitation appears to be based on the memory effect on the saccadic system similar to that of positive reinforcement and natural reward (Nakamura & Hikosaka, 2006). We note that the involvement of motivational circuitry in accessing information in long-term and short-term memory is intuitively appealing since successful retrieval may be both endogenously rewarding and reinforced by the successful performance (e.g., correct answer or fluent conversation).

The proposition that based on its pattern of connectivity and its morphological diversity the basal ganglia may have a key role in coordinating saccadic action with ongoing cognitive activities is further supported with evidence of significant functional coupling and co-activation of the striatum with dorso-lateral prefrontal cortex and the rostral anterior cingulate cortex, cortical areas implicated in executive function (e.g., Yeterian & Pandya, 1991). The convergence of afferents from almost entire cortex (Postuma & Dagher, 2006) including cortical and subcortical afferents from the

circuitries of memory and motivation (Lawrence, Sahakian, & Robbins, 1998) together with the fact that striatum co-activates with executive prefrontal regions (Postuma & Dagher, 2006), regulates access to WM storage (McNab & Klingberg, 2008), and mediates oculomotor responses (Hikosaka et al., 2000), strongly suggests that the basal ganglia may be synchronizing memory functions of search and maintenance with saccadic facilitation and inhibition in a manner of the "central executive" (Baddeley & Hitch, 1974).

By taking into account that both exogenous cognitive tasks and internally generated thoughts require processes such as encoding, retrieval, maintenance and manipulation of information, and response selection, planning and execution, the LTM-WM model of NVGPs outlined here offers a framework within which cognitive and motor functions can be related to each other both phenomenally and neurally. In this model, the pattern of functional coupling among cortical regions and subcortical structures implicated in various memory functions within each system substantiates the claim that spontaneous patterns of ocular activation reflect cognitive operations relevant to memory. Accordingly, the model provides a framework within which specific mechanisms through which eye movements might be involved in performance on non-visual tasks may be examined.

Figure 1



Note: ImSC – intermediate layer of the superior colliculus; BG – basal ganglia; Th – thalamus; MTL – medial temporal lobe; VLPFC – ventrolateral prefrontal cortex; DLPFC – dorsolateral prefrontal cortex; PPC – posterior parietal cortex; full line – noncompetitive connection; broken line – competitive connection

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