December 2014

The Development of an Eye-Tracking Method to Assess Cognitive Flexibility Using a Switching-Task Paradigm

Melissa Lu Pinke
University of Wisconsin-Milwaukee

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by

Melissa Lu Pinke

A Thesis Submitted in

Partial Fulfillment of the

Requirements for the Degree of

Master of Science

in Communication Sciences and Disorders

at

University of Wisconsin Milwaukee

December 2014

ABSTRACT

THE DEVELOPMENT OF AN EYE-TRACKING METHOD TO ASSESS COGNITIVE FLEXIBILTY USING A SWITCHING-TASK PARADIGM

by

Melissa Lu Pinke

The University of Wisconsin-Milwaukee, 2014
Under the Supervision of Professor Sabine Heuer

Introduction: Cognitive flexibility, a domain of the executive functions, has been demonstrated to influence functional communicative ability, specifically the ability to maintain the topic of conversation, take appropriate conversational turns, self-monitor, repair communicative breakdowns, and use of alternative communication modalities. The assessment of cognitive flexibility is essential for the clinical evaluation and treatment of individuals with neurological disorders interfering with communication, however, confounds related to language comprehension and expression impact test validity. This is due to the reliance on verbal and physical response requirements, the understanding of complex linguistic instruction, and concomitant cognitive and physical impairments. Therefore, new methods designed to reduce these confounds are needed.

Cognitive flexibility has been validly indexed between mono-and bilingual speakers using nonlinguistic switching tasks. Nonlinguistic switching tasks require participants to match stimuli according to a specific search criterion, such as color or shape. In the non-switch (singe-task) condition, the matching criterion remains

the same across all trials and the associated cognitive demand is low. In the switching condition (mixed-task), the matching criterion switches unpredictably between search criterion and the associated cognitive demand is high. The difference in cognitive demand between the non-switch and switch conditions and within the switch condition allows for the calculation of cost, a measure of cognitive flexibility.

The nonlinguistic switching tasks used to examine cognitive flexibility within the mono-and bilingual speakers are promising for use with individuals with language impairments of a neurological origin. However, motoric response requirements possibly invalidate test results due to the presence of concomitant physical impairments. Therefore, the application of eye-tracking methods has excellent potential because eye tracking does not require verbal, written, or gestural responses; or the manipulation of devices, such as a computer mouse or joystick.

Purpose: The purpose of this study was to develop and validate a novel eye-tracking task to assess cognitive flexibility using a switching task paradigm, and to determine the sensitivity to differences in cognitive switching demand between and within the single and mixed-task conditions.

Method: The eye movements of 20 language-normal participants were recorded as they looked at a computer screen and participated in experimental single- and mixed-task conditions. The eye-tracking measures latency of first fixation, first pass gaze duration, and first fixation duration on the target image were computed

across all trials. The general switching cost, specific switching cost, and mixing cost, as indicated by response differences between and within the single-and mixed-task and switch conditions were calculated.

Results: The eye-tracking measures latency of first fixation on the target and first pass gaze duration on the target significantly indexed general switching cost and mixing cost, while first fixation duration on the target failed to demonstrate significance.

Pearson Correlation Coefficients were computed between eye-movement measures and test performance on standardized measures of cognitive flexibility including the Comprehensive Trail Making Test (CTMT) and Visual Elevator subtest of the Test of Everyday Attention (TEA). Some significant correlations were observed between the T-scores and raw times scores of the Comprehensive Trail Making Test and latency of first fixation on the target, however, no eye-tracking measures correlated significantly with the Visual Elevator subtest of the Test of Everyday Attention.

Implications: The novel eye-movement method validly indexed switching cost. The eye-tracking indices latency of first fixation and first pass gaze duration provided promising evidence that the eye-tracking task is sensitive to differences in cognitive demand. The nonlinguistic nature, lack of motoric requirements, and inclusion of practice trials render it a promising assessment tool for individuals with aphasia. Continued development of the eye-tracking method using the nonlinguistic switching task is warranted in order to enhance our understanding of

the relationship between functional communication and cognitive flexibility and to improve the assessment methods for individuals with neurologic communication deficits.

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LIST OF ABBREVIATIONS

American Speech Language Hearing Association Functional Assessment of Communication Scale .... ASHA FACS

Comprehensive Trail Making Test .... CTMT

First fixation duration on the target .... FFDT

First pass gaze duration on the target... FPGDT

Latency of first fixation on the target...LFFT

Test of Everyday Attention .... TEA

ACKNOWLEDGEMENTS

I would like to express sincerest gratitude to my advisor Dr. Sabine Heuer, for her support, guidance, and patience throughout the course of this project. In addition, I would like to thank members of my committee, Dr. Wendy Huddleston and Dr. Carol Seery, for their contributions to the work.

The Development of an Eye-Tracking Method to Assess Cognitive Flexibility Using a Switching-Task Paradigm

Cognitive flexibility, or the ability to shift mental set, has been implicated as the domain of the executive functions responsible for influencing functional communication ability (Frankel, Penn, & Ormond–Brown, 2007; Fridriksson, Nettles, Davis, Morrow, & Montgomery, 2006; Penn, Frankel, Watermeyer, & Russell, 2010; Purdy, 2002). Deficits in cognitive flexibility impact functional communication skills including the ability to take turns, self-monitor, maintain the conversational topic, repair communicative breakdowns, and utilize a variety of communication modalities (Frankel et al., 2007; Penn et al., 2010). Understanding the nature of deficits of cognitive flexibility associated with language impairments of a neurological origin is important in terms of theoretical implications as well as clinical assessment and treatment.

Serious methodological confounds, however, challenge the validity of standardized assessments of cognitive flexibility in individuals with neurologic and linguistic impairment. This is due to the reliance on verbal and physical response requirements, the understanding of complex linguistic instruction, and concomitant cognitive impairments (Keil & Kaszniak, 2002).

Cognitive flexibility has been validly indexed in monolingual and bilingual speakers using a nonlinguistic switching task paradigm (Bialystok & Martin, 2004; Calabria, Hernandez, Branzi, & Costa, 2012; Prior & MacWhinney, 2010). The nonlinguistic switching tasks used to assess cognitive flexibility within the bilingual population have excellent potential for use with individuals with neurologic communication impairments because they refrain from the use of linguistic stimuli and do not require verbal or written responses. These tasks, however, often demand a physical response such as the manipulation of devices such as a computer mouse or response button. The integration of eye-tracking response methods with nonlinguistic switching tasks further reduces critical response confounds associated with traditional methods of assessment and thus improve the validity of cognitive assessment.

The Executive Functions

The executive functions include the capacities that monitor higher cognitive processes and "enable a person to engage successfully in independent, purposive, self-serving behavior" (Lezak, 1995, p. 42). Intact executive functions promote the formulation of goals, the initiation of behavior, the anticipation of consequence, planning, and situational adaption within every day life (Purdy, 2011). Executive functions deficits, however, have been indicated to contribute to functional communication impairment in people with aphasia (Frankel et al., 2007; Fridriksson et al., 2006; Penn et al., 2010; Purdy, 2002), including reduced communicative effectiveness, limited use of alternative communication modalities, and diminished ability to repair communicative breakdowns (Purdy, 2002). Executive functions are especially important in the presence of aphasia because additional cognitive skills must be relied upon to compensate for the loss of language in order to successfully communicate (Penn et al., 2010).

Executive functions play an important role in communication; however, research investigating the relationship between language and cognition is complicated by broad definitions and a lack of agreement regarding theoretical construct and terminology. The domains of executive functioning in a model described by Lezak (1995) include planning, sequencing, organizing, and monitoring goal-directed behavior, while the Miyake et al. (2000) model included working, memory, inhibition, and mental set switching. Another framework developed by Barkley (1997) proposed working memory, internalization of speech, reconstitution, and regulation of affect as the components of executive functioning. According to Keil and Kaszniak (2002), the executive functions domains include "working memory, self-monitoring and regulating, inhibiting irrelevant stimuli, and switching between concepts or actions, generation and application of strategies, temporal integration and integrating multimodal inputs from throughout the brain" (p. 306).

The lack of agreement regarding the domains of executive functioning further challenges assessment because the specific processes that are assessed often overlap or are unclear. For example, Frankel et al. (2007) regarded the Wisconsin Card Sorting Test (Grant & Goodglass, 1990) as a test of concept formulation and abstract reasoning while Purdy et al. (2002) a test of cognitive flexibility. Furthermore, the research of Fridriksson et al. (2006) considered the Wisconsin Card Sorting Test to evaluate functions of abstract reasoning, set switching, working memory, and problem solving.

Despite these differences, all models of executive functions include the domains of inhibition and mental set switching, both of which are indicative of cognitive flexibility. Inhibition refers to the ability to prevent a habitual response or ignore impeding irrelevant information (Barkley, 1997) and is traditionally assessed with the Simon arrows task, Stroop color-naming task, and trail making tests. Mental set switching refers to the ability to change behavior in response to situational demands (Miyake et al., 2000) and has been measured with the Wisconsin Card Sorting Test, Go/No-Go tasks, and switching tasks.

Executive functions deficits in aphasia: Presence and relation to functional communication measures.

In the Unites States, one million people live with aphasia and an estimated 80,000 individuals are diagnosed each year. Aphasia is an acquired neurogenic communication disorder. The hallmark of aphasia is impaired language with varied deficits manifesting in language expression, language comprehension, reading, and writing (Hallowell & Chapey, 2008). In addition to linguistic deficits, individuals with aphasia often exhibit concomitant deficits of the executive functions (Beeson, Bayles, Rubens, & Kaszniak, 1993; Chiou & Kennedy, 2009; Frankel et al., 2007; Fridriksson et al., 2006; Glosser & Goodglass, 1990; Penn et al., 2010; Purdy, 2002).

Deficits of executive functioning negatively impact functional communication ability in individuals with aphasia (Frankel et al., 2007; Fridriksson et al., 2006; Penn et al., 2010). The executive functions, specifically mental set switching, influences the ability to maintain the conversational topic, engage in appropriate turn taking, monitor the effectiveness of a message, repair communicative breakdowns, and use alternative modes of communication (Frankel et al., 2007) and is commonly assessed with standardized measures such as the American Speech-Language-Hearing Association Functional Assessment of Communication Skills for Adults (ASHA FACS; Frattali, Thompson, Holland, Wohl, & Ferketic, 1995). Functional communication refers to the ability to express or convey a message regardless of the modality and to independently and successfully communicate across a variety of natural environments and is facilitated by mental set switching ability. However, the relationship between mental set switching ability and language is less clear.

Several researchers have explored the relationship of executive functions and functional communication in people with aphasia. Fridriksson et al. (2006) examined the relationship between the executive functions and functional communication ability in monolingual individuals with aphasia (n=25) with emphasis on cognitive flexibility. All participants were reported between the ages of 33 and 84 and were 1 month to 14 years post onset of stroke.

Two standardized tests of cognitive flexibility, the Color Trails Test (D'Elia, Satz, Uchiyama, & White, 1996) and the Wisconsin Card Sorting Test-64 (Kongs, Thompson, Iverson, & Heaton, 2000) were administered. A significant relationship was revealed between performance on the Color Trails Test and ratings on the ASHA FACS (Frattaili et al., 1995). A greater amount of examiner prompts or errors on the Color Trails Test corresponded with reduced ratings on the *Qualitative Dimensions* and *Communication Independence* components of the ASHA FACS.

Results of the Wisconsin Card Sorting Test-64 revealed that individuals with less severe functional communication impairments were able to complete a significantly greater number of categories on the Wisconsin Card Sorting Test-64 than those with more severe communicative impairments. However, due to test complexity, less than half of the individuals with aphasia were successful in completing a single category (Fridriksson et al., 2006). Further, the individuals with less severe communication impairments required fewer prompts on the Color Trails Test than those individuals with more severe communication impairments, emphasizing the crucial link between functional communication ability and executive functions. Results also suggested that the commonly used Wisconsin Card Sorting Test might not be a valid measure of cognitive flexibility in individuals with more severe forms of aphasia. However, results of the study should be considered with caution regarding the participants' age range and time post aphasia onset. The sample of individuals with aphasia was very heterogeneous and executive functions deficits are likely to increase with age, regardless of presence of aphasia.

Frankel et al. (2007) explored the relationship between executive functioning ability and functional communication in a 58-year old female with aphasia. Conversational samples with unfamiliar and familiar partners were collected to examine functional communication ability and a test battery was administered to assess the executive functions. The conversational samples obtained were analyzed for the following communicative characteristics: turn taking, topic management, and repair. The executive functions test battery assessed attention, verbal and nonverbal working memory, visual memory, planning, generation, and concept formation. See Table 1 for a summary of measures used to assess executive functions domains for this and all following studies.

The conversational analysis revealed appropriate frequency, length, content as well as intact turn taking and topic management abilities (topic initiation, maintenance, and switching). Deficits were observed in conversational repair. Results of the executive functions test battery demonstrated intact attention, sustained attention, interference suppression, long-term memory, and planning. Executive functions deficits were indicated in response inhibition, concept-formation and generation.

Based on these results, the functional communication of the individual with aphasia was impacted by both linguistic and executive functions impairments (Frankel et al., 2007). Concept formation and generation were influenced by the occurrence of perseveration, a result of the reduced ability to shift attention, which is a component of cognitive flexibility. Additionally, poor message generation and an inability to choose alternative communication strategies interfered with the individual's ability to successfully repair conversational breakdowns. Thus, deficits in executive functions, as indexed by previously established executive functions measures and conversational analysis, demonstrated a negative effect on functional communication ability.

A major criticism of the Frankel et al. (2007) study was the small sample size (n=1). While the study provided support for the involvement of executive functions deficits in aphasia and the subsequent impact on communication ability, the inclusion of additional participants would have strengthened the results. The executive functions test battery administered in this study was designed to avoid cognitive, linguistic, and motoric limitations often co-occurring with aphasia. However, several tests relied upon intact working memory (Wisconsin Card Sorting Test, Tower of London, Raven's Progressive Matrices), timed and verbal responses (Stroop color-naming test), motor skills (Trial Making Test). Thus, it remains unclear if poor test performance was due to deficits in the executive functioning or concomitant linguistic, cognitive, or motoric impairments.

Table 1
Assessments of executive functioning

Author	Cognitive concept	Executive functions Test
Bialystok, Craik, and Luk (2008) *N = 48 monolingual adults; 48 bilingual adults*	Working Memory	Forward and backward Corsi block span Self-ordered pointing
	Response inhibition	Sustained attention to response task Stroop color-naming task Simon arrows task
Bialystok and Martin (2004) *N = 36 monolingual children; 31 bilingual children*	Working Memory	Forward digit span
	Mental set switching	Dimensional card sorting task
Choiu and Kennedy (2009) *N= 14 adults with aphasia; 14 healthy controls*	Attention	Test of Everyday Attention-Visual elevator subtest
	Response inhibition	Trail making test
	Mental set switching Fluency	Delis-Kaplan Executive function System Design Fluency
Frankel, Penn, and Ormond-Brown (2007) *N = 1 adult with aphasia*	Memory	Medical College of Georgia complex figures
	Non-verbal working memory	Self-ordered pointing
	Verbal Working	Digit Span backwards
	Visual attention and scanning	Bell's cancellation tests
	Response inhibition	Trail making test Echopraxic tasks Stroop color-naming task
	Cognitive Flexibility	Wisconsin Card Sorting Test
	Planning	Tower of London
	Fluency	Five point test Design Fluency
	Concept formation and abstract reasoning	Raven's Progressive Matrices
Fridriksson, Nettles, Davis, Morrow, and Montgomery (2006) *N = 25 adults with aphasia*	Response inhibition Cognitive Flexibility	Color Trails Test Wisconsin Card Sorting Test

Table 1
Continued

Author	Cognitive concept	Executive functions Test
Murray (2012) *N = 39 adults with aphasia; 39 healthy controls*	Memory	Wechsler Memory Scale-Revised (Forward and backward memory span Working Memory Protocol
	Attention	Test of Everyday Attention Rating Scale of Attentional Behavior
	Visual scanning and attention	Behavioral Inattention Test
	Fluency	Ruff Figural Fluency Test
Penn, Frankel, Watermeyer, and Russell (2010) *N = 8 monolingual adults with aphasia; 2 multilingual adults with aphasia*	Memory	Complex figures Self-ordered pointing
	Response inhibition	Trail making test Stroop color-naming task
	Cognitive Flexibility	Wisconsin Card Sorting Test
	Planning	Tower of London
	Fluency	Five Point Test Design Fluency
Prior and MacWhinney (2010) *N= 27 monolingual adults; 32 bilingual adults*	Mental set switching	Nonlinguistic switching task
Purdy (2002) *N = 15 adults with aphasia; 12 healthy controls*	Cognitive Flexibility	Wisconsin Card Sorting Test
	Planning	Tower of London Tower of Hanoi Porteus Maze Test

Penn et al. (2010) examined the executive functions in monolingual (n=8) and multilingual (n=2) individuals with aphasia. All participants were within the chronic stages of recovery and were fluent speakers of English.

Similar to Frankel et al. (2007), the executive functions were measured through the administration of an executive functions test battery and the analysis of conversational speech samples. The results of the executive functions test battery indicated that the multilingual individuals with aphasia performed significantly better than the monolingual individuals with aphasia across the constructs of response inhibition, memory, cognitive flexibility, planning, and fluency.

The multilingual individuals with aphasia also demonstrated better functional communication ability compared to the monolingual participants. More precisely, the conversational analysis indicated that the multilingual participants displayed intact turn taking, topic management, and repair abilities, while the majority of the monolingual individuals exhibited functional communication deficits within these domains.

The enhanced cognitive flexibility of the multilingual speakers with aphasia contributed to the differences in communication (Penn et al., 2010), such that the multilingual individuals benefited from the use of alternative modalities to support communicative success such as external cues, facial expression, and gesture. This indicated that intact cognitive flexibility, as measured by tasks assessing the ability to switch mental set, influenced communicative success. Thus, mental set switching ability facilitated functional communication ability. In contrast, the monolingual individuals with aphasia, who exhibited reduced cognitive flexibility, were less successful communicators due to limited strategy use, presence of perseverations, dependence upon the communication partner, and topic digression. Therefore, while the exact relationship between the executive functions and language is unclear, cognitive flexibility appears to play a role in communication ability.

While the Penn et al. (2010) study provided insight into the executive functions and communication differences between monolingual and multilingual individuals with aphasia, it suffered from a small (n=10) and unbalanced sample size (n=8 monolingual individuals; n=2 multilingual individuals). In addition to the limited number of multilingual speakers with aphasia, language background of the multilingual individuals varied greatly. Finally, conversation analysis was implemented to assess functional communication ability, however, a standardized measure such as the ASHA FACS (Frattali et al., 1995) would further supplement the relationship between impairments of executive functioning and communication ability.

In summary, a significant relationship has been identified between executive functioning ability and functional communication. More specifically, in individuals with linguistic deficits, cognitive flexibility as measured by mental set switching, influenced communication ability. However, study sample sizes were small (Frankel et al., 2007; Penn et al., 2010), unbalanced (Penn et al., 2010), and failed to include individuals with more severe forms of aphasia because of the complex and novel tasks involved in the assessment of executive functioning (Fridriksson et al., 2006). In order to understand the impact of executive functioning on functional communication across a variety of types and severities of aphasia, including multilingual speakers, it is imperative to develop a method of assessing the executive functions that reduces linguistic, cognitive, and motoric confounds.

The Assessment of Cognition in Individuals with Aphasia

Cognitive processes have been assessed in people with aphasia independently from linguistic deficits. Purdy (2002) compared the cognitive flexibility of individuals with aphasia and neurological healthy controls through the assessment of performance accuracy, efficiency, and speed using the Wisconsin Card Sorting Test (WCST; Grant & Berg, 1993). All participants were identified as native English speakers, estimated with normal intelligence prior to cerebral vascular insult, and passed vision and hearing screenings.

Purdy (2002) administered the Wisconsin Cards Sorting Test formally and without procedural modification to the individuals with aphasia and the controls. The results indicated a significant reduction in accuracy, efficiency, and speed in individuals with aphasia as compared to the control group. The Wisconsin Cards Sorting Test required intact memory, language comprehension, cognitive, and motoric abilities. However, Purdy (2002) failed to formally assess memory, making it difficult to control for the influence of impaired memory on test performance. While the Wisconsin Cards Sorting Test did not require verbal responses, an inherent difficulty for individuals with expressive aphasia, the Wisconsin Cards Sorting Test did require the comprehension of complex task instruction. While practice trials were administered prior to the test, the Wisconsin Cards Sorting Test may still not be an appropriate method of assessment for individuals with more severe forms of aphasia.

Chiou and Kennedy (2009) examined the attention-switching abilities in adults with mild to moderate aphasia who were at least 6 months post stroke (n=14) and neurologically healthy controls (n=14) using a Go/No-Go paradigm.

During the Go/No-Go task, participants were instructed to either execute or inhibit a response (eg. pressing or not pressing a button) based upon the stimulus type. 'Go' stimuli elicited a response and 'no-go' stimuli necessitated response inhibition. The stimuli included visual (capital letters) and auditory stimuli (letter names).

The task included two conditions, (a) switching with rules and (b) switching without rules. During the switching without rules condition, participants were instructed to follow a simple no-go rule throughout the task (eg. Do not respond to the O), whereas in the switching with rules condition, a modality specific no-go rule was provided visually (eg. Do not respond when you *hear* O; Do not respond when you *see* X). Overall, the participants with aphasia exhibited reduced mental set switching ability, as indicated by slower response time and increased errors when switching to a new rule.

Chiou and Kennedy (2009) highlighted reduced mental set switching abilities in individuals with aphasia. However, the use of linguistic stimuli (letters) might not be appropriate for individuals with linguistic impairments. Further, adequate linguistic and reading comprehension skills were necessary for participants to respond appropriately because rules were presented visually during each trial. When assessing the executive functions of individuals with various types and severities of aphasia, it is essential to reduce linguistic involvement and complexity in order to produce reliable and valid test results. This is because linguistic deficits can confound the performance on tasks that assess executive functions. Finally, while performance on the ASHA FACS was assessed, it was not related to mental set switching ability, which would have elucidated the relationship between executive functions deficits and functional communication.

Murray (2012) examined the influence of attention, memory, and executive functions on functional communication in adults with left-hemisphere stroke induced fluent or non-fluent aphasia and healthy controls. Subtests of the Test of Everyday Attention (TEA; Robertson, Ward, Ridgeway, & Nimmo-Smith, 1994) were administered to evaluate attention switching (Visual Elevator), sustained attention (Elevator Counting task), and divided attention (Telephone Search Task with Counting).

The participants with aphasia performed significantly worse than the control group on all subtests of the TEA. Further, the results indicated a significant correlation between functional communication as indexed by the ASHA FACS and the Visual Elevator task ($r=.53$, $p=.001$), the Elevator Counting task ($r=.33$, $p=.05$), and Telephone Search task with counting ($r=.49$, $p=.001$). This is indicative that attention switching, sustained, and divided attention are most significantly related to language and communication skills. Attention switching or mental set switching, as measured by The Visual Elevator task, demonstrated the most prominent correlation.

Murray (2012) accounted for impaired linguistic ability through the use of nonverbal assessment measures and the provision of alternative response methods as deemed appropriate. The Elevator subtest, for example, required a verbal response. Therefore, in order to compensate for expressive language deficits, individuals with aphasia were provided a visual number line. However, the scoring of the Visual Elevator subtest is determined by time, thus the reliance on a number line potentially complicates and confounds performance results. Murray (2012) indicated that the performance of individuals with aphasia might be further influenced by the use of covert language or subvocal rehearsal based strategies.

Challenges associated with traditional assessments of the executive functions in individuals with aphasia.

The role of cognitive flexibility in aphasia is poorly understood in part because valid methods to assess individuals with aphasia are lacking (Keil & Kaszniak, 2002). The assessment of cognitive flexibility in individuals with brain injury is confounded by the presence of linguistic, cognitive, and motoric deficits. Linguistic confounds specifically challenge the validity of traditional assessments because they rely upon (a) the comprehension of complex task instruction, (b) the ability to complete multi step directions, and c) verbal response requirements that might impact performance (Keil & Kaszniak, 2002). The assessment of cognitive flexibility often includes novel or unusual tasks. These tasks frequently use explicit and lengthy instructions and often involve multi-step directions. This may be confounding because people with language impairments might perform poorly due to a lack of comprehension of task instructions and not necessarily because they do not have the resources to perform the actual tasks. For example, the Wisconsin Card Sorting Test has been shown to be too difficult for people with aphasia to complete (Fridriksson et al., 2006; Purdy, 2002). Further, individuals with more severe forms of aphasia are often excluded from research due to the inability to adhere to standardized testing procedures (Fridriksson et al., 2006; Murray, 2012; Penn et al., 2010).

In addition to linguistic deficits, motor impairments such as hemiparesis, paralysis, limb apraxia, and apraxia of speech might interfere with an individual's ability to execute a response accurately. Adequate visual perception, hand-eye coordination, visual–spatial orientation, motor planning, and fine motor skills are necessary for tracking an object on a computer screen, pushing buttons, raising one's hand, writing, or providing verbal responses. Therefore, physical impairments might impact test performance. Finally, the cognitive impairments often associated with aphasia include memory deficits (Caplan, & Waters, 1995; Caspari, Parkinson, LaPointe, & Katz, 1998; Friedmann, & Gvion, 2003) and attention deficits (LaPointe & Erickson, 1991; McNeil et al., 2004; McNeil et al., 2005; Murray, Holland, & Beeson, 1997; Robin & Rizzo, 1989), which also confound results.

To improve the appropriateness of the assessment of executive functions for people with aphasia, modifications of standardized assessment tools including the removal of time constraints, simplification of task instruction, the supplementation of verbal instruction with gesture or writing, and administration of practice items have been implemented (Frankel et al., 2007; Murray, 2012). These modifications, however, compromise test validity of standardized tests (Keil & Kaszniak, 2002). Thus, it is important to identify valid measures of executive functions that adjust for linguistic, cognitive, and physical impairments.

Task Switching

Mental set switching ability has been validly assessed using a switching task paradigm. The experimental switching tasks used to assess cognitive flexibility require individuals to complete multiple conditions including single-task or non-switch condition(s) where the same task is performed consistently across consecutive trials, and mixed-task or switch condition(s) wherein tasks requirements switch unpredictably between trials, resulting in switch- and non-switch trials. Increased response time during switch trials is generally evident when the performance of switch trials is compared to the performance of non-switch trials (Prior & MacWhinney, 2010; Wylie & Allport, 2000). The increased response time associated with switch trials is attributed to the cost of involvement of the executive functions to monitor cognitive processing during the switch (Wylie & Allport, 2000).

Several measures to index the difference in cognitive demands have been proposed. The response difference between single-task and mixed-task conditions has been used to calculate general switching cost (Kray & Lindenberger, 2000). Specific switching cost has been calculated as the response difference between the switch and non-switch trials of the mixed-task block (Kray & Lindenberger, 2000;

MacWhinney & Prior, 2010). Finally, mixing cost has been determined as the response difference between the single-task conditions and the non-switch trials of the mixed-task condition (Kray, Li & Lindenberger, 2002; Prior & MacWhinney, 2010).

The source of cost differs among the measures. While general switching cost has been attributed to the global cognitive processes that are required to maintain and select the appropriate task set, specific switching cost is related to the transient ability to activate the appropriate task set and deactivate the previous task set (Kray & Lindenberger, 2000; Prior & MacWhinney, 2010). Finally, mixing cost has been associated with overall reduced efficiency on repeated trials of the mixed-task condition compared to the single-task condition due to continued activation of multiple task sets (Kray, Li, & Lindenberger, 2002). However, the fact that both general switching and mixing cost are derived from the differences between single and mixed-task conditions, suggests that there is some overlap in the concepts that they assess, while specific switching cost assesses differences within the mixed-task condition only.

Switching tasks: Methods used in bilingual literature.

Switching tasks are sensitive to differences in cognitive flexibility between monolingual and bilingual speakers (Bialystok et al., 2008; Bialystok & Martin, 2004; Prior & MacWhinney, 2010). Bialystok and Martin (2004) examined differences in the cognitive flexibility of neurologically healthy monolingual and Chinese-English bilingual speaking children using a computerized card-sorting task. The computerized card-sorting task administered was composed of four conditions: (a) sort by color, (b) sort by color or shape, (c) sort by color or object, and (d) sort by function or location. Within each of the conditions, switch and non-switch trials occurred. Switch trials were defined as the initial sorting rule for a set of stimuli, whereas non-switch trials required participants to sort the same set of stimuli based upon a different set of criteria, or rule. For example, the color task included five red squares and five blue squares. The initial non-switch series instructed the participants to press the X when a red square appeared and the O when a blue square appeared. Conversely, the switch series required the participants to press the X when a blue square appeared and the O when a red square appeared.

The results of the Bialystok and Martin (2004) study indicated an overall better performance during non-switch trials than switch trials for all participants. Further, the bilingual children significantly outperformed monolingual children on sorting conditions of color or shape and color or object, demonstrating enhanced cognitive flexibility on nonlinguistic tasks. Data, however, were reported in terms of accuracy of performance, not switching cost, which would provide additional information related to cognitive flexibility.

To further investigate the notion of augmented executive functions in lifelong bilingual adult speakers, Prior and MacWhinney (2010) examined the efficiency of female monolingual individuals and bilingual individuals using a task-switching paradigm. During the switching task, participants were instructed to match visual stimuli by shape (circle or triangle) or color (red or green). The experiment included three components: (a) two single-task blocks of non-switch trials matching by color only and shape only, (b) three mixed-blocks of switch trials of shape and color, and (c) two single-task blocks of non-switch matching by color only or shape only. During each trial, the matching rule was presented visually in order to cue participants to match the stimuli according to either shape or color. Participants responded by selecting the image according to the associated response key.

The results of the non-verbal switching task were analyzed for both response rate and accuracy. Overall, the non-switch trials incurred faster and more accurate responses than switch trials as demonstrated identical performance of monolingual and bilingual speakers. The bilingual speakers, however, were significantly faster than monolingual individuals during non-switch trials. Thus, the switching cost, or difference in response time between non-switch and switch trials, was smaller for bilingual speakers. While significant difference between monolingual and bilingual participants was not indicated in terms of accuracy, bilingual participants displayed greater cognitive flexibility by switching faster between non-switch and switch trials.

The nonlinguistic task-switching method employed by Prior and MacWhinney (2010) was successful in demonstrating differences in the cognitive flexibility of monolingual and bilingual speakers. Switching cost, as calculated by the difference in response time of non-switch and switch trials, might be a sensitive measure of cognitive flexibility for individuals with aphasia. The simple task instruction, limited reliance on memory due to visual cues, absence of time constraints, the nonlinguistic nature of the task, and lack of cultural bias due to the neutral nature of the stimuli render switching tasks suitable for individuals with aphasia. Given the physical impairments associated with stroke, motoric response requirements might challenge test validity and limit inclusion based on severity of deficits. An alternative response method such as eye tracking, however, has excellent potential to accommodate for the presence of physical impairment and thus reduced confounds.

Eye Tracking

Eye-tracking methods have been previously validated as a measure of cognitive and linguistic processing. Eye tracking methods have been used to index processes of attention (Heuer & Hallowell, 2014), working memory (Ivanova & Hallowell, 2011), priming (Odekar, Hallowell, Kruse, Moates, Lee, 2009), language comprehension (Allopenna, Magnuson, & Tanenhaus, 1998; Cooper, 1974; Dickey, Choy, &Thompson, 2007, Dickey & Thompson, 2009; Hallowell, 1999; Hallowell, Kruse, Shklovsky, Ivanova, & Emeliyanova, 2006; Hallowell, Wertz, & Kruse, 2002; Tanenhaus, Magnuson, Dahan, & Chambers, 2000; Tanenhaus & Spivey-Knowlton, 1996), and language expression (Choy & Thompson, 2010; Griffin, 2004; Meyer, Van der Meulen, & Brooks, 2004) in individuals with and without aphasia.

Eye tracking is a method of studying the acquisition and processing of information. This is essential for research in perception and cognition as eye-tracking methods have the ability to provide on-line measures of elements of cognitive processing (Duchowski, 2002). The duration and location of eye fixation is indicative of cognitive processing. Viewers tend to look at objects or images that they are thinking about and fixation duration is assumed to reflect the time to encode visual information and the time to operate on the encoded data (Just & Carpenter, 1976). Because eye tracking captures an individual's response to stimuli through eye movements, it does not require overt verbal, gestural, or physical limb movement necessary in the manipulation of a device. Therefore, it allows for the examination of cognitive processes without response confounds related to linguistic, cognitive, or physical deficits (Ivanova and Hallowell, 2011; Odekar et al., 2009).

The eye-tracking measures often used to examine cognition and attentional processes include first fixation duration on a target, latency of first fixation on a target, and first-pass fixation duration on a target toward a specific area of interest. First fixation duration on a target (FFDT) is the duration of the very first fixation in a region of interest (Duchowski, 2002; Odekar et al., 2009). The initial fixation in scene viewing is influenced by the acquisition of information, however, research is less clear regarding the role of semantic informativeness on first fixation duration on a target . For example, the first fixation duration on a target on an object that does not belong to a scene was determined as longer than for an object that does (Rayner, 1998). It remains uncertain whether this is due to the increased time required for object identification or for cognitive integration of the object into the scene (Duchowski, 2002). In contrast, De Graef, Christiaens & d'Ydewalle (1990) and Henderson (1992) found that the first fixation duration on a target on an object was not related to semantic informativeness. Given that first fixation duration on a target is representative of cognitive processing beyond simply the identification of an object, Henderson (1992) suggested first fixation duration on a target as the preferred measure of fixation in scene viewing.

Latency of first fixation on the target (LFFT) refers to the time spent looking anywhere within a display before fixating on the area of interest. Research on latency of first fixation provides divergent results. While Loftus and Mackworth (1978), Henderson and Hollingworth (1998), De Graef et al. (1990), and Odekar et al. (2009) found that the semantic informativeness of stimuli affected the timing of fixations, most authors found significantly longer latencies of first fixations allocated to semantically related images in visual scenes. Odekar et al. (2009) found that significantly shorter mean latency of first fixation was allocated to semantically related target images as opposed unrelated images in visual priming task.

First-pass gaze duration on the target (FPGDT) refers to the sum of fixations between when a viewer first fixates on and first fixates away from an area of interest. A longer first-pass gaze duration on the target has been associated with images that were semantically related to a target word compared to unrelated foil images (Odekar et al., 2009), and has been found to be longer for semantically informative objects, such as target objects in scene perception tasks (Henderson & Hollingworth, 1998).

Purpose

The goal of this study was to develop and validate an eye-tracking method to index mental set switching ability, a measure of cognitive flexibility, in individuals without neurological impairment based upon performance on a nonlinguistic switching task. The purpose of developing a novel method was to address the potential confounds that impact the validity and usability of traditional assessments of cognitive flexibility for use with individuals with neurogenic deficits.

The experimental nonlinguistic switching task included a single-task condition and a mixed-task condition of matching images by color and shape. In the single-task condition the matching criterion remained the same across all trials, such that participants were required to match images by color or by shape only. The cognitive demand associated with consecutive non-switch trials was low due to the consistency of the matching criterion.

The magnitude of general and specific switching cost as well as mixing cost were used to determine if the eye-tracking method accurately indexes differences between low and high switching task demands. Further, eye-tracking indices were compared to the performance on standardized assessments of executive functions including the Comprehensive Trail Making Test (CTMT; Reynolds, 2002) and the Visual Elevator subset of the TEA (Robertson et al., 1994) to conclude whether the novel task is a valid measure of cognitive flexibility.

Research questions.

1. Will eye-movements, as measured by first fixation duration on the target, latency of first fixation on the target, and first pass gaze duration on the target be sensitive to differences in switching demands between the single-task conditions and the overall mixed-task condition (general switching cost)?
2. Will eye-movement indices be sensitive to differences in switching demands between non-switch and switch trials of the mixed block (specific switching cost)?
3. Will eye-movement indices be sensitive to differences in switching demands between non-switch trials of the single-task block and non-switch trials of the switch task block (mixing cost)?
4. Will eye-tracking measures correlate significantly with standardized measures of executive functioning?

Expected outcomes.

Hypothesis 1.

General switching cost between the single-task and mixed-task condition was expected to be significant. The cognitive demands associated with the mixed-task condition were hypothesized to be significantly greater compared to the cognitive demands associated with the single-task condition. Accordingly, significantly greater first fixation duration on the target, first pass gaze duration on the target, and lower latency of first fixation on the target were expected for the single-task condition than the mixed-task condition.

Hypothesis 2.

Specific switching cost between non-switch and switch trials within the mixed block was expected to be significant. Accordingly, significantly greater first fixation duration on the target, first pass gaze duration on the target, and lower latency of first fixation on the target were hypothesized for the non-switch trials compared to the switch trials within the mixed-task condition.

Hypothesis 3.

Mixing cost between the single-task trials and the *non-switch* trials of the mixed-task was expected to be significant due to increased cognitive demands required to maintain two mental sets in the mixed task (e.g. matching by color and shape) as opposed to maintaining a single mental set in the single task. Accordingly, significantly greater first fixation duration on the target, first pass gaze duration on the target, and lower latency of first fixation on the target were hypothesized for the single-task trials than the non-switch trials of the mixed-task condition.

Hypothesis 4.

The eye-movement method was expected to validly index attention switching under varying switching demands. Accordingly, significant correlations were expected for eye-movement indices and standardized measures of the Comprehensive Trail Making Test (Reynolds, 2002) and the Visual Elevator subtest of the Test of Everyday Attention (Robertson et al., 1994). Specifically, measures associated with single-task processing, trials 1-3 of the Comprehensive Trail Making Test, were hypothesized to correlate significantly with the single-task eye movement measures. It was predicted that the standardized mixed-task measures, including trails 4 and 5 of the Comprehensive Trail Making Test and the Visual Elevator Task, would correlate significantly with eye-tracking indices of the mixed-task.

Method

Approval for this research was granted by the Institutional Review Board at The University of Wisconsin-Milwaukee. Prior to participation in the study, each participant provided written consent. See the Appendix A for the consent form.

Participants

Twenty neurologically healthy, monolingual individuals, ages 23-29 (M =24.5, SD=1.57) were recruited from the University of Wisconsin Milwaukee. As determined through questionnaire (See Appendix B), all participants were self-reportedly free of language, learning, and cognitive impairment. Further, all participants successfully passed vision and hearing screenings (See Appendix C). The vision screening included aspects of central visual acuity, peripheral visual acuity, color vision, and observation of pupillary and ocular motility. During the screening and subsequent eye-tracking session, participants were allowed to wear contact lenses or glasses. The Lea Symbols Line Test was administered to screen visual acuity; participants were required to correctly identify five of five symbols at a viewing distance of .6 meters. The Amsler grid, a grid containing evenly spaced horizontal and vertical lines, was administered to screen for central vision impairment and will require participants to indicate an absence of visual distortion. Furthermore, the color vision screening required participants to correctly identify four of four images from "Color Vision Testing Made Easy" (Waggoner, 1994).

A binaural pure tone hearing screening was administered to ensure appropriate perception of verbal instruction. During the screening, participants identified tones presented through supra-aural headphones. In accordance with the screening procedures developed by the American Speech-Language-Hearing Association, frequencies of 1000, 2000, and 4000 Hz were presented at 25 dB SPL (American Speech-Language-Hearing Association, 1997). The identification of each tone was required.

Procedure Overview

Upon completion of preliminary screening procedures, the standardized tests and experimental eye-tracking tasks were administered. Half of the participants completed the standardized tests prior to the experimental eye-tracking tasks, with the presentation order reversed for the remaining.

The presentation order of the standardized tests included the administration of the Comprehensive Trail Making Test (Reynolds, 2002) first, and either Version A or Version B of the Visual Elevator subtest of the Test of Everyday Attention (Robertson et al., 1994) to follow.

The novel eye-tracking task was comprised of four experimental blocks, including a single-task color matching block, a single-task shape matching block, and two mixed-task color and shape matching blocks. Prior to each experimental condition, training was completed to familiarize participants with the task procedures for each experiential condition. Half of the participants completed the single-task color matching block, followed with the single-task shape matching block, while the remaining half completed the single-task shape matching block first followed with the single-task color matching block. For all participants, the study concluded with two mixed-task blocks.

Standardized Tests

Comprehensive trail making test (CTMT).

The Comprehensive Trail Making Test (CTMT; Reynolds, 2002) is a standardized neuropsychological assessment sensitive of attention, inhibition, and cognitive flexibility. During the trail-making tasks numbers, number words, and or letters on a page were connected with a line in a specified order as quickly and accurately as possible. The complete CTMT was administered in accordance with standardized testing procedures. This included a total of five trails and corresponding sample items. In trails 1-3, the numbers 1-25 were scribed randomly within circles on a page, and the participant was instructed to draw a line to connect the numbers in numerical order. In trail 4, the numbers 1-25 were represented with either numerals (eg. 1,2,3) contained within circles or number words (eg. four, five, six) contained within rectangles, and the participant is instructed to connect the numbers in numerical order. In trail 5, the numbers 1-13 and letters A-L were presented, and the participant was instructed to connect the numbers and letters in an alternating sequence (eg. 1-A-2-B-3-C). During each individual trail, the examiner recorded time, in seconds, as the participant completed the task as quickly and accurately as possible.

The raw score and T-score of the CTMT is reflective of the number of seconds required to complete the trail (Reynolds, 2002). The number of errors was not included within the raw score because, during completion of the test, the examiner informs the participant of errors. Thus, errors were accounted for by additional time required to make the corrections. The T-score, a score based on age and completion time, was also calculated for trails 1-5, with a composite T-score derived from the sum.

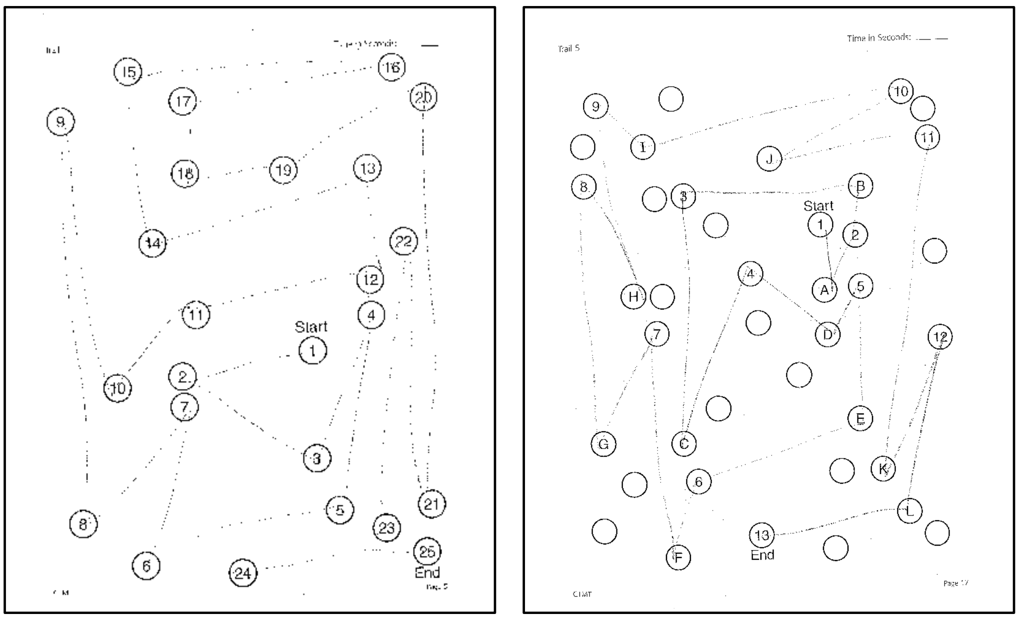

Figure 1. Example of the Comprehensive Trail Making Test (Reynolds, 2002).

Test of everyday attention (TEA).

The Test of Everyday Attention (TEA; Robertson et al., 1994) assessed a variety of different functions of attention including focused, divided, and sustained attention in both visual and auditory modalities. The Visual Elevator subtest was selected to assess attention-switching ability. During the Visual Elevator subtest, participants were presented with a series of elevator doors and arrows from the TEA stimulus test booklet; see Figure 2 for an example of the stimuli. Each elevator door image represented *a* single floor while bold up and down arrows represent a change in direction. Participants were instructed to count the elevator doors until an arrow is reached. If the arrow pointed up, the participant stated "up" and continued to count up; if the arrow pointed down, the participant said "down" and began to count in reverse. During the test, the examiner pointed to each image, moving to the next only after the participant had given a response, thus allowing the participant to self-pace.

Participants were randomly assigned to complete either Version A or Version B of the Visual Elevator test. Excluding the practice items, both versions of the Visual Elevator test contained 10 total trials. Each trial was timed and accuracy and timing scores were calculated. The *accuracy score* was determined by the number of correct final responses out of 10, whereas the *timing score* was calculated by the duration of time required to complete all correct trials divided by the number of total switches within those trials. The number of arrows in a given trial established the number of total switches.

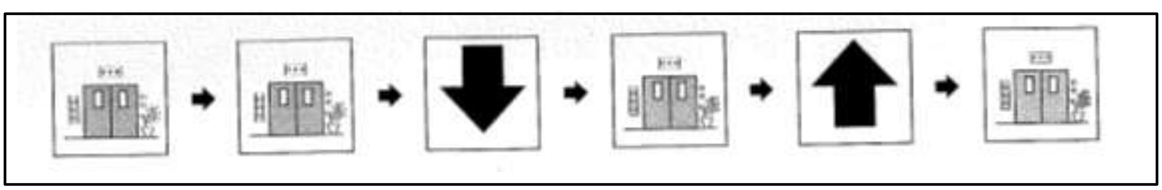

Figure 2. Example of the Visual Elevator Test (Robertson et al., 1994). The correct response is "one, two, down, one, up, two."

Eye-Tracking Procedures

During the experimental eye-tracking tasks, participants were seated in front of a computer screen and viewed image displays on a 24-inch ASUS VE 248H LCD computer monitor while their eye movements were recorded. Eye movements were recorded using the LC Technologies (2011) EyeFollower, a binocular, remote pupil center/corneal reflection system with a sampling rate of 120 Hz. The LC Technologies (2011) EyeFollower is completely non-invasive, with no part of the eye-tracking equipment making physical contact with the participant, nor requiring the stabilization of the head with a headrest. The patented Eye Gaze Technology software algorithm allowed for head movements without sacrificing eye-tracking accuracy.

Calibration.

A nine-point calibration was completed for each participant. During the calibration process, participants were instructed to maintain a stable head position while following a blinking yellow dot on the computer screen with both eyes. Upon the completion of the calibration process, participants were no longer required to maintain a stationary head position, thus allowing free movement during the experimental task.

Stimuli

Forty-eight image displays were created using Microsoft PowerPoint software. Each display contained three objects (red and blue circles and squares), two at the top of the screen (target and foil) and one at the center (reference). The visual matching code, located directly above the reference object, indicated the matching criterion; see Figure 3 for an example of the display. The code for color matching was indicated with two solid yellow triangles, while the code for shape matching was indicated with the outline of two black triangles.

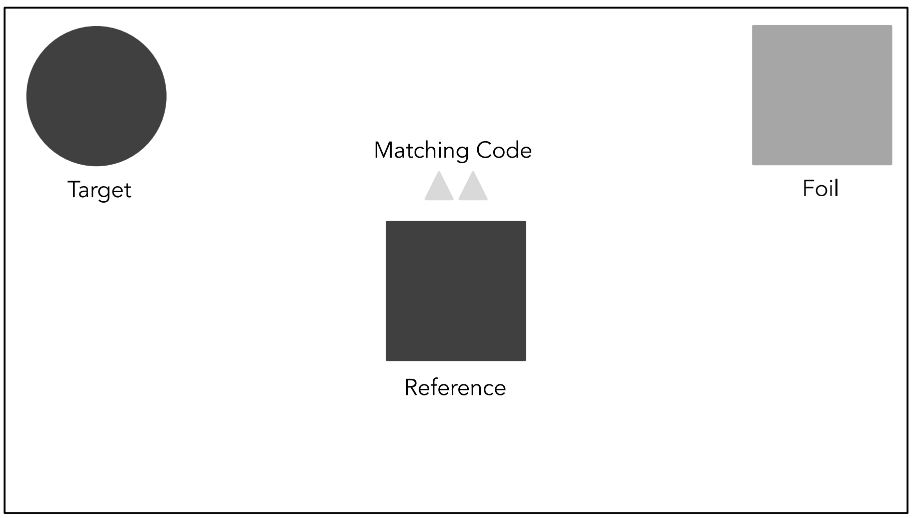

Figure 3. Example of the switching task image display. Each image display contained four elements including the reference image, target, foil, and matching code. The reference image was located centrally within the display, with the matching code located directed above. The target and foil were positioned in the upper left and right quadrants.

Each image display was presented for 4000 ms followed by a blank screen with a cross hair in the center, presented for 500 ms. The stimuli were balanced for location of the target image (upper left or right quadrant), shape (circle or square), and color (blue or red) of the target. Further, the stimuli were balanced for congruency and incongruence; see Figure 4 for further explanation. Target and foil images were presented in a visual angle of 9.6 degrees at a viewing distance of 60 cm.

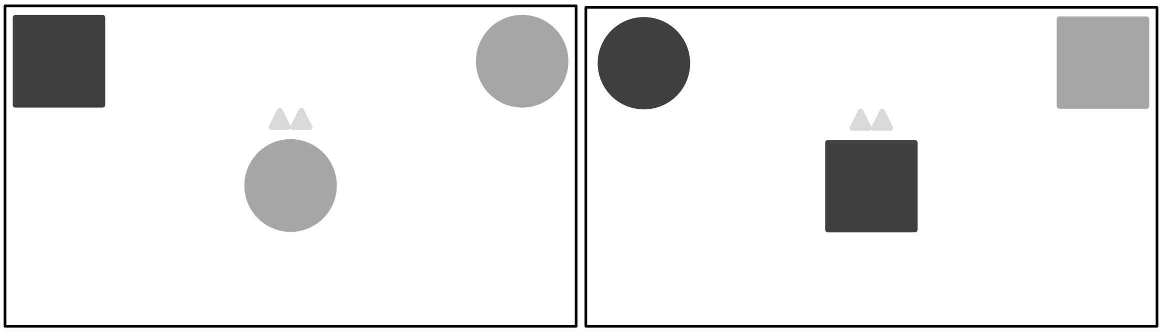

Figure 4. Example of congruent and incongruent image displays. The image on the left was considered *congruent* because the reference image in the center matches both the color and shape of the target image located in the upper right quadrant. The image on the right was considered *incongruent* because the reference image matches only the color of the target image located in the upper left quadrant.

Procedure

For an overview of the eye tracking task procedures view Table 2.

Table 2
Organization of experimental eye-tracking tasks

Task	Block	Training	Experimental
Non-switch *Participants were randomly assigned to begin with either color or shape matching.*	Single-task color matching	8 trials	24 trials
	Single-task shape matching	8 trials	24 trials
Switch *All participants completed Mixed-task block 1 and then Mixed-task block 2.*	Mixed-task block 1	16 trials	48 trials
	Mixed-task block 2	*No training was occurred prior to mixed-task block 2.*	48 trials

Non-switch Condition

Single-task color matching.

The training for single-task color matching trials began as the participant viewed a color matching display while instructions were presented verbally. The instruction stated, "This is an example of color matching. The two yellow triangles indicate that you are to match by similar color. Look at the color above that matches the color in the center." Review Figure 5 for the specific instructions for color matching.

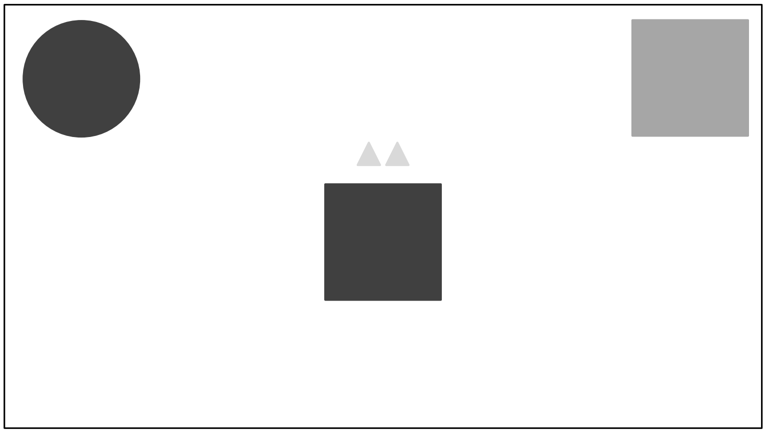

Figure 5. Instructions for color matching. Participants were instructed to "Look at the color above that matches the color in the center." The target response was located within the upper left corner (blue). The feedback provided for an incorrect response states, "You looked at red, the answer is blue."

Next, a series of eight practice trials were completed. The instructions for the practice trials stated, "Please complete the following practice items by looking at the color above that matches the color in the center." Performance of the practice items was observed on an additional computer screen, and tallied by the examiner. The participants were required to achieve a pass criterion of 60% (5/8 trials) accuracy during the practice trials. Failure to achieve the pass criterion resulted in repetition of the training procedure, with failure upon the second attempt cause for exclusion. Based on this criterion, no participants were excluded from participation in the study.

Upon successful completion of the practice protocol, a total of 24 experimental single-task color-matching trials were completed. Half of the participants completed color-matching trials followed by shape-matching trials with the presentation order reversed and counterbalanced for the remaining half.

Single-task shape matching.

The training procedure for single-task shape matching trials was consistent with the training for color-matching trials. However, the instructions stated, "This is an example of shape matching. The two shapes indicates that you are to match by similar shape. Look at the shape above that matches the shape in the center." Review Figure 6 for details regarding the instruction for shape matching trials. Similarly, participants were prompted to "Complete the following practice items (n=8) by looking at the shape above that matches the shape in the center." Following the practice items, a series of 24 experimental trials were administered, with the instructions restated immediately prior.

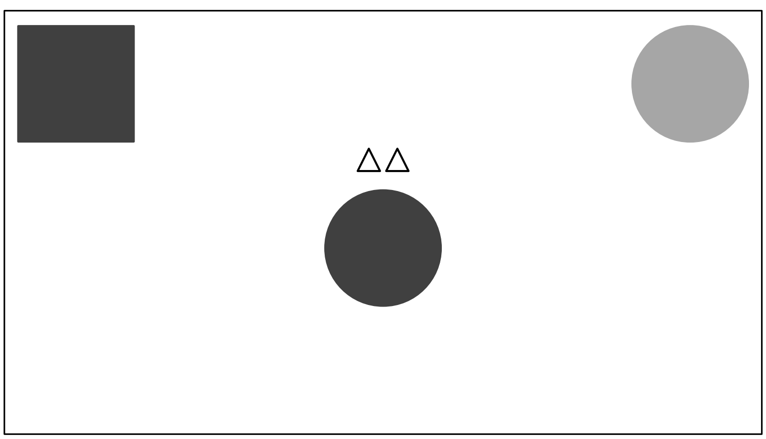

Figure 6. Instructions for shape matching. Participants were instructed to "Look at the shape above that matches the shape in the center." The target response is located within the upper right corner (circle). The feedback provided for an incorrect response stated, "You looked at square, the answer is circle."

Switch Condition

Mixed-task blocks 1 and 2.

Two mixed-task blocks containing color and shape matching were conducted after completion of the non-switch condition, with a training session completed prior to block 1 only. Participants were provided verbal instruction with a series of three corresponding image displays. The instruction stated, "The next trials switch unpredictably between matching by color and matching by shape. First look at the matching symbol and then look at the color or shape that matches the object in the center. For example, first shape matching, the correct response is square; then color matching, the correct response is red; and finally shape matching, the correct response is circle." Participants were asked to "Please complete the following practice items. First look at the matching symbol. Then look at the shape or color above that matches the object in the center." A total of 16 practice items were then administered. Each participant was required to achieve 60% accuracy (10/16 trials) during the practice in order to participate in the experimental condition, with failure resulting, again, in the repetition of the training. Training occurred prior to block 1 only. Each of the mixed-task blocks contained a total of 49 trials each, of which the first was considered a dummy trial. All participants completed the switch condition in the same order, first block one and then block 2 with a brief transition break in between. The stimuli of each block were divided equally among image (shape=24 and color=24), congruency (congruent=24, incongruent=24), and switch type (switch=24 and non-switch=24).

The stimuli were presented in a pseudo-randomized order. Verbal instruction was provided before the onset of each of the switch blocks.

Analysis

Eye-tracking analysis.

NYAN 2 Professional Edition software (Joos & Weber, 2011) was used to present and extract the data. Fixations were defined as having relative stability within 1.4 degrees of visual angle, vertically and horizontally (LC Technologies, 2011) for a minimum duration of 100 ms. (Manor & Gordon, 2003). The size of the areas of interest of targets and foils extended 10 cm horizontally, and 10 cm vertically. Only fixations within those areas of interest and the viewing time of 4000 ms were included in the analysis. The dependent measures FFDT, LFF, & FPGD were computed using NYAN 2 for areas of interest. The statistical analysis was computed using SPSS software.

Single trial data were averaged across participants. For hypotheses 1,2, and 3, paired samples t-tests were used to calculate significant mean difference. The Bonferroni method of adjustment was applied to control for the presence of a type one error (.05/3=.017). For hypothesis 4, Pearson product correlation coefficients were computed.

Power analysis.

A statistical power analysis was performed for an estimation of effect size based on data from a previous study (Heuer, 2014) (N= 16), using first pass gaze duration measures to index attention allocation comparing single- to dual-task processing on a visual search task in young language-normal adults. The effect size in this study was .76, considered to be medium using Cohen's (1988) criteria, with an alpha = .05 and power = 0.89, (GPower 3.1.9.2; Faul, Erdfelder, Lang & Buchner, 2007). Thus, the sample size of n = 20 was considered adequate for the main objective of this study.

Validity.

Construct validity is defined as the degree to which a measure accurately reflects an examined behavior (Schiavetti, Metz, & Orlikoff, 2011). Therefore, construct validity was determined by whether the novel eye-tracking task was sensitive to changes in cognitive demand through the presence of general, specific, and mixing cost.

Concurrent validity is assessed through examining the relationship between an experimental measure and a standardized test measure (Schiavetti et al., 2011), thus the existence of a positive correlation between the experimental nonlinguistic task with novel eye tracking and results of the Comprehensive Trail Making Test and the Visual Elevator subtests of the Test of Everyday Attention were used to determine concurrent validity.

Results

Hypothesis 1

Paired samples t-tests were conducted to determine if the **general switching cost,** as indexed by differences between single and mixed-task conditions, was significant. Means and standard deviations for all measures are reported in Table 3. The results were significant for latency of first fixation on the target and first pass gaze duration on the target, demonstrating that the demands of the mixed-task condition were greater than those of the single-task condition. The mean latency of first fixation on the target for the mixed-task condition was significantly greater than the mean of the single-task condition $t\ (19) = -22.83$, $p < .001$. The mean first pass gaze duration on the target for the mixed-task condition was also significantly greater than the mean of the single-task condition $t\ (19) = 6.74$, $p < .001$. The result for first fixation duration on the target was insignificant $t\ (19) = 0.89$, $p < .38$.

Table 3
Means and Standard Deviations for the Single and Mixed-task Conditions

Measure	Mean	SD	N
LFFT			
Single-task	0.53	0.08	20
Mixed-task	1.02	0.13	20
FFDT			
Single-task	0.85	0.48	20
Mixed-task	0.79	0.39	20
FPGDT			
Single-task	2.75	0.85	20
Mixed-task	2.45	0.82	20

Hypothesis 2

Paired samples t-tests were conducted to test the hypothesis that the specific switching cost, as indexed by differences in cognitive demands between non-switch and switch trials within the mixed block would be significant for the eye-tracking measures first fixation duration on the target, first pass gaze duration on the target, and latency of first fixation on the target.

Means and standard deviations are reported in Table 4. After the Bonferroni adjustment, none of the comparison reached significance. The mean latency of first fixation on the target of non-switch and switch trials within the mixed-task block was insignificant t (19) = -2.16, $p < .04$. Accordingly the mean first fixation duration on the target, t (19) = -0.99, $p < .34$, and mean first pass gaze duration on the target, t (19) = -0.28, $p < .78$, were also found insignificant.

Table 4
Means and Standard Deviations for the Non-switch and Switch Trials of the Mixed-task Condition

Measure	Mean	SD	N
LFFT			
Non-switch trials	1.00	0.14	20
Switch trials	1.04	0.13	20
FFDT			
Non-switch trials	0.77	0.35	20
Switch trials	0.81	0.44	20
FPGDT			
Non-switch trials	2.44	0.84	20
Switch trials	2.45	0.81	20

Hypothesis 3

Paired samples t-tests were used to determine whether **mixing cost** as indexed by differences between the single-task condition and *non-switch* trials of the mixed-task condition was significant. Significant mixing cost was observed for the eye-tracking measures latency of first fixation on the target and first pass gaze duration on the target. See Table 5 for reported means and standard deviations. The mean latency of first fixation on the target of the single-task condition was significantly smaller than the mean LFFT of the non-switch trials of the mixed-task condition t (19) = -22.21, $p < .001$. The mean first pass gaze duration on the target of the single-task condition was significantly greater than the mean FPGDT of the non-switch trials of the mixed-task condition t (19) = 5.99, $p < .001$. The first fixation on the target was found insignificant t (19) = 0.89, $p < .38$.

Table 5
Means and Standard Deviations for the Single-task Condition and Non-switch Trials of the Mixed-task Condition

Measure	Mean	SD	N
LFFT			
Single-task	0.53	0.08	20
Non-switch trials	1.00	0.14	20
FFDT			
Single-task	0.85	0.48	20
Non-switch trials	0.77	0.35	20
FPGDT			
Single-task	2.75	0.85	20
Non-switch trials	2.44	0.84	20

Hypothesis 4

Correlation coefficients were computed between eye-tracking measures and standardized tests. A *p* value of less than .05 was required for significance. Significant results between some test measures of the Comprehensive Trail Making Test and latency of first fixation on the target, were observed while correlations with first fixation duration on the target and first pass gaze duration on the target remained insignificant. Refer to Tables 6 and 7 for correlation coefficients.

The Comprehensive Trail Making Test includes three non-switch trails (Trails 1,2, and 3) and two switch trails (Trails 4 and 5). Performance on the single-task condition and mixed-task condition correlated significantly with T-scores of each of the non-switch trails (trails 1,2,3). In addition, the single-task condition correlated significantly with T-scores of switch Trail 5, however, the mixed-task condition did not.

Different correlations were observed between the T-scores and raw time scores. For the single-task condition, only raw time scores of Trails 3 (non-switch) and trail 5 (switch) correlated significantly. For the mixed-task condition, raw time scores of Trails 2 and 3 (non-switch) and trail 5 (switch) correlated significantly.

Finally, none of the eye-tracking measures correlated significantly with performance on the Visual Elevator test. See Table 8 for Pearson Product analysis.

Table 6
Pearson Correlation Analysis of T-scores of the Comprehensive Trail Making Test and Eye-tracking Measures

	Pearson Product Coefficient N=20				
	Tscore Trail 1 *(p)*	Tscore Trail 2 *(p)*	Tscore Trail 3 *(p)*	Tscore Trail 4 *(p)*	Tscore Trail 5 *(p)*
LFF					
Single-task condition	-.48* (.03)	-.49* (.03)	-.54* (.01)	-.37 (.11)	-.46* (.04)
Mixed-task condition	-.49* (.03)	-.61** (.03)	-.51* (.02)	-.44 (.05)	-.37 (.11)
FFDT					
Single-task condition	-.07 (.77)	.08 (.74)	-.18 (.46)	-.01 (.96)	.217 (.36)
Mixed-task condition	-.11 (.66)	.06 (.80)	-.36 (.12)	-.19 (.41)	.24 (.30)
FPGD					
Single-task condition	.14 (.56)	.04 (.86)	.12 (.60)	-.02 (.93)	.27 (.25
Mixed-task condition	.14 (.56)	.13 (.57)	.12 (.60)	-.05 (.85)	.30 (.20)

Note. ** Correlation is significant at the .01 level (2-tailed); * Correlation is significant at the .05 level (2 tailed)

Table 7

Pearson Correlation Analysis of the Raw Time Scores of the Comprehensive Trail Making Test and Eye-tracking Measures

	Pearson Product Coefficient N=20				
	Raw Time Trail 1 *(p)*	Raw Time Trail 2 *(p)*	Raw Time Trail 3 *(p)*	Raw Time Trail 4 *(p)*	Raw Time Trail 5 *(p)*
LFF					
Single-task condition	.40 (.08)	.42 (.07)	**.54*** (.02)	.40 (.078)	**.53*** (.02)
Mixed-task condition	.41 (.07)	**.51*** (.02)	**.52*** (.02)	.42 (.07)	.52* (.02)
FFDT					
Single-task condition	.06 (.81)	-.05 (.87)	.23 (.37)	-.028 (.91)	-.23 (.33)
Mixed-task condition	.17 (.48)	.03 (.90)	.37 (.11)	.01 (.97)	-.34 (.15)
FPGDT					
Single-task condition	-.07 (.77)	.06 (.81)	-.10 (.67)	-.01 (.98)	-.25 (.27)
Mixed-task condition	-.09 (.72)	-.01 (.98)	-.11 (.64)	-.01 (.98)	-.31 (.18)

Note. ** Correlation is significant at the .01 level (2-tailed); * Correlation is significant at the .05 level (2 tailed)

Table 8
Pearson Correlation Analysis of the Visual Elevator subtest of the Test of Everyday Attention

	Pearson Product Correlation N=20					
	Raw Accuracy Score *(p)*	Total Time *(p)*	Number of Switches *(p)*	Timing Score (p)	Scaled Score Equivalents of Raw Accuracy Sore *(p)*	Scaled Score Equivalents of Raw Timing Score *(p)*
LFF						
Single-task condition	-.01 (.95)	.17 (.49)	.02 (.94)	.24 (.31)	.12 (.63)	-.09 (.70)
Mixed-task condition	.05 (.85)	.19 (.42)	.03 (.91)	.33 (.16)	.24 (.92)	-.35 (.14)
FFDT						
Single-task condition	-.06 (.79)	-.07 (.77)	-.12 (.62)	.02 (.95)	-.22 (.35)	-.11 (.64)
Mixed-task condition	.19 (.53)	.12 (.61)	.05 (.83)	.08 (.75)	.14 (.55)	-.07 (.78)
FPGDT						
Single-task condition	.03 (.91)	.06 (.81)	-.07 (.72)	.14 (.57)	-.09 (.70)	-.19 (.43)
Mixed-task condition	-.08 (.73)	-.02 (.94)	-.19 (.42)	.14 (.57)	-.15 (.54)	-.23 (.32)

Note. ** Correlation is significant at the .01 level (2-tailed); * Correlation is significant at the .05 level (2 tailed)

Accuracy

Trials in which no fixations were allocated to the target image were excluded from the data analysis. See Table 8 for the number of excluded trials in the single and mixed-task conditions.

Table 9
Excluded trials

	Number of excluded trials		
	Invalid responses	Inaccurate responses	Total
Single-task condition	6/960	1/960	7/960
Single-task color	5/480	0/480	5/480
Single-task shape	1/480	1/480	2/480
Mixed-task condition	5/1,920	2/1,920	7/1,920
Total	11/2,880	3/2,880	14/2,880

Discussion

The purpose of this study was to investigate whether eye movements would be sensitive to differences in cognitive switching demands, indicated by general switching cost, specific switching cost, and mixing cost.

Findings confirmed hypotheses 1 and 3, that the eye-tracking measures latency of first fixation on the target and first pass gaze duration on the target indexed significant general switching cost and mixing cost. Hypothesis 2 was not confirmed, indicated by non-significant specific switching cost across all eye-tracking measures.

The general switching cost and mixing cost were based upon the difference *between* the single-task and mixed-task conditions, while the specific switching cost based on the differences *within* the mixed-task conditions. This implies that eye-tracking measures indexed increased cognitive demands associated with maintaining multiple task sets in the mixed-task condition compared to the single-task condition. Similarly, eye movement measures indexed greater cognitive demands associated with the non-switch trials of the mixed-task condition compared to the non-switch trials of the single-task condition. The lack of difference between the non-switch and switch trials within the mixed-task condition is possibly accounted for by an equal increase in task demand across both trial types due to the need to consistently identify the matching criterion and inhibit the previous matching criterion. If switching demands were indeed equal (in terms of monitoring two search criteria and being prepared to suppress the irrelevant task), no significant differences between unpredictably occurring switch and non-switch trials would be observed.

Prior and MacWhinney reported similar results of significant mixing cost in a similar task that provided a visual matching code, but required response via pushing a button (Prior and MacWhinney, 2010). Unlike Prior and MacWhinney (2010), the eye-tracking method did not index significant difference between the non-switch and switch trials of the mixed-task condition (specific switching cost). Additionally, Prior and MacWhinney (2010) noted that while the non-switch trials received quicker responses than the switch trials, the non-switch responses were also significantly more accurate. In contrast, minimal error rate occurred during the eye-tracking task.

A contributing factor to differences in results might be that the task administered by Prior and MacWhinney (2010) was self-paced, such that the next trial began after a response had been given versus the eye-tracking task which provided a consistent 4000 ms duration for each trial regardless of how quick the participant initially responded. It is possible that the results might differ if the responses would have been self-paced in the eye-tracking task.

Overall, results of this study demonstrated that the eye-tracking measures latency of first fixation on the target and first pass gaze duration on the target indexed differences in cognitive switching demands between the single-task and mixed-task condition, while first fixation duration on the target failed to reach significance. The difference in sensitivity of the three measures might be influenced by several factors. The duration of the first fixation on the target has been most frequently explored in scene viewing. The novelty and semantic informativeness of stimuli has been reported to influence the duration of the first fixation, but results regarding those factors varied across studies. The lack of significance of this measure might be due to the uncertainty of what this measure is assessing, or that results differ when applying the measure to a response selection task rather than free scene viewing. Further, the measure was highly variable within and between participants suggesting that it is influenced, at least, by more factors than the manipulated task complexity. First pass gaze duration might have measured additional processes other than cognitive demands associated with the switching tasks. It is possible that the longer first pass gaze duration on the target during tasks associated with lower cognitive demand was because participants reached the target quicker and continued to dwell within the area of interest until the end of the trial, while the latency until first fixation on the target did capture most closely the cognitive demands associated with the various switch tasks.

The second purpose of the study was to investigate whether eye-tracking measures correlated significantly with standardized measures of cognitive flexibility (Comprehensive Trail Making Test and the Visual Elevator subtest of the Test of Everyday Attention). Results did not confirm hypothesis 4, and therefore, strong concurrent validity could not be established.

For the Comprehensive Trail Making Test, the only measure to demonstrate significant correlation was the latency of first fixation on the target. As discussed above, this measure is related to the quickness of response and seemed most sensitive to changes in switching demands on the experimental task and was the only measure to index and significant correlations with the standardized tests. The lack of significant first pass gaze duration on the target is likely because participants continued to dwell on the target once they identified it in anticipation of the next trial. Dwelling on the target in anticipation of the next trial is not indicative of switching ability, and might therefore be the reason why no significant correlations between this measure and the standardized test performance was observed. First fixation duration on the target did not correlate with any of the standardized measures nor did it capture significant cost on the experimental task.

As expected, the single-task condition correlated significantly with all non-switch trails, meaning as the time until first fixation on the target image decreased (indicating a quicker response), T-scores also increased. In addition, a significant correlation was indicated between the mixed-task condition and T-scores. It is possible that overall performance on a single-task measure is predictive of switching efficiency, or that those who perform the single-task condition more efficiently are also more efficient during switching.

It was hypothesized that the mixed-task condition would correlate significantly with the switch trails 4 and 5. However, the only significant result indicated that those who performed better on the single-task condition of the eye-tracking task performed better on the trail 5, the most complex switching task.

Different patterns were observed between the raw time scores of the Comprehensive Trail Making Test and the latency of first fixation on the target. The single-task condition correlated significantly with only trail 3 and the mixed condition with only trails 2 and 3. It is possible that the lack of correlation with the first trail is related to the fact that it was the least difficult of the trails (connecting numbers in order without visual distractors). Unlike the T-scores, the raw time scores correlated significantly for both single- and mixed-task conditions for the most complex switch trail (Trail 5). Because raw data was extracted from the eye-tracking task, the raw time score might be a more comparable measure to assess the correlation. Overall, the pattern indicates that performance on the single- and mixed-task conditions correlated significantly with raw time scores for the most complex non-switch trail and switch trail.

Trail 4 involved switching between numbers and number words and was the only trail that required linguistic processing. The lack of correlation observed between the experimental conditions and trail 4 might be due to the involvement of different cognitive processes during linguistic tasks compared to nonlinguistic tasks.

It was hypothesized that the Visual Elevator subtests of the Test of Everyday Attention would correlate with the mixed-task condition of the eye-tracking test, however, significance was not observed. During the Visual Elevator subtests, participants responded verbally. It is possible that the heavy linguistic load of the task, related to both verbal response and possible use of subvocal strategies, the test might be assessing different processes. In contrast with the eye-tracking task, which provided a consistent window of response time for each trial, the examiner paced the test according to each participant. Therefore, it is possible that differences in pacing or examiner influence affected performance efficiency and thus scoring.

Weak concurrent validity was observed between the selected eye-tracking measures and the Comprehensive Trail Making Test and the Visual Elevator subtest of the Test of Everyday Attention. Future research should examine whether other nonlinguistic measures are more suited for the assessment of cognitive flexibility such as the Color Trail Test (D'Elia et al., 1996) or the Wisconsin Card Sorting Test (Grant & Berg, 1993).

Clinical Implications

Significant differences in cognitive processing were observed with the inclusion of extensive practice trials. The fact that practice effects did not override switching cost effects suggested that the novel eye-tracking method has great potential to validly index cognitive flexibility in individuals with brain injury who might otherwise be excluded from more complex tasks requiring intact verbal, motoric, or cognitive abilities. This is because adequate instruction and practice may be provided to ensure task comprehension without compromising test results.

Contrary to complicated response requirements associated with standardized tests of cognitive flexibility such as the Wisconsin Card Sorting Test that often result in procedural adaptation or exclusion of those with more severe deficits (Frankel et al., 2007; Fridriksson et al., 2006; Penn et al., 2010; Purdy, 2002), the nonlinguistic switching task with eye-tracking response was sensitive to the higher-level cognitive processes that occur when switching mental set despite its simplicity. The simplicity of the nonlinguistic switching task, as confirmed by the minimal error rate in neurologically healthy individuals, provides promise that the task is potentially suitable for those with linguistic and cognitive deficits.

Future Research

The study of executive functions using eye-tracking methods is a novel pursuit. While we investigated the latency of first fixation, first pass gaze duration, and first fixation duration time, additional eye-tracking measures such as proportion of fixation duration (defined as total duration of fixations on a specific area of interest divided by the duration of all fixations), might also be sensitive to changes in cognitive demands involved in switching tasks. Further analysis by stimulus type 1) color versus shape, and 2) stimulus congruency versus incongruence within the single and mixed-task conditions will be conducted to determine influence of stimulus type on switching cost. In addition, only data in the area of interests associated with the correct target response was analyzed for the current study. It is possible that the pattern of eye movements dedicated to the foil, code, and reference image might reveal further insight into cognitive processing efficiency. For instance, differences in the fixation duration on the matching code between the single-task and mixed-task condition should be explored to determine whether differences in processing the matching code contribute to differences in switching and mixing cost. Finally, exploring the impact of training on the performance of nonverbal cognitive tasks using eye-movement measures would provide further insight into the relationship between cognitive processes and the eye movement measures to index them.

Summary

The novel eye-movement method validly indexed switching cost. The eye-tracking indices latency of first fixation and first pass gaze duration provide promising evidence that the eye-tracking task is sensitive to differences in varying cognitive switching demands. The nonlinguistic nature, lack of motoric requirements, and inclusion of practice trials render it a promising assessment tool for individuals with aphasia. Continued development of the eye-tracking method using the nonlinguistic switching task is warranted in order to enhance our understanding of the relationship between functional communication and cognitive flexibility and to improve the assessment methods for individuals with neurologic communication deficits.

References

Allopenna, P.D., Magnuson, J.S., & Tanenhaus, M.K. (1998). Tracking the time course of spoken word recognition using eye movements: Evidence for continuous mapping models. *Journal of Memory and Language*, *38,* 419-439. doi:10.1006/jmla.1997.2558

American Speech-Language-Hearing Association. (1997). *Guidelines for audiologic screening.* Retrieved from www.asha.org/policy. doi: 10.1044/policy.GL1997-00199

Barkley, R. (1997). Behavioural inhibition, sustained attention, and executive function: Constructing unifying theory of ADHD. *Psychological Bulletin*, *121,* 65-94.

Beeson, P., Bayles, K., & Rubens, A. & Kaszniak, A.W., (1993). Memory impairment and executive control in individuals with stroke-induced aphasia. *Brain and Language*, *45*(2), 253-275.

Bialystok, E., Craik, F., & Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 34(4), 859-873. doi: 10.1037/0278-7393.34.4.859

Bialystok, E., & Martin, M. (2004). Attention and inhibition in bilingual children: evidence from the dimensional change card sort task. *Developmental Science*, *7*(3), 325-339. doi: 10.1111/j.1467-7687.2004.00351.x

Calabria, M., Hernandez, M., Branzi, F., & Costa, A. (2012). Qualitative differences between bilingual language control and executive control: evidence from task switching. *Frontiers in Psychology, 2* (399), 1-10. doi: 10.3389/fpsyg.2011.00399

Caplan, D., & Waters, G. (1995). Aphasic disturbances of syntactic comprehension and working memory capacity. *Cognitive Neuropsychology*, *12* (6), 637-649. doi: 10.1080/02643299508252011

Caspari, I., Parkinson, S.R., LaPointe, L.L., & Katz, R.C. (1998). Working memory and aphasia. *Brain and Cognition*, *37*(2), 205-223.

Chiou, H., & Kennedy, M. (2009). Switching in adults with aphasia. *Aphasiology*, *23*(7-8), 1065-1075. doi: 10.1080/02687030802642028

Choy, J.J., & Thompson, C.K. (2010). Binding in agrammatic aphasia: Processing to comprehension. *Aphasiology, 24(*5), 551-579. doi: 10.1080/02687030802634025

Cohen, Jacob. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Lawrence Erlbaurm Associates.

Cooper, R.M. (1974). The control of eye fixation by the meaning of spoken language. A new methodology for the real-time investigation of speech perception, memory, and language processing. *Cognitive Psychology, 6*, 84-107.

Costa, A. (2005). Lexical access in bilingual production. In J.F. Kroll, & A. De Groot (Eds.), *Handbook of bilingualism: Psycholinguistic Approaches* (pp. 308-324). New York: Oxford University Press.

D'Elia, L. F., Satz, P., Uchiyama, C.L., & White, T. (1996). *Color Trails Test.* Odessa, FL: Psychological Assessment Resources, Inc.

De Graef, P., Christiaens, D. & d'Ydewalle, G. (1990). Perceptual effects of scene context on object identification. *Psychological Research, 52*, 317-329.

Dickey, M.W., Choy, J., & Thompson, C.K, (2007). Real-time comprehension of wh-movement in aphasia: Evidence from eyetracking while listening. *Brain and Language, 100*(1), 1-22. doi: 10.1016/j.bandl.2006.06.004

Dickey, M.W., & Thompson, C.K. (2009). Automatic processing of wh- and np-movement in agrammatic aphasia: Evidence from eyetracking. *Journal of Neuroloinguistics, 22*(6), 563-583. doi: 10.1016/j.jneuroling.2009.06.004

Duchowski, A. (2002). A breadth-first survey of eye-tracking application. Behavior *Research Methods, Instruments, & Computers, 34* (4), 455- 470.

Frankel, T., Penn, C., & Ormond–Brown, D. (2007). Executive dysfunction as an explanatory basis for conversation symptoms of aphasia: A pilot study. *Aphasiology, 21(*6-8), 814-828. doi:10.1080/02687030701192448

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39,* 175-191. Download PDF

Frattali, C.M, Thompson, C., Holland, A., Wohl, A., & Ferketic, M. (1995). *American Speech-Language-Hearing Association Functional Assessment of Communication Skills for Adults.* Rockville, MD: American Speech-Language-Hearing Association.

Fridriksson, J., Nettles, C., Davis, M., Morrow, L., & Montgomery, A. (2006). Functional communication and executive function in aphasia. *Clinical linguistics & phonetics, 20*(6), 401-410. doi:10.1080/02699200500075781

Friedmann, N. & Gvion, A. (2003). Sentence comprehension and working memory imitation in aphasia: A working dissociation between semantic-syntactic and phonological reactivation. *Brain and Language*, *86*(1), 23-39.

Glosser, G., & Goodglass, H. (1990). Disorders in executive control functions among aphasic and other brain-damaged patients. *Journal of Clinical and Experimental Neuropsychology*, *12*(4), 485-501. doi: 10.1080/01688639008400995

Grant, D.A., & Berg, E.A. (1993). *Wisconsin Card Sorting Test.* Tampa, FL: Psychological Assessment Resources.

Griffin, Z.M. (2004). Why look? Reasons for eye movements related to language production. In J.M. Henderson & F. Ferreira (Eds.), *The integration of language, vision, and action: Eye movements and the visual world.* New York: Psychology Press.

Hallowell, B. (1999). A new way of looking at linguistic comprehension. In W. Becker, H. Deubel, & T. Mergner (Eds.), *Current occulomotor research: Physiological and psychological aspects.* New York: plenum Press.

Hallowell, B., & Chapey, R. (2008). Introduction to language intervention strategies in adult aphasia. In R. Chapey (Ed.), *Language intervention strategies in aphasia and related neurogenic communication disorders* (5th ed., pp. 3-19). Philadelphia: Wolters Kluwer Health/Lippincott Williams & Wilkins.

Hallowell, B., Kruse, H., Shklovsky, V.M., Ivanova, M.V., & Emeliyanova, M. (2006, November) Validity of eye tracking assessment of auditory comprehension in aphasia. Poster presented at the American speech-Language-Hearing Association Convention. Miami Beach, FL.

Hallowell , B., Wertz, R.T., & Kruse, H. (2002). Using eye movement Reponses to index auditory comprehension: An adaption of the revised Token Test. *Aphasiolgy,16,* 587-594. Doi: 10.1080/02687030244000121

Henderson, J.M. (1992). Object identification in context: The visual processing of natural scenes. *Canadian Journal of Psychology,* 46, 319-341.

Henderson, J.M., & Hollingworth, A. (1998). Eye movements during scene viewing: An overview. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 269-294). Amsterdam: Elsevier.

Heuer, S., & Hallowell, B. (2009). Visual attention in a multiple-choice task: Influences of image characteristics with and without presentation of a verbal stimulus. *Aphasiology, 23*(3), 351-363. doi: 10.1080/02687030701770474

Heuer, S., & Hallowell, B. (2014). A novel eye-tracking method to assess attention allocation in individuals with and without aphasia using a dual-task paradigm. Submitted Manuscript.

Heuer, S. (2014, November) Assessment of dual-task performance in young and old adults using eye-tracking. Annual Convention of the American Speech-Language-Hearing Association, Orlando, FL.

Ivanova, M., & Hallowell, B. (2011). Validity of an eye-tracking method to index working memory in people with and without aphasia. *Aphasiology. doi*: 10.1080/02687038.2011.618219

Joos, M. & Weber, S. (2011). NYAN 2 (Version 2.0) [Professional Edition software]. Dresden, Germany: Interactive Minds.

Just, M.A., & Carpenter, P.A. (1976). Eye fixations and cognitive processes. *Cognitive Psychology, 8,* 441-480.

Keil, K., & Kaszniak, A.W. (2002). Examining executive function in individuals with brain injury: A review. *Aphasiology*,*16*(3), 305-335. Doi:10.1080/02687030143000654

Kongs, S.K., Thompson, L.L., Iverson, G.L., & Heaton, R.K. (2000). *Wisconsin Card Sorting Test-64 card version.* Odessa, FL: Psychological Assessment Resources, Inc.

Kray, J., Li, K., & Lindenberger, U. (2002). Age-related changes in task-switching components: The role of task uncertainty. *Brain and Cognition, 49*, 363-381. doi: 10.1006/brcg.2001.1505

Kray, J., & Lindenberger, U. (2000). Adult age differences in task switching. *Psychology and Aging, 15*(1), 126-147.

LaPointe, L.L., & Erickson, R. J. (1991) Auditory vigilance during divided task attention in aphasic individuals. *Aphasiology, 5*(6), 511-520. doi: 10.1080/02687039108248556

LC Technologies. (2011). Superior Eye Tracking Technology [Brochure]. Fairfax, VA: LC Technologies, Inc. Retrieved from http://www.eyegaze.com/

Lezak, M.D. (1995). *Neuropsychological Assessment* (3rd ed.). New York, NY: Oxford University Press.

Loftus, G.R. & Mackworth, N.H. (1978). Cognitive determinants of fixation location during picture viewing. *Journal of Experimental Psychology: Human Perception and Performance, 4(*4), 565-572. doi: 10.1037/0096-1523.4.4.565

Manor, B.R., & Gordon, E. (2003). Defining the temporal threshold for ocular fixation in free-viewing visuocognitive tasks. *Journal of Neuroscience* Methods*, 128,* 85-93.

McNeil, M.R., Doyle, P.J., Hula, W.D., Rubinsky, H.J., Fossett, T.R.D. & Matthews, C.T. (2004). Using resource allocation theory and dual-task methods to increase the sensitivity of assessment in aphasia. *Aphasiology*, 18(5,6,7), 521-542.

McNeil, M. R., Matthews, C., Hula, W. D., Doyle, P. J., Rubinsky, H. J., & Fossett, T. R. D. (2005). A dual-task tool for quantifying normal comprehension of aphasic connected speech production: A constructive replication. *Aphasiology, 19*(3-5), 473-484. doi: 10.1080/02687030444000895

Meyer, A.S., Van der Meulen, F., & Brooks, A. (2004). Eye movement during speech planning: Speaking about present and remembered objects. *Visual Cognition*, 11, 553-576. doi: 10.1080/13506280344000248

Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A., & Wager, T.D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" task: A latent variable analysis. *Cognitive Psychology*, *41*(1), 49-100. doi: 10.1016/j.bbr.2011.03.031

Murray, L.L., Holland, A.L., & Beeson, P.M. (1997) Grammaticality judgments of mildly aphasic individuals under dual-task conditions. *Aphasiology*, *11*(10), 993-1016. doi: 10.1080/02687039708249423

Murray, L. L. (2012). Attention and other cognitive deficits in aphasia: Presence and relation to language and communication measures. *American Journal of Speech-Language Pathology, 21,* S51-S64. doi:10.1044/1058-0360(2012/11-0067)

Odekar, A., Hallowell, R., Kruse, H., Moates, D., & Lee, C. (2009). Validity of eye movement methods and indices for capturing semantic (associative) priming effects. *Journal of Speech, Language, and Hearing Research 42*, 31-48. doi: 1092-4388/09/5201-0031

Penn, C., Frankel, T., Watermeyer, J., & Russell, N. (2010). Executive function and conversational strategies in bilingual aphasia. *Aphasiology*, *24*(2), 288-308. doi: 10.1080/02687030902958399

Prior, A., & MacWhinney, B. (2010). A bilingual advantage in task switching. *Bilingualism: Language and Cognitive 13*(2), 253-262. doi: 10.1017/S1366728909990526

Purdy, M. (2002). Executive function ability in persons with aphasia. *Aphasiology*, *16*(4-6), 549-557. doi: 10.1080/02687030244000176

Purdy, M. (2011). Executive Functions: Theory, Assessment, and Treatment. In M.L. Kimbarow (Ed.), *Cognitive communication disorders* (pp. 77-118). San Diego, CA: Plural Publishing Inc.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, 124, 372-376.

Reynolds, C. (2002). *Comprehensive Trail-Making Test.* Austin TX: Pro Ed.

Robertson, I.H., Ward, T., Ridgeway, V., & Nimmo-Smith, I. (1994). *Test of Everyday Attention.* Bury St. Edmonds, Suffolk, England: Thames Valley Test Company.

Robin, D.A., & Rizzo, M. (1989). The effect of focal cerebral lesions on intramodal and cross-modal orientation of attention. *Clinical Aphasiology*, *18*, 61-74.

Schiavetti, N., Matz, D., & Orlikoff, R. (2011). *Evaluating research in communicative disorders.* Upper Saddle River: Pearson Education, Inc.

Tanenhaus, M.K., Magnuson, J.S., Dahan, D., & Chambers, C. (2000). Eye movements in lexical access in spoken-language comprehension: Evaluating a linking hypothesis between fixations and linguistic processing. *Journal of Psycholinguistic Research*, *29*(6), 557-580.

Tanenhaus, M.K., & Spivey-Knowlton, M.J. (1996). Eye-tracking. *Language and Cognitive Processes*, *11*(6), 583-588.

Waggoner, T. (1994). *Color Vision Testing Made Easy.* Orlando, FL: Vision Associates.

Wylie, G. & Allport, A. (2000). Task switching and the measurement of "switch costs." *Psychological Research*, *63*, 212-233.

Appendix A
Consent Form

UNIVERSITY OF WISCONSIN – MILWAUKEE
CONSENT TO PARTICIPATE IN RESEARCH

THIS CONSENT FORM HAS BEEN APPROVED BY THE IRB FOR A ONE YEAR PERIOD

1. General Information

Study title: Assessment of Cognitive Functions Using an Eye-tracking Method

Person in Charge of Study (Principal Investigator):
- Melissa Pinke, Graduate student, Department of Communication Sciences and Disorders
- Sabine Heuer, Ph.D., Assistant Professor, Aphasia Lab director, Department of Communication Sciences and Disorders

2. Study Description

You are being asked to participate in a research study. Your participation is completely voluntary. You do not have to participate if you do not want to.

Study description:
This study involves the exploration of cognitive processes using traditional methods and novel eye-tracking methods. You will also be asked to complete a brief vision and hearing screening and will be asked several questions related to your health history. Then you will be asked to complete 1) traditional standardized tests of attention and 2) experimental tasks using eye tracking. During the experimental tasks, your eye movements will be recorded as you look at a computer screen and listen to words. The study will take approximately 90 minutes.

3. Study Procedures

What will I be asked to do if I participate in the study?
If you agree to participate, you will complete the following:

1. **Screening:**
    - A brief vision and hearing screening will be conducted.

    - The vision screening will examine visual acuity and color vision. You will be allowed to wear corrective contact lenses or glasses during the screening and experimental tasks.
    - During the hearing screening you will hear a variety of tones presented through headphones. The tones might sound very faint, please raise your hand whenever you hear a tone.
    - We will ask you questions about information related to age, language use, and health history.
  - In the event that you are not eligible for participation in the study based, you will be excluded from the study and the screening data collected to this point will be destroyed. You will, however, be paid with the amount prorated according to the proportion of the study you have completed. The study is estimated to take 90 minutes; therefore, if you participated for 15 minutes, your prorated payment would be $2.00.

2. **Standardized Assessment:**
   - You will complete two standardized test. These include the Comprehensive Trail Making Test (CTMT) and Visual Elevator subtest of the Test of Everyday Attention (TEA).
   - During the CTMT you will be asked to connect numbers and letters in a specific sequence as quickly as possible. The CTMT includes five different trials.
   - The Visual Elevator subset of the TEA assesses attention switching. You will be presented with images of elevators doors and arrows. You will be asked to count each of the elevator doors until an arrow is reached. When you reach an arrow, you will say either "up" or "down" and then continue counting elevator doors in the appropriate direction.
3. **Calibration of eye-tracking device:**
   - Your eye movements will be recorded using an LC Technologies EyeFollower system. Before the experiment takes place, we need to calibrate the device. This will allow us to monitor your eye movements. During the calibration, you will be seated comfortably in front of a computer screen. You will be asked to look at the computer screen and follow a blinking yellow dot with your eyes. This procedure takes less than a minute. We will ask you to hold your head still during calibration. Afterward, you may move your head freely.
4. **Experimental tasks:** During the experimental tasks you will be asked to look at images and listen to words while we record your eye movements.

4. Risks and Minimizing Risks

What risks will I face by participating in this study?
There are no foreseeable risks for participating in this research study. Eye tracking is completely non-invasive. No part of the equipment will be in contact with you. The light is not harmful or noticeable. All data will be stored safely without any personal identification.

5. Benefits

Will I receive any benefit from my participation in this study?
You will receive free vision and hearing screenings. Your participation in the study provides support for the development of a valid assessment of cognitive flexibility for use with people with stroke.

6. Study Costs and Compensation

Will I be charged anything for participating in this study?
You will not be responsible for any of the costs from taking part in the research study.

Are subjects paid or given anything for being in the study?
In appreciation for your participation in this study, you will receive $15.00. If you choose not to complete the experiment, you will be paid with the amount prorated according to the proportion of the study you have completed.

7. Confidentiality

What happens to the information collected?
Records obtained during the screening procedure and the standardized test record forms will be kept confidential and locked in filing cabinets within the secure UWM Aphasia Laboratory. No identifying information will be stored with the records. Only Principle Investigators and immediate study personnel will have access to raw data.

The payment forms, which will have your name on it, will be stored separately in a lockable filing cabinet. The payment form will not include your experiment ID number. Only Principle investigators will have access to the payment forms. They will be destroyed when the study is completed.

Only Principle Investigators and immediate study personnel will have access to raw data. Data will be stored and locked in the Aphasia laboratory at UWM at all times. However, the Department of Communication Sciences and Disorders and the Institutional Review Board at UW-Milwaukee, or appropriate federal agencies like the Office of Human Research Protections may review this study's records.

Some of the aggregated data will serve in future studies.

8. Alternatives

Are there alternatives to participating in the study?
There are no known alternatives available to you other than not taking part in this study.

9. Voluntary Participation and Withdrawal

What happens if I decide not to be in this study?
Your participation in this study is entirely voluntary. You may choose not to take part in this study. If you decide to take part, you can change your mind later and withdraw from the study. You are free to not answer any questions or withdraw at any time. Your decision will not change any present or future relationships with the University of Wisconsin Milwaukee. The investigator may stop your participation in this study if they feel it is necessary to do so.

If you decide to withdraw, or if you are withdrawn from the study before it ends, we will use the information we collected up to that point.

If you are a student at the University of Wisconsin Milwaukee, your refusal to take part in the study will not affect your grade of class standing.

10. Questions

Who do I contact for questions about this study?
For more information about the study or the study procedures or treatments, or to withdraw from the study, contact:

Melissa Pinke
Department of Communication Sciences and Disorders
Enderis Hall 859, P.O. Box 413
Milwaukee, WI 53201
(414) 229-053

Who do I contact for questions about my rights or complaints towards my treatment as a research subject?
The Institutional Review Board may ask your name, but all complaints are kept in confidence.

Institutional Review Board
Human Research Protection Program
Department of University Safety and Assurances
University of Wisconsin – Milwaukee
P.O. Box 413
Milwaukee, WI 53201
(414) 229-3173

11. Signatures

Research Subject's Consent to Participate in Research:
To voluntarily agree to take part in this study, you must sign on the line below. If you choose to take part in this study, you may withdraw at any time. You are not giving up any of your legal rights by signing this form. Your signature below indicates that you have read or had read to you this entire consent form, including the risks and benefits, and have had all of your questions answered, and that you are 18 years of age or older.

____
Printed Name of Subject/ Legally Authorized Representative

____ __________________
Signature of Subject/Legally Authorized Representative Date

Principal Investigator (or Designee)
I have given this research subject information on the study that is accurate and sufficient for the subject to fully understand the nature, risks and benefits of the study.

____ __________________
Printed Name of Person Obtaining Consent Study Role

____ __________________
Signature of Person Obtaining Consent Date

Appendix B

Case History Form

Age: ___________

Gender: Male Female

1. Are you a native speaker of English?
   Yes No

2. Are you a native speaker of another language?
   Yes No

3. Have you ever had a learning/developmental/language disability?
   Yes No

4. Have you ever had a neurological incident (stroke, traumatic brain injury)?
   Yes No

Appendix C

Hearing and Vision Screening Form

Hearing Screening

	1000 Hz	2000 Hz	4000 Hz
Right ear			
Left ear			

Vision Screening

1. **Check if observed:**

❑ asymmetry of pupils / dilation
❑ skin lesions
❑ swelling
❑ erythema / redness
❑ warmth / tenderness
❑ ocular drainage

2. **Central visual acuity**

Corrective lenses: YES NO

Snellen fraction: _________

3. **Peripheral visual acuity** (Mark quadrant in error)

right eye left eye

temp.	nasal	nasal	temp.

4. **Pupillary examination**

5. **Ocular motility testing**
   Simple test of alignment

Right eye
- ❑ Reflection temporal to pupil
- ❑ Reflection nasal to pupil

Left eye
- ❑ Reflection temporal to pupil
- ❑ Reflection nasal to pupil

Cover test (requires good vision)
Right eye covered
- ❑ Movement observed in left pupil
- ❑ Loss of fixation observed in left pupil

Left eye covered
- ❑ Movement observed in right pupil
- ❑ Loss of fixation observed in right pupil

Extraocular motility
- ❑ abnormal speed
- ❑ labored movement
- ❑ limited range of movement
- ❑ assymmetry
- ❑ nystagmus

6. **Central and peripheral visual fields**
   On Amsler grid, subject reported seeing:
- ❑ lines that were bent / crooked
- ❑ lines that were distorted (describe)___________________
- ❑ spots on the grid
- ❑ portions of the grid missing

7. **Color vision**
   Subject failed to i.d. ___ cards (#)

8. **Visual attention**
- ❑ poor visual attention as observed during eye movement testing