Time Windows for Indexing Language Comprehension in Adults With and Without Aphasia

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This thesis titled

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Abstract

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Time-course analysis on eye-tracking data has been proven useful by previous researchers who have studied language processing of spoken and written input. Researchers found that language processing is a time-locked activity that can be based on eye movements. However, the ideal time windows for capturing when a person comprehends verbal stimuli have not been determined for people with and without language impairment.

In the current study, existing data from 40 participants with aphasia (PwA) and 40 participants without aphasia (control) were analyzed. These data were collected for a larger study incorporating the Multiple Choice Test of Auditory Comprehension (MCTAC). The MCTAC consists of eight subtests of linguistic stimuli of varying length and complexity. Mean proportion of fixation duration (PFDT) on the target item was observed across time windows with additive duration from 200 ms and increasing by 200 ms for consecutive time windows through the end of each trial. Between-group and within-group comparisons were performed based on the mean PFDT values and patterns across time windows for every MCTAC subtest included in the study.

We predicted that PwA would demonstrate the maximum mean PFDT at a later time window, as compared to the control group. The results demonstrated the highest
mean PFDT at the final time window for both groups in all MCTAC subtests. We predicted that PwA data would demonstrate a significant negative correlation between time windows with the maximum mean PFDT and the total scores from Auditory Comprehension (AC) component of the Western Aphasia Battery–Revised (WAB–R; Kertesz, 2007). Significant positive correlations between the time window with maximum mean PFDT and WAB–R AC score were found for all MCTAC subtests except for Subtest 8. In addition, variations of mean PFDT patterns across time windows were observed based on individual data from both groups.

In conclusion, observation of PFDT across time windows with progressively longer durations revealed that current procedures entail adequate timing to index language comprehension among individuals with and without aphasia. Case-by-case data analyses should also be conducted to address individual variations, especially among people with aphasia.
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Chapter 1: Introduction

Eye-movement data tracked during a verbal task were found to be related to the specific linguistic aspects, such as phonemes, morphemes, words, phrases, or sentences. Time-course analysis has been applied to eye-tracking data to understand online language processes that occur in real time. These two methods were found useful in research that studied the unfolding of spoken language and factors that may influence the efficiency of language processing. These methods have potential to improve our understanding of language comprehension, including individual factors (e.g., degrees of comprehension strengths and deficits) and linguistic factors (e.g., length of verbal stimuli, sentence complexity, grammaticality, and types of linguistic elements).

In the current study, language comprehension among individuals with aphasia as compared to individuals without any language impairment was studied in real time using eye-tracking. The motive of this current study was based on literature about theories of normal language processing, and the use of eye-tracking methods and time-course analysis to study normal and disordered language processing and comprehension.

Theories of Normal Language Processing

Language processing involves operations of categorizing and analyzing language input in order to understand or otherwise respond to the basic stimulus characteristics, linguistic structure, or semantic content of auditory or written stimuli. Information can be processed at acoustic-phonetic, phonemic, morphemic, word, phrase, clause, sentence, and discourse levels. Word recognition and sentence comprehension are the outcomes of
Language processes, in which listeners or readers appreciate the language information that they obtained.

Language processing is complex for several reasons. Firstly, multiple levels of language structure such as lexical, phonological, morphological, syntactic, semantic, and discourse, are processed concurrently (MacDonald, Pearlmutter, & Seidenberg, 1994). Secondly, language functions are dispersed in different parts of the brain, such as Broca’s area and Wernicke’s area in the left hemisphere, and primary auditory cortex, primary visual cortex and frontal cortex of both hemispheres (Gernsbacher & Kaschak, 2003). Finally, involvement of psycholinguistic factors, such as pragmatics and conversational use of language, further complicate the processes that are involved in understanding and responding to linguistic input (Gernsbacher & Kaschak, 2003). Many studies have been conducted to address such issues and corresponding assumptions. In this section, previous studies on language processing at word and sentence levels will be discussed.

**Language processing during spoken word recognition.** The immediate response of listeners to a sentence that has been presented auditorily is based on the incoming acoustic stimulus and a set of internal structural constraints (Marslen-Wilson & Welsh, 1978). In some studies, frameworks or models of language processing have been discussed and further investigated at different levels (e.g., Alloppena, Magnuson, & Tanenhaus, 1998; Marslen-Wilson & Welsh, 1978).

In the study by Marslen-Wilson and Welsh (1978), two frameworks, bottom-up and top-down processes, were investigated during recognition of spoken words in continuous speech. In the bottom-up process, the acoustic input acts as the primary
determinant for final interpretation and it is not influenced by the higher level of lexical constraints. In contrast, top-down processes depend on higher level constraints associated with listeners’ linguistic knowledge. In the Marslen-Wilson and Welsh (1978) study, participants were presented with three practice passages and two versions of three test passages, each containing 1000 words read by a male speaker at 160 words per minute. Among the 3000 words, 80 common three-syllable words were mispronounced. In the shadowing task, participants were required to repeat the mispronounced words exactly as they were being said. In the mispronunciation task, participants were given written test passages, and participants were required to circle the mispronounced words in the given text.

Marslen-Wilson and Welsh (1978) found listeners’ judgments of phonemic cues were based on context appropriateness, which facilitates detection and restoration of the mispronounced words. The reaction times required to restore mispronounced words with one syllable error were significantly higher than the reaction times required to restore words with three syllable errors. The authors concluded that the lexical constraints in the top-down process interacted with the information of the bottom-up process in order to maximize listeners’ abilities in interpreting the acoustic input. The combination of top-down and bottom-up processes in lexical activation is known as the “cohort model.”

In a study by Allopenna et al. (1998), the “cohort model” proposed by Marslen-Wilson and Welsh (1978) was compared to the “continuous mapping model.” In the cohort model, the onset of a word activates a set of lexical candidates that compete for word recognition. Lexical activation is reduced as the listener detects mismatches with
the continuing speech input. However, in continuous speech, the word onsets are not clearly marked. In the continuous mapping model, lexical access is assumed to be continuous; not only are the words with the same initial segments being activated, but the activation also includes words with overall similarities.

Allopenna and colleagues (1998) investigated these two models during spoken word recognition by examining the competitor effects for objects that have the same rhyme as the target. Eight sets of stimuli were presented to participants. Each set contained four pictures: referent (a target word such as “beaker”), cohort (a word with similar onset, such as “beetle”), rhyme (a word with similar ending, such as “speaker”), and an unrelated (a word without any phonological relationship, such as “carriage”).

Using a computer mouse, participants were given instructions to move the pictures of objects on the computer screen. The duration taken by participants to recognize the target words in continuous speech was analyzed by using eye-tracking data. From this study, Allopenna and colleagues (1998) found that the lexical activation during word recognition also includes rhyme competitors that have initial word segments with more than one different feature; this supports the continuous mapping model for word recognition in sentences.

In addition to the models of lexical activation, researchers have also been investigating the conditions and factors that may influence recognition of spoken words. Several studies found that recognition of spoken words can be influenced by phonological effects (e.g., Allopenna et al., 1998; Marslen-Wilson & Warren, 1994; Spivey, Grosjean, & Knoblich, 2005; Vitevitch, Stamer, & Sereno, 2008), semantic
effects (e.g., Mirman & Magnuson, 2009; Van Petten, Coulson, Rubin, Plante, & Parks, 1999; Yee & Sedivy, 2006), frequency effects (e.g., Dahan, Magnuson, & Tanenhaus, 2001), and contextual factor (e.g., Brink, Brown, & Hagoort, 2001; McAllister, 1988).

**Phonological effects.** As mentioned earlier, Allopenna et al. (1998) found that competing words, with similar onset or rhyme as the target words, were activated when the stimulus is presented. In a prior study, Marslen-Wilson and Warren (1994) found that recognition of word can also be influenced by phonemic features such as voice, placement, and manner, which are aspects of a phoneme.

In that study, Marslen-Wilson and Warren (1994) constructed stimuli sets, each consisting of two words and a nonword, which differ in terms of place of articulation for the final phoneme. The stimuli were randomly presented in pairs (Word 1 + Word 2, Word 1 + Nonword, and Word 2 + Nonword) in three experiments. Participants were required to press the “Y” button when they heard a word and the “N” button when they heard a nonword during Experiment 1, type the word that they heard and rate the confidence of their responses following the presentation of stimuli using the gating method during Experiment 2, and choose a letter that corresponded with the final phoneme during Experiment 3.

Marslen-Wilson and Warren (1994) found that, for all three experiments, reaction times to nonword were significantly longer as compared to word stimuli. The authors found that interpretations of phonetic cues were based on the ability to activate lexical items. Based on their findings, Marslen-Wilson and Warren (1994) concluded that
lexical representation has a continuous link to the featural level, and word recognition can be predetermined by the microstructure variation of features.

In a study of neighborhood density effects during word recognition, Vitevitch et al. (2008) developed two hypotheses: (a) lexical activation is greater for longer words (e.g., trisyllabic words) as compared to shorter words (i.e., monosyllabic or bisyllabic words) and (b) lexical activation of words that contain many similar sounds (“late uniqueness point”) is reduced compared to words with fewer similar sounds (“early uniqueness point”). In this study, Vitevitch et al. (2008) conducted two experiments to examine the phonological effect within a word.

In Experiment 1, bisyllabic words with a strong-weak stress pattern were presented in white noise at a +12 dB signal-to-noise ratio (S/N) through headphones. The words were presented once, and participants were required to type the word using a computer keyboard. In Experiment 2, additional nonword stimuli were added to the stimuli used in the first experiment. The word and nonword stimuli were presented randomly through headphones, and participants were required to press either the WORD or NONWORD button on the computer.

Findings from both experiments demonstrated that words with early uniqueness points can be identified faster and more accurately than words with late uniqueness. The authors also concluded that the uniqueness point can be influenced by other factors, such as morphological markers, besides the phonological input.

**Semantic effects.** In a study by Van Petten et al. (1999), semantic effect was examined by analyzing the event-related potential (ERP) measure of brain activity during
spoken word recognition in continuous sentences. A gating technique was utilized in which participants were presented repeatedly with the first fragment of words at increasing durations known as isolation point (IP). For example, the IP may be set at 50 ms, 100 ms, or 150 ms of a word. At the second and following presentations, the duration is doubled, producing longer word fragments. The lengthening of duration was continued until the end of the word. The participants were required to guess the word being presented at each IP. Using the gating technique, the authors conducted two experiments.

In Experiment 1, the gating technique was utilized during presentation of words with the same onset (e.g., “dollar” and “dolphin”) and words with same endings (e.g., “dollar” and “scholar”). Participants were required to identify the target word at each IP. In Experiment 2, the word identification at the different IP was compared to the changes seen via ERP measures when words are presented in congruent sentences (e.g., “Sir Lancelot spared the man’s life when he begged for MERCY”) and noncongruent sentences (e.g., “Sir Lancelot spared the man’s life when he begged for MERMAID/FANCY”).

In the first experiment, Van Petten et al. (1999) found that the participants’ ability to identify the correct target words was above 60% at the first IP and the accuracy of responses increased as the IP duration increased. In the second experiment, ERP findings demonstrated that participants identified the target words at an earlier IP for congruent sentences and at a later IP for noncongruent sentences. They concluded that semantic processing was triggered before the acoustic signal was completed. These findings show
that language processing is based not only on the phonological input, but also influenced by semantic representation.

Yee and Sedivy (2006) conducted two experiments to study the activation of semantic information during spoken word recognition. In the first experiment, the time course of semantic activation was explored by observing eye fixations following an auditory stimulus. Each visual display consisted of four pictures, which included a target object, a semantically related object, and two semantically and phonologically unrelated objects.

The authors assumed that semantic representation must be active when a listener maps a word onto its referent picture. This assumption was followed by some cautions. For example, semantic priming effects, and phonological effects (in which words are matched based on the acoustics rather than by meaning) may interfere with word recognition. Yee and Sedivy (2006) found that the proportion of eye fixations to the semantically related target picture is significantly higher than to any of the other types of images in a display. The phonologically related items also attract more fixations than unrelated items.

In the second experiment of the same study, Yee and Sedivy (2006) investigated semantic activation of unpictured onset competitor of the target word. The target objects in Experiment 1 were replaced with objects for which the corresponding names have the same onset (e.g., “lock” was replaced with “logs”). It was assumed that words semantically related to onset competitors of the new target words would also draw a high proportion of eye fixations. This was supported by the findings in Experiment 2. The
overall effect of semantic activation was greater in Experiment 1 as compared to Experiment 2. It was concluded that word recognition is based not only on the match between acoustic input and the phonological form of the target words, but also on semantic information. This conclusion is consistent with the findings discussed by Van Petten et al. (1999).

**Frequency effects.** Dahan et al. (2001) conducted two experiments to study frequency effects during spoken word recognition. In Experiment 1, each visual display consisted of three pictures: a target picture (e.g., bench), a high-frequency word with similar onset (e.g., bed), a low-frequency word with similar onset (e.g., bell), and a picture of an unrelated item. In Experiment 2, the high-frequency words were paired with low-frequency words with a similar onset (e.g., bed-bell).

One of the words from each pair was randomly selected as a referent and was presented with three phonologically unrelated distractors. Based on this study, Dahan et al. (2001) found that participants demonstrated a greater number of eye fixations on high-frequency words as compared to low-frequency words, and the fixation latencies towards high-frequency words were significantly shorter. The authors concluded that frequency of words has immediate effects on word recognition.

**Contextual factors.** In most of the word recognition studies discussed earlier (e.g., Allopenna et al., 1998; Marslen-Wilson & Welsh, 1978; Van Petten et al., 1999), the target words were presented in continuous speech rather than in isolation due to the effects of contextual cues from other words in the sentence stimuli. According to McAllister (1988), in order to reach an accurate interpretation, contextual information
within a sentence is consistently used by listeners based on grammatical and semantic appropriateness.

In a more recent study, Brink et al. (2001) investigated the contextual influences on spoken word recognition by analyzing time course in an ERP experiment. The ERP measure was based on the N400 effect, which is the negative polarity that peaks at around 400 ms after the word onset. In previous studies, N400 effect has been associated with semantic processing, lexical access, and semantic integration. The influence of contextual cues in sentences on word recognition processes among individuals without language or neurological impairments were observed in previous studies.

Participants’ responses were recorded based on sentences in each of three conditions: (a) the final word in each sentence was a semantically congruent word (e.g., “The painter colored the details with a small paint brush.”), (b) the final word in each sentence was a semantically noncongruent word but with similar onset (e.g., “The painter colored the details with a small pension.”), and (c) the final word in each sentence was a semantically noncongruent and phonologically unrelated word (e.g., “The painter colored the details with a small labyrinth.”). During the experiment, each participant wore an elastic cap attached with 29 electrodes; 5 electrodes were distributed at the midline of the scalp and 12 pairs of electrodes were distributed at lateral sites. Participants were required to listen attentively and try to understand the sentence stimuli. In order to prevent blinking during presentation of auditory stimuli, participants were asked to look at a fixation point, an asterisk on a computer screen, which remained for 1600 ms after the offset of the stimulus.
Brink et al. (2001) found the N400 effect during the semantically noncongruent conditions and the N200 effect for the semantically congruent sentences in which the negative polarity peaked at around 200 ms after the word onset. It was concluded that contextual cues, provided by the words in a presented sentence, have early influences on word recognition process. Although the word onset and semantic features could activate a number of lexical representations, the activation was based on the contextual constraints provided by the sentence.

**Language processing during sentence comprehension.** As mentioned earlier, frameworks or models of language processing have been discussed and investigated at different levels of language. Sentence processing that utilizes syntactic and semantic information is carried by lexical elements, and can be explained by two theoretical frameworks: (a) the structure-driven framework and (b) the lexical-driven framework (Friederici, 1995; Shapiro, Hestvik, Lesan, & Garcia, 2003). In the structure-driven framework, two phases of sentence processing are involved: initial phase entailing identification of words according to syntactic categories that build up the input structures, and the second phase entailing thematic role allocation based on syntactic structures and lexical information.

A sentence is processed “based solely on syntactic information (lexical categories, phrasal categories, and perhaps argument structure) and extra-syntactic information is subsequently used to help converge onto a final interpretation” (Shapiro et al., 2003, p.4). In contrast, according to the lexical-driven framework, initial analyses are based on lexical information, including the frequency of occurrence, which provides the internal
constraints that influence a high preference of initial interpretation and lexical compatibility with context at the initial stage. Different analyses may only be activated at a later stage after more input is presented and processed.

Other researchers have discussed how incoming inputs are incrementally processed as listeners apply the relevant constraints that are activated as the linguistic input unfolds (e.g., Altmann & Kamide, 1999; Altmann & Steedman, 1988). According to Altmann and Steedman (1988), classic psychological theories of language processing assume that a single analysis is selected based on the sentence structure in order to resolve syntactic ambiguities. It was concluded in these theories that alternative analyses will only be attempted when the initial analysis proves to be inconsistent with the context of the sentence.

Altmann and Steedman (1988) examined an alternative hypothesis, which stated that an interactive word-by-word interpretation in the context of a sentence is entailed in the selection of syntactic analyses. The authors argued that multiple syntactic analyses were initially considered at the same time, followed by discrimination of the analyses to determine “weak” as opposed to “strong” interpretations, which are based on the context. Two experiments were conducted to examine this argument.

In Experiment 1, 32 pairs of target sentences (“NP-attached sentence” and “VP-attached sentence”) were constructed and presented in two contexts (“NP-supporting context” and “VP-supporting context”) according to the type of target sentences (Altmann & Steedman, 1988). In the NP-supporting context, two referents were introduced after the verb (e.g., “A burglar broke into a bank carrying some dynamite. He
planned to blow open a safe. Once inside he saw that there was a safe with a **new lock** and a safe with an **old lock**. The NP-attached target sentence (e.g., “The burglar blew open the safe with the new lock and made off with the loot.”) was presented following the NP-supporting context. In the VP-supporting context, only one referent was introduced following the verb (e.g., “Once inside he saw that there was a safe with a new lock and a strongbox with an old lock.”).

The VP-attached target sentence (e.g., “The burglar blew open the safe with the dynamite and made off with the loot.”) was presented following the VP-supporting context. The sentences were presented on a computer screen one at a time and participants were required to press a continue button after they finished reading each presented sentence. Reaction times between the appearance of a sentence and the pressing of the continue button by the participants were recorded and analyzed.

The NP-supporting contexts/NP-attached sentences and the VP-supporting contexts/VP-attached sentences were randomly presented to the participants. Following each sentence, a simple yes/no question was presented (e.g., “Did the burglar find the strongbox?”) and the participants were required to press the YES or NO button. The yes/no questions were presented to encourage comprehension of referential context, but responses to them were not included in the analyses of this study.

In Experiment 2, Altmann and Steedman (1988) utilized the 32 sets of stimuli from Experiment 1. In comparison to Experiment 1, only the first two sentences were presented in sentence form (e.g., “A burglar broke into a bank carrying some dynamite. He planned to blow open a safe.”), while the two following sentences were presented in
phrase form (e.g., “The burglar/blew open/the safe/with the dynamite/and made off/with the loot.”). Experiment 2 was also conducted based on participant-paced reading task. Each new phrase appeared to the right of the preceding phrase, which remained on the computer screen. RT between the appearance of a sentence or phrase and the pressing of the continue button was also recorded. Following each set, two yes/no questions were presented (e.g., “Did the burglar find the strongbox?” and “Did the burglar steal anything?”) which required the participants responses on the YES or NO button.

As in Experiment 1, the presentation of yes/no questions was to encourage participants’ comprehension of referential context and their responses were not included in analyses. Based on results from the two experiments, Altmann and Steedman (1988) concluded that sentence comprehension is based not only on the syntactic component, but also takes into account the semantic and contextual components. Therefore, interpretations do not only occur at the completion of clause or sentence, but also during incomplete fragments of phrases.

Based on previous studies, Altmann and Kamide (1999) found that the presence of referring expressions, such as adjectives and modifiers, assist in the incremental processing of a sentence in a piecemeal manner by narrowing down the interpretation to the relevant referent that can be achieved even before hearing a noun. Thus, they predicted that the semantic information provided by verbs is also sufficient to support sentence comprehension even before the direct objects following the verbs are presented auditorily.
In their study, Altmann and Kamide (1999) hypothesized that when the verb-based selection is restricted to only one of the objects in the visual scene, the proportions of eye fixations on the target object will increase significantly as compared to the condition when a verb could be applied to more than one target object. They measured the saccadic eye movements of the participants as they listened to auditory stimuli.

The authors devised 16 sets of stimuli, which consisted of a single visual scene and two recorded sentences. For example, a visual scene displayed a picture of a boy sitting on a floor, surrounded with four objects (i.e., a toy train set, a toy car, a cake, and a balloon). Accompanying sentence stimuli for this scene included: (a) *The boy will move the cake* and (b) *The boy will eat the cake*. The results of this study supported the notion that sentence processing can be projected towards the upcoming object based on the verb, which determines the thematic fit between the context of the sentence and the verb itself.

**The Use of Eye-Tracking in Studying Online Language Processing**

While processing auditory linguistic input, people tend to move their eyes with respect to the linguistic references whether or not they are aware of doing so (Tanenhaus Spivey-Knowlton, Eberhard, & Sedivy, 1995). The eye movements are said to be time-locked to online language processing, with reference to the ongoing auditory speech stream.

In experimental paradigms that involve overt physical responses, such as pressing a button or performing physical acts by moving objects according to instructions, participants might not respond as quickly as they can comprehend (Hallowell, 1999; Hallowell, Wertz, & Kruse, 2002; Odekar, Hallowell, Kruse, Moates, & Lee, 2009;
Yang, Wang, Chen, & Rayner, 2009). According to Hannula and Ranganath (2009), disproportionate eye fixations during recognition of pictures on a visual display was documented to occur a second before the overt response made by an individual. Therefore, eye tracking might increase the accuracy of online processing analyses compared to data based on overt physical responses by participants.

Eye-tracking methods have been used by researchers to study language comprehension among individuals with and without language impairment. Eye movement methods for assessing language comprehension offer several advantages such as: (a) providing an alternative communication mode that does not require talking, writing, or gesturing; (b) allowing stimulus adaptations to control for deficits in perception, attention, and ocular motor movements; (c) minimizing reliance on participants’ ability to understand test instructions; and (d) supplying real-time measurement of language comprehension by utilizing continuous recording of language processes without interruption by further verbal instructions, prompts for responses, and demands for conscious planning of responses (Hallowell, 1999; Hallowell et al., 2002). By utilizing eye-tracking methods, physical challenges can be avoided during language processing and comprehension tasks.

Eye-tracking methods to study normal language comprehension. Initially, many researchers believed that it was impossible to determine the influences of nonlinguistic information during syntactic processing, due to experimental techniques that involve physical movements, such as pressing a button or moving the objects, that could not be performed in natural contexts (Tanenhaus et al., 1995). In contrast,
observation of eye movements under natural conditions yields information about the underlying mental processes during spoken language comprehension (Odekar et al., 2009; Tanenhaus et al., 1995). Research studies utilizing eye-tracking methods have shown that eye-tracking techniques represent a distinctive manner to demonstrate information processing in real time while an individual is auditorily presented with linguistic input (Hallowell & Lansing, 2004).

According to Hallowell and Lansing (2004), two types of eye movement have significance in studies of cognitive and linguistic processes, saccadic eye movements (or saccades) and eye fixations. Saccades are quick rotations of the eye that allow fixation of images onto the fovea (the retinal area with the greatest visual acuity), and eye fixations are the observed pauses between eye movements. In addition to the visual stimuli, saccades and eye fixations can be influenced by other types of stimuli, such as auditory inputs. In a condition where auditory input is presented together with visual stimuli, our eyes tend to focus more on the object related to the auditory stimulus rather than other visual inputs that are also captured.

In a study by Hallowell (1999), eye fixations of participants were recorded and compared as they scanned image displays in each of two conditions—with and without a verbal stimulus. This study demonstrated significantly greater proportions of eye fixation allocated to target images during the 10 seconds of picture scanning during the verbal condition, compared to free-scanning trials in which no verbal stimulus was presented. Based on this study it can be assumed that humans will naturally allocate more focus on a
specific object or picture when stimuli are presented in dual modal condition (visual and auditory) as compared to single modal condition (visual only).

In several language processing studies, researchers have found that eye movements provide natural reactions by participants during word and sentence comprehension tasks. According to Huettig, Rommers, and Meyer (2011), a set of methods known as the visual world paradigm (VWP) has enabled observations of eye movements to capture language processes at phonological, lexical, morphological, semantic, syntactic, and discourse levels. Key properties of the VWP include: (a) bimodal stimuli presentation where linguistic stimuli are presented auditorily together with visual displays, (b) identification of timing for eye movements according to specific elements in the linguistic stimuli, and (c) focus of data analyses in comparing the allocation of eye movements to different regions on the visual displays (Huettig et al., 2011). Although data analyses are based on eye movements on the visual display, researchers who have used the VWP always require participants to also physically manipulate objects in order to confirm participants’ comprehension of the linguistic stimuli.

Several researchers who conducted the VWP studies examined different levels and aspects of language processes, such as phonological similarities (e.g., Allopenna et al., 1998), word recognition (e.g., Marslen-Wilson & Welsh, 1978; Tanenhaus et al., 1995), semantic activation (e.g., Mirman & Magnuson, 2009; Yee & Sedivy, 2006), phrasal domains (e.g., Chambers, Tanenhaus, Eberhard, Filip, & Carlson, 2002), and sentence processing (e.g., Altmann & Kamide, 1999; Kamide, Altmann, & Haywood,
In studies utilizing the VWP, the fixation and the sequence of eye movements toward target objects, words and sentences in continuous spoken speech have been said to be closely time-locked for people with no cognitive or linguistic deficits (Allopenna et al., 1998; Tanenhaus et al., 1995). Therefore, findings from observations of eye movements allow researchers to monitor continuous online processing in various perceptual and linguistic contexts (Chambers et al., 2002).

As discussed earlier, Allopenna and colleagues (1998) found that when a listener is presented with an auditory input, there is a connection between lexical activation and eye movements on the target. Raw eye position data were observed between two points: (a) right after the onset of the target word and (b) once the participant clicked the computer mouse on the target correct item. The authors assumed that when a person looks at a target item during a specific time, the action of looking at the target image is directly related to the activation of the target word in the listener’s lexicon.

Allopenna et al. (1998) observed the eye position patterns within each 100 ms time slice in three different conditions: (a) observation of eye position corresponding to the target item as compared to all competitor images, (b) observation eye position on the target item as compared to the cohort competitor (the word with a similar onset to the target word), and (c) observation of eye position on the target item as compared to the rhyme competitor (the word with a similar ending to the target word). They found significant increments of eye position corresponded to the target object and the cohort competitor during the second 100 ms interval (100-200 ms). Participants’ eye position on the rhyme competitor also increased after 300 ms but never exceeded the proportion of
fixation for the cohort competitor. They also found that the eye position corresponding to the target significantly increased as compared to the cohort competitor after 400 ms.

Although participants’ eye positions corresponding to the unrelated object were observed, there were proportionately few of these. Based on their findings, Allopenna et al. (1998) concluded that the duration for the eyes to reach a target corresponds closely to the actual participants’ behavior. Therefore, they reasoned, eye-tracking methods may provide an adequate sensitivity level needed to explore the time course of competitor effects in spoken word recognition (Allopenna et al., 1998).

A shortcoming of the study by Allopenna and colleagues (1998) is that observation of raw eye position data may not capture actual mental processes during language comprehension. Although eye position is typically recorded at 30 to 120 Hz, it is important to keep in mind that visual information is processed only when the eyes are stabilized at a fixated point for a duration long enough to process the information (Hallowell et al., 2002; Hannula & Ranganath, 2009). Therefore, a threshold must be set a priori to differentiate eye fixations from other ocular motor activities such as saccades and motor programming (Odekar et al., 2009).

Although eye movement methods have been proven to be useful in language processing studies, whether eye movement methods can generate the same results as tasks involving physical responses remains a question. To answer this question, Hallowell et al. (2002) developed the Multiple Choice Test for Auditory Comprehension (MCTAC) by adapting a standardized language comprehension test, the Revised Token
Test (RTT) developed by McNeil and Prescott (1978). The researchers compared participants’ responses in three different conditions.

In the original RTT procedures, participants’ comprehension was assessed by observing their ability to manipulate tokens according to spoken instructions. In the MCTAC pointing condition, multiple-choice pictorial displays were developed based on the RTT stimuli. The auditory commands were modified by deleting any involvement of physical manipulating behavior such as “touch” or “put” (e.g., “Touch the blue circle” was modified to “Blue circle”). The participants were required to point to the pictures related to its verbal stimuli.

In the eye movement condition, the MCTAC displays were presented on a computer screen. Rather than having the participants point to the target picture such as in pointing condition, an eye-tracking device was used to monitor participants’ eye movements on the computer screen while listening to the auditory stimuli. In this study, no significant difference was found from the comparison of eye movement method, experimental pointing method and traditional method. Hallowell et al. (2002) concluded that eye-tracking may be an appropriate method to assess individuals with language impairment.

**Eye-tracking methods to study comprehension among people with aphasia.**

In recent years, eye-tracking studies have been extended to develop theoretical frameworks of language comprehension among individuals with neurological impairments (e.g., Dickey & Thompson, 2009; Mirman, Yee, Blumstein, & Magnuson, 2011; Thompson, Dickey, & Choy, 2004; Yee, Blumstein, & Sedivy, 2004). Physical
responses required from individuals with aphasia who experience concomitant problems, such as motor deficits, may exacerbate the challenges faced by these individuals during language assessments (Hallowell, 1999; Hallowell et al., 2002; Patterson & Chapey, 2008).

In this case, assessment findings based on physical responses may not reflect true language and communication ability (Salis & Edwards, 2009). Studies using eye-tracking methods have been conducted to determine the factors influencing visual function to improve evaluation methods during language assessment conducted on individuals with aphasia (e.g. Hallowell, Douglas, Wertz, & Kim, 2004; Hallowell et al., 2002; Heuer & Hallowell, 2007; McKelvey, Hux, Dietz, & Beukelman, 2010).

**Word recognition of individuals with aphasia.** Yee et al. (2004) investigated the lexical activation occurring in different types of aphasia, Broca’s and Wernicke’s aphasia. In the study by Yee et al. (2004), time-course analysis was done based on eye movement measures derived from individuals with Broca’s and Wernicke’s aphasia. It was proposed that individuals with aphasia exhibit different levels of lexical activation compared to individuals without language impairment and the activation levels vary for different types of aphasia. This study involved 5 individuals with Broca’s aphasia, 4 individuals with Wernicke’s aphasia, and 12 age-matched controls.

Based on their findings, Yee and colleagues (2004) concluded that the eye-tracking paradigm is not only natural but also offers a continuous measure of lexical activation. They also found that both types of aphasia being investigated entail lexical processing deficits related to the dynamics of lexical activation. The eye movement
measures demonstrated that the participants with Broca’s aphasia have extremely reduced levels of lexical activation at the word onset of competitors, and showed no preference to distractors based on the semantically related word onset. These findings are consistent in comparison with the control group.

On the other hand, participants with Wernicke’s aphasia yielded an abnormally high level of activation following the strong activation of the word onset when compared to the control group. Unlike the participants with Broca’s aphasia, individuals with Wernicke’s aphasia demonstrated preference towards semantically related competitors at their onset, as measured by eye fixations.

These findings are similar to previous studies that had used a metalinguistic lexical decision paradigm (e.g., Milberg, Blumstein, & Dworetzky, 1988) in which participants were presented auditorily with pairs of words or word-like stimuli that had a different phonetic representation at the onset of the word and were required to make lexical decisions for the second stimulus based on the first stimulus. It was concluded that lexical activation among individuals with aphasia varies according to the types of aphasia.

In a more recent study, Mirman et al. (2011) also examined lexical activation of individuals with Broca’s and Wernicke’s aphasia. The authors utilized a combination of the eye-tracking paradigm and computational modeling, which was used to acquire information about the time course of lexical activation of individuals with aphasia. This study involved 6 participants with Broca’s aphasia, 5 participants with Wernicke’s
aphasia, and 24 control participants (12 college-aged adults and 12 older adults with an average age of 67 years).

Participants were given auditory stimuli, which were presented simultaneously with visual displays, each containing four pictures: a target word, a rhyme competitor, and two pictures associated with words that are phonologically and semantically unrelated to the cohort competitor (words with a similar onset) and rhyme competitors (words with a similar ending).

Mirman and colleagues (2011) found different lexical activation levels and duration demonstrated by participants with Broca’s and Wernicke’s aphasia. Participants with Wernicke’s aphasia have showed slower deactivation of lexical competitors, which resulted in increased cohort competition effects with minimal rhyme competition differences. These findings were in contrast with the results they gathered from participants with Broca’s aphasia, who demonstrated an increase in rhyme effects but reduced cohort competition.

The two studies described above showed that by using eye-tracking methods, researchers could study: (a) the lexical activations of individuals with aphasia in real time and (b) the differences demonstrated by individuals with and without aphasia during lexical activations. The above studies further supported the idea that different characteristics of lexical activation is based on different types of aphasia, which can be associated with a site of lesion in the brain and a list of hallmark features (Hallowell & Chapey, 2008).
However, it is important to remember that those studies involved a limited number of participants. It is crucial to conduct further studies with larger samples in order to improve the investigation of the proposed conclusion. It is also important to consider individual variability found in previous studies (e.g., Caramazza, Capitani, Rey, & Berndt, 2001; Johnson & Cannizzaro, 2009) among people who are clinically diagnosed with the same type of aphasia, which are not addressed in the studies discussed above.

**Sentence comprehension of individuals with aphasia.** In studying language comprehension at the sentence level, Thompson et al. (2004) used eye tracking to examine the comprehension of individuals with Broca’s aphasia on wh-movement structures in simple non-canonical wh-questions and in complex object clefts. Participants were auditorily presented with short stories, accompanied by visual displays, and followed by either a simple non-canonical wh-question (e.g., “Who did the boy kiss that day at school?”), a complex object cleft sentence (e.g., “It was the girl that the boy kissed that day at school.”), or a yes-no question that required a verbal response from the participants. Eye movements were tracked during the presentation of stories and questions as participants looked at visual displays.

Each visual display contained four pictures; the subject, the object, the location, and a distractor (an item not mentioned in the story). Results obtained from participants with Broca’s aphasia were compared to the control group. In the simpler wh-question condition, participants in both groups looked at the target items more often than the competing items. However, participants with Broca’s aphasia demonstrated significantly
poorer comprehension in the object cleft condition, which was more complex.

Reactivation of wh-elements during sentence processing was only witnessed during the wh-question condition, and no visual evidence of reactivation was seen in the object cleft condition.

Dickey and Thompson (2009) also studied the comprehension of wh-movement, specifically the object-relative clauses, and the non-canonical NP-movement, which are typically impaired in agrammatic aphasia. In this study, participants with and without aphasia were presented simultaneously with three-sentences stories via a loudspeaker, and visual displays, each containing two actors, a location and a distractor (an item not mentioned in the story). Each short story was followed by an instruction “Point to the…,” which was manipulated to produce sentences with object-relative clauses or non-canonical NP-movement. Eye movements were observed while participants followed the instruction given after the story.

It was found that participants with agrammatic aphasia had significantly impaired comprehension of object-relative clauses and passive structures. Participants with aphasia demonstrated significantly decreased accuracy of response when presented with sentences containing object-relative clauses and passive structures. In order to analyze the pattern of eye movements, Dickey and Thompson (2009) divided the sentences into five regions based on the phrases used to construct the sentences.

For example, a sentence “Point to who the bride was tickling in the mall” was divided to Region 1 “Point to who,” Region 2 “the bride,” Region 3 “was tickling,” Region 4 “at the mall,” and post-offset region known as Region 5. The time-course
analysis performed on the eye fixations on each region demonstrated that participants with aphasia exhibited a weaker theme preference and evidence of competition at a later point in sentences than control participants.

The findings from these studies demonstrated not only those individuals with aphasia have lower levels of comprehension, but they may have language processing mechanisms that differ from individuals without aphasia. That is, their language deficits may be accompanied by deficits in nonlinguistic cognitive aspects of information processing (i.e., memory and attention) which may affect their performance during comprehension tasks. In addition, these studies required physical responses from the participants with aphasia (e.g., “Point to the …”).

Language deficits were found to differ among individuals with aphasia themselves. Language processing tends to be affected differently by different types of aphasia. Still, even within specific aphasia syndromes, individual variations exist in terms of their comprehension deficits and comprehension patterns. For example, Caramazza and colleagues (2001) reanalyzed data obtained from a total of 59 participants with Broca’s aphasia from several different studies that were divided into two groups. Data from 16 participants overlapped between the two groups. The authors compared participants’ performance in comprehending active and passive sentences between these two groups. Based on their findings, Caramazza et al. (2001) concluded that individuals with Broca’s aphasia differed in their sentence comprehension ability despite similar clinical symptoms of language deficit.
In studies by Dickey and Thompson (2009), exclusion criteria for individuals with motor disabilities were not reported. Because these studies involved physical responses, motor difficulties might have impacted participants’ ability to respond, thus, affecting findings. Therefore, findings derived from the study should be treated cautiously. In addition, studies of individuals with aphasia also commonly involve a limited number of participants and rarely have been extended to clinical or real-world settings.

**Influencing factors in using the eye-tracking methods.** Although eye-movement methods and measures offer a more natural way to study language processing than experimental methods that rely on physical responses, it is important to note that multiple images themselves, when presented simultaneously without an accompanying auditory stimulus, tend to instigate disproportionate looking. The disproportion of eye movements may interfere with the validity of the research findings.

As mentioned earlier, eye-tracking studies involving individuals without language impairment and individuals with aphasia have been conducted to determine the factors influencing allocation of visual attention (e.g., Hallowell et al., 2004; Heuer & Hallowell, 2007; McKelvey et al., 2010). Heuer and Hallowell (2009) listed three factors that may influence processing of visual input: (a) complexity of the stimulus, (b) image characteristics overlapping between target and non-target images, and (c) the number of stimuli presented. In their study, the influence of image characteristics (i.e., color, orientation, size, and luminance) on visual attention was investigated.

Although it was found that target images presented together with verbal stimuli received greater proportions of fixation duration, the authors noted that verbal stimuli did
not override the influence of image characteristics within a display. The findings of this study were similar to a study conducted by Kamide and colleagues (2003), who found that physical characteristics (e.g., relative position, color, contrast, and spatial frequency), and semantic attributes may favor certain objects on a visual display. Kamide et al. (2003) also found that more eye movements were executed towards animate object compared to the inanimate objects in their study.

Visual similarity is another factor that may influence eye movements during cross modal language processing, in which verbal stimuli are presented auditorily and participants’ responses are observed via eye movements on visual displays. Mirman and Magnuson (2009) used the visual feature norms (listed by McRae, Cree, Seidenberg, & McNorgan in 2005) and visual concept-picture similarity ratings to control visual features that may affect participants’ responses during semantic processing experiments.

The visual feature norms, which consist of 541 concepts that had been used in various previous studies of semantic memory tasks, were developed by McRae and colleagues (2005) to be used by other researchers in constructing experimental stimuli and generalizing representations for implemented models. By using the visual feature norms, the researchers were able to tease apart visual similarity from nonvisual semantic similarity. The visual concept-picture similarity ratings were conducted because it is impossible for human raters to completely ignore the nonvisual concepts while performing the similarity rating of the target images.

During the visual concept-picture similarity ratings participants who are not involved in the main study were presented with four pictures: a target image (e.g.,
tomato), a near neighbor (e.g., strawberry), a distant neighbor (e.g., potato), and an unrelated image (e.g., magazine), and were given the target word so that participants could rate the visual similarity between the target image and the other three images on a 5-point scale. Based on this study, Mirman and Magnuson (2009) found a high correlation between measures of visual similarity: (a) number of shared visual features, (b) proportion of shared visual features, and (c) rated similarity. In summary, the studies discussed above demonstrate how various visual factors influence participants’ responses during experiments involving eye-tracking methods. Therefore, it is important to control multiple aspects of all visual stimuli used in experiments involving eye movement measurements in order to increase validity of results.

**Time-Course Analysis in Studying Online Language Processing**

As discussed earlier, language processing is a complex activity and occurs rapidly to reach a final interpretation in order to comprehend the input. In order to understand spoken or written language, listeners or readers must process the received auditory or written input. Humans have the capability to initiate and complete processing operations such as lexical activation, syntactic parsing, and grammatical judgments within short durations (Ingram, 2007). Several studies discussed earlier entailed analyses of the time course related to language processing at different language levels.

Although language processing takes place in a very short time, the relative time course taken to accomplish those processes is not clear (Yang et al., 2009). Mirman and Magnuson (2009) presumed that studying spoken word recognition is challenging because speech signal processing is very fast and is semantically very complex, though it
is done with little effort even in noisy environments and in ambiguous syntactic contexts. The properties of each level provide information to determine the timing of points in the analysis of the input, and these time-bound linguistic structures are known as temporal structures (Marslen-Wilson & Tyler, 1980).

According to Mirman and Magnuson (2009), identification and interpretation of auditory input is between 100 to 150 words per minute. Time-course analysis has been used by researchers to examine online processing of language at various levels, such as in word recognition and sentence comprehension. Some studies that utilized time-course analysis had been discussed earlier in the Theories of Language Processing section (e.g., Allopenna et al., 1998; Marslen-Wilson & Welsh, 1978). In this section, time-course analysis as a research method will be discussed in greater detail.

At the onset of a spoken word, listeners develop a perceptual interpretation of incoming speech sounds in the word, which is determined by internal lexical constraints and later is confirmed or discarded once the speech output is completed (Marslen-Wilson & Welsh, 1978). The anticipation of an upcoming word in a sentence is also determined by semantic constraints (Kamide et al., 2003). These two phenomena affect listeners’ expectations about upcoming sounds and words, which are later confirmed once the speech output is complete. Furthermore, a combination of top-down and bottom-up processing that takes place during word recognition minimizes the required capacity to arrive at the final interpretation of the received acoustic-phonetic input (Marslen-Wilson & Welsh, 1978).
The presence of onset and rhyme competitors represented by pictures increases latency of eye movements to the target and induces increases eye movements to the competitors (Allopenna et al., 1998). Therefore, in a condition where no other competing input is present, an individual requires a shorter time to make a decision about a target and it can be completed even before hearing the end of the word. Tanenhaus et al. (1995) found that the duration needed to make eye movements towards the target object depends on the competitors presented on the visual display and the phonological similarity of the target word and the competitors.

Time-course analysis on eye movement data has generally been conducted in two ways: (a) by observing eye movements based on frame-by frame analyses, and (b) by observing RT according to specific linguistic input. In a study by Allopenna and colleagues (1998), raw eye position data were recorded at a rate of 30 frames in one second; each frame is within 33.3 ms duration. Frame-by-frame analyses for each item were conducted on the first 800 ms at 100 ms interval. They found different patterns of eye positions corresponding to a target object and its competitors, as described earlier in the eye-tracking section.

In an earlier study, Tanenhaus et al. (1995) studied participants’ responses while listening to ambiguous sentences (e.g., “Put the apple on the towel in the box” as opposed to “Put the apple that is on the towel in the box”). The type of sentences were presented in two different conditions: (a) a target object (e.g., an apple) was presented with other objects (e.g., a towel and a box), and (b) two objects related to the target word were presented (e.g., an apple on the table and another apple on the towel). The authors found
that in the condition where no other object in a display had a similar name, individuals
could identify the target object even before hearing the end of the word.

In the Tanenhaus et al. (1995) study, the researchers examined the raw eye
positions on the visual displays based on a time continuum analyzed in 500-ms
increments. Each x/y coordinate corresponding to an object in the visual display was
labeled (e.g., A, B, C, D, A’, and B’) and mapped on the time continuum.

By studying the time course of sentence presentation, syntactic processing,
including sentence parsing, thematic allocation, and syntactic and semantic
interpretations judgments can also be analyzed in real time. Friederici (1995) described
three ways to study the temporal structure of comprehension processing: (a) conducting
reaction time studies known to be sensitive to language processing, (b) comparing the
temporal structures demonstrated by language-normal individuals with those who have
language processing problems due to neuropsychological deficits, and (c) monitoring
brain activity during sentence processing by studying ERP patterns. Friederici (1995)
measured participants’ brain activity to document temporal structures during sentence
processing.

In the study, significant ERP pattern, which is the negative polarity and peaking at
400 ms after full information of a lexical entry, was made available to participants.
However, different distributions of waveforms and time courses were found for different
types of linguistic violations presented earlier in a sentence, which suggests that different
brain systems are involved in different types of processing, and their activation takes
place at different points in time. From this study, it was concluded that syntactic
processing occurs in phases with the earlier phase involving processing of full lexical access. This is later followed by another phase known as structural reanalysis, which takes place when the initial syntactic structure cannot be mapped onto the semantic and lexical elements.

In a study by Shapiro and Hestvik (1995), the cross-modal lexical priming (CMLP) task was used to investigate the sentence processing framework. In the CMLP task, spoken paragraphs were presented as auditory stimuli and at the same time single printed words were presented as visual lexical probes. Each paragraph ended with a sentence containing VP-ellipsis (e.g., “The policeman defended himself, and the fire [1] man did [2] too, according to someone [3] who was there.”). A visual lexical probe (e.g. related probe “robber” or control probe “roller”) was presented at the three different positions. In this study, participants were required to press the WORD or NONWORD button.

In the second experiment, the subordinated VP-ellipsis construction was investigated, in which two clauses were connected by “because” (e.g., “The policeman defended himself because the fire [1] man did [2], according to someone [3] who was there.”). Based on the analyses of the reaction times (RT) to the lexical activation, Shapiro and Hestvik (1995) found that RT to the related probes were significantly faster than the control probes in both experiments. The study also demonstrated that the lexical activation occurs at different time courses depending on the type of relationship between clauses in a sentence.
Following the study discussed above, Shapiro et al. (2003) also examined the online operation that takes place in reaching the final interpretation of a sentence containing VP-ellipsis by using the CMLP. Participants were auditorily presented with sentences that contain two clauses structures (e.g., “The gambler who won 10 hands in a row [1] winked [2] his eyes, and the pit boss who was in on [3] the elaborate scheme did [4] too.”), and visually presented with written related probes or control probes for each clause (e.g. MONEY/PAPER was presented during the first clause, and EMPLOYER/PUBLIC during the second clause). Following the presentation of the auditory stimuli and the visual probes, participants were required to press the WORD or NONWORD button. Shapiro and colleagues (2003) found significant RT differences between related probes compared to control probes during the second clause but not in the first clause.

Because auditory comprehension involves operations that are fast-paced and relatively automatic, time course analysis allow researchers to study language processes and factors contributing to language processing even at the lowest level. As discussed earlier, several techniques were found to be effective in demonstrating online processing in real time. These techniques include brain potential studies (e.g., Friederici, 1995) and eye-tracking studies (e.g., Hallowell, 1999; Mirman & Magnuson, 2009; Odekar et al., 2009) that have been utilized in online language processing studies.

Unfortunately, the time-course methods described above can be problematic, especially when conducted using eye fixation data. For example, as proposed by Allopenna and colleagues (1998), raw eye position data were observed based on time
slices that were non-additive. Observations were conducted within specific time bins such as 0-100 ms, 100-200 ms, 200-300 ms and so on. In previous studies (e.g., Hannula & Ranganath, 2009; Hannula, Ryan, Tranel, & Cohen, 2007), a pause between eye movements should be at least 100 ms duration to be considered an eye fixation. Eye fixations on visual displays could occur at any time during the experiment; however, if the eye fixation is observed based on the time slices, we may lose eye fixation data that were segmented in separate time bins.

Observation of eye fixations according to RT also might not provide an accurate interpretation of language comprehension. In previous studies described above (e.g., Dickey & Thompson, 2009; Shapiro & Hestvik, 1995; Shapiro et al., 2003), RT were based on participants’ physical responses, such as pressing a button or pointing to an image, to indicate the comprehension of the linguistic stimuli. When a person is presented with multiple images, the person initially requires some time to scan through the images (Mirman & Magnuson, 2009). The first eye fixation may not reflect comprehension of a linguistic stimulus due to the possibility of a person randomly looking at the target image.

Even towards the end of the visual presentation, researchers (e.g., Allopenna et al., 1995) found that participants continued to move their eyes toward competing images in addition to the target image. Although the proportion of looking at the target image was significantly higher, the exact eye fixation corresponding to the point when a person comprehends the linguistic input could not be identified. Proportion of fixation duration, calculated by dividing total fixation duration on a specific image with the total fixation
duration on the visual display (e.g., Blair, Watson, Walshe, & Maj, 2009; Hallowell et al., 2002; Ivanova & Hallowell, 2012), might provide more accurate information regarding participants eye movement responses across time.
Chapter 2: Purpose of the Study

Time-course analysis based on eye-tracking measures may provide valuable information about language processing as a person is listening to an auditory stimulus. It may yield pertinent information about the duration needed by adults (with and without language impairment) to arrive at a point where a verbal stimulus (i.e., word, phrase, sentence, or paragraph) is comprehended. Four issues have been raised based on the methods and findings in previous studies: (a) time-course analysis on every raw x/y coordinate corresponding to eye position, (b) observation of eye movements according to segmented time slices, (c) the use of RT on eye movement data to indicate language comprehension, and (d) the duration of presented verbal stimuli.

Researchers, such as Allopenna et al. (1998), Dahan et al. (2001), Dickey and Thompson (2009), Kamide et al. (2003), Mirman and Magnuson (2009), and Tanenhaus et al. (1995), have been analyzing time course of eye movements in language processing studies; however, these analyses were not focused on the eye fixations, but included all kinds of eye movements. Because the human brain can only process visual input acquired during eye fixations, inclusion of saccades and other types of eye movement in the analyses may yield inaccurate results.

Analyzing eye fixations according to time slices as proposed by Allopenna et al. (1998) is also problematic. An actual eye fixation that occurs in a specific time segment might be cut to different time slices, which will lead to loss of eye fixation data. Analyses of RT of eye fixation may also be problematic for two reasons: (a) the first eye
fixation may not indicate the ability to comprehend a linguistic stimulus, and (b) eye movements on competitor images can also be found across time.

In previous studies (e.g., Hallowell et al., 2002; Ivanova & Hallowell, 2012), participants were presented with visual displays with durations that are equal to twice the average duration of verbal stimuli, rounded up to the nearest second, plus two additional seconds. The visual display durations were found to be adequate to elicit responses that indicate the ability of participants to understand the presented stimuli. However, the actual duration needed by individual with or without aphasia is unknown.

Identification of required duration to understand a verbal stimulus might change our perspective about comprehension time windows during language processing. Modification of methods that involve eye movement analyses across time might help to improve previous approaches used in language processing studies and during language assessments in clinical settings. Verbal and visual stimuli may be presented within an adequate amount of time and no more than necessary, thus, reducing the duration it takes to complete an assessment.

Specific Aims

In the current study, eye tracking was used to study eye fixation across time by observing the proportion of fixation duration on the target object (PFDT) across time windows with additive duration. Analyses of PFDT across time windows were conducted based on verbal stimuli with increasing difficulty in terms of length, number of critical elements, and complexity. PFDT patterns across time were analyzed using data
collected from individuals without language impairment and individuals with aphasia to compare the performance by these two groups.

The aim of this study was to: (a) document and compare the PFDT at different time windows (with progressively longer durations) observed among individuals without language impairment and individuals with aphasia when presented with verbal stimuli, and (b) determine linguistic factors, such as sentence length, sentence complexity, the number of critical elements present in a sentence, and the type of critical elements that may influence the time course of language comprehension of individuals without language impairment and individuals with aphasia.

**Hypotheses**

For hypothesis 1, we predicted that participants with aphasia (PwA) would demonstrate the maximum mean PFDT at a later time window, as compared to the control group. Based on previous studies that utilized eye-tracking methods and time course analysis in comparing language comprehension among individuals with aphasia (e.g., Dickey & Thompson, 2009; Mirman, Yee, Blumstein, & Magnuson, 2011; Thompson et al., 2004; Yee et al., 2004), it was found that participants with aphasia required a longer period of time, compared to control groups, in order to process auditory stimuli. Because individuals with aphasia generally require a longer time to arrive at the target, it was assumed that PwA would need a longer time window to reach the average of maximum PFDT, while the control group would show an average of maximum PFDT at a time window with a shorter duration. A decrease of mean PFDT was also expected after participants identified the image that matches the verbal stimuli. Due to differences
in language ability, control participants and PwA might demonstrate different time windows when the maximum mean PFDT is reached and different patterns of mean PFDT throughout the trials.

Following Hypothesis 1, two post hoc analyses were conducted using descriptive analyses: (a) to identify the discriminatory time window between the PwA and the control group; and (b) to document patterns of PFDT, demonstrated by the PwA and the control group, when presented with verbal stimuli that increase in length, number and type of critical elements, and complexity (e.g., phrases and grammatical sentences).

For hypothesis 2, we predicted that the WAB-R Auditory Comprehension (AC) score obtained by each PwA would be statistically correlated with the time window in which the maximum PFDT occurs; PwA with higher scores in the WAB-R AC would demonstrate maximum PFDT at an earlier time window. According to Dickey and Thompson (2009), the level of language comprehension determines the duration needed for an individual to understand auditory stimuli. Individuals with better auditory comprehension ability score higher on the WAB-R AC (Kertesz, 2007). In this study, it is expected that PwA with higher WAB-R AC scores would demonstrate increasing PFDT earlier than participants with lower WAB-R AC scores. Likewise, PwA with higher WAB-R AC scores would show the highest PFDT in a shorter time window. PFDT and WAB-R AC scores were analyzed as continuous variables.

Following Hypothesis 2, two post hoc analyses were conducted by using descriptive analyses: (a) to identify the time windows that discriminate the performance of PwA who obtain the WAB-R AC scores at the level of below, equal to, or above the standard
deviation; and (b) to document patterns of PFDT, demonstrated by PwA who obtain the WAB-R AC scores at the level of below, equal to, or above the standard deviation, when presented with verbal stimuli that vary in length, number and type of critical elements, and complexity (e.g., phrases and grammatical sentences).
Chapter 3: Method

Participants

Existing data from a total of 80 participants, 40 control participants without neurological disorders and 40 PwA, were obtained from the Neurolinguistics Laboratory at Ohio University. These data were collected in 2011, as part of a larger study on language comprehension among individuals with aphasia. For all PwA, CT scans or MRI results verifying presence of brain damage secondary to stroke in the left hemisphere at least one month post-onset were documented.

PwA were assessed with the Auditory Verbal Comprehension (AC) component from the Western Aphasia Battery–Revised (WAB–R; Kertesz, 2007) to determine their levels of auditory comprehension. The WAB-R AC was designed to measure an individual’s sentence comprehension ability related to prepositions, grammatical structures with varied levels of complexity, single nouns in different categories, and sentences of varied length. The WAB-R AC consists of three subtests: (a) yes/no questions, (b) auditory word recognition, and (c) sequential commands.

The WAB-R AC score has a positive correlation (at least 0.5) with all components in the WAB–R such as Reading, Praxis, Construction, Naming, Information Content, Repetition, Writing, and Fluency. Based on the standardization conducted on 150 individuals with different types of aphasia, the WAB-R AC subtest has a mean score of 5.7 and a standard deviation of 2.9 (Kertesz, 2007). In data analysis of the current study, PwA were arranged in a continuum based on their WAB-R AC total scores.
Inclusion criteria and screenings.

**Inclusion criteria for all participants.** All participants who were included in the study had passed a visual screening based on guidelines developed by Hallowell in 2008. The guidelines include: (a) correct identification of all four images in the *Color vision testing made easy* color contrast screening task (Waggoner, 1994), (b) near visual acuity as outlined by Hyvärinen, Näsänen, and Laurinen (1980), for 100% accuracy in identifying .5-inch-square pictures of common objects presented at a distance of 12 to 24 inches, with and without glasses or contact lenses, (c) no sign of drainage, swelling, redness, nystagmus, visual neglect, or visual attention deficit, based on experimenter observation, and (d) peripheral vision within normal limits per peripheral finger counting task.

In addition to visual acuity, participants were screened for hearing acuity. Hearing screening was conducted at 500, 1000, and 2000 Hz. Participants had passed the hearing acuity screening at 30dB SPL for all frequencies.

**Additional inclusion criteria for control participants.** Based on self-report of control participants, they had no history of brain injury or psychiatric illness. Participants also had no concomitant language or cognitive disorders (e.g., dementia or learning disability), per self-report and experimenter’s observation. These additional criteria were included because the presence of these criteria might confound participants’ performance on the test.

**Additional inclusion criteria for participants with aphasia.** Individuals with aphasia included in this study were required to be diagnosed with aphasia, with diagnosis
confirmed by a speech-language pathologist. Participants also had no history of psychiatric illness, learning disability, or cognitive disorders per self-report. These additional criteria were included because their presence might confound the participants’ performance in this study.

**Instrumentation**

The instruments used in this study were important for: (a) hearing screening, (b) presenting auditory screening and test stimuli to participants who are using and not using hearing aids, and (c) monitoring eye movements on visual displays.

Participants’ hearing levels were screened using a Maico MA25 Audiometer (Maico Diagnostics) for 500, 1000, and 2000 Hz at 30dB SPL. Sound-field hearing screening stimuli were presented via Boston Media Theater speakers (Boston Acoustics, Inc.). Auditory stimuli during the experiment were presented via Boston Media Theater headphones (Boston Acoustics, Inc.) to participants who were not using hearing aids and via Boston Media Theater speakers to participants who were using hearing aids.

The Eyefollower 2.0 Eyegaze System (LC Technologies) was used to monitor participants’ eyes on visual displays during the presentation of auditory stimuli. The Eyefollower 2.0 Eyegaze System was used to record eye movements and measured participants’ gaze points at a rate of 120 Hz (LC Technologies, Inc., 2009).

A Gossen Starlite 2 light meter was used to guide control for luminance during stimulus design prior to the experiment. Luminance of all images presented on the computer monitor was measured. In order to eliminate the factors influencing allocation
of visual attention, images were manipulated during stimulus design in order to fall into an acceptable range of luminance (measured in candelas per square meter, cd/m²).

The total luminance present in the room was also measured between experimental participants in order to assure constancy throughout the entire experiment. Through this careful stimulus design, luminance was kept constant across participants and conditions, which minimized the effects of influencing factors on the allocation of visual attention.

**Stimuli**

The stimuli in this study were based on items from an experimental eye-tracking test of auditory comprehension, the Multiple Choice Test of Auditory Comprehension (MCTAC), which are currently under development in the Neurolinguistics Laboratory at Ohio University. This test consists of a series of visual displays, presented on a computer screen, and verbal stimuli, which were auditorily presented either via headphones (for non-hearing aid users) or in soundfield (for hearing aids users). Each visual display consists of four pictures; one target item and three foil pictures.

All three visual foils, functioning as distractors, could potentially be used to elicit a similar linguistic structure with the same length, containing similar semantic elements as in its verbal stimulus. For example, in Subtest 1, each verbal stimulus consists of two words with a combination of COLOR and SHAPE (e.g., verbal stimulus–“Black circle”). Each foil on the same visual display could be used to elicit a phrase with a combination of the same semantic categories (e.g., Foil 1–“Black square,” Foil 2–“White circle,” and Foil 3–“White square”). The target and foil pictures occupy the four corners of the visual display; the target items are randomly placed in one of the corners.
The design of nontarget foils numbers entailed manipulation of critical elements in each stimulus. In the example given above, in Foil 1, only the second element, SHAPE, is modified. The first element, COLOR, remains the same as the target item. In Foil 2, the first element, COLOR, is modified, and the second element, SHAPE, remains the same as in the target item. In Foil 3, both elements are modified while maintaining its similarity to Foil 1 and Foil 2.

By utilizing careful and specific visual constructions, timing of breakdown of language comprehension may be associated with the length of phrases or sentences, types of critical elements, and complexity of verbal stimuli. The visual displays were accompanied by verbal stimuli that vary in terms of linguistic levels (phrase and sentence), number of words, number of critical elements, and grammatical complexity.

The MCTAC was developed based on an adaptation of the Revised Token Test by McNeil and Prescott (1978). The MCTAC contains eight subtests comprised of phrases and sentences with increasing length and critical elements. Each subtest in the MCTAC consists of five items; within a subtest, each item has the same number of words and the same type of word categories represented as the critical elements. The critical elements in the MCTAC consist of shapes, modifiers (such as colors and sizes), and spatial concepts.

In Subtest 1, verbal stimuli consist of five 2-word phrases with two critical elements—COLOR + SHAPE (e.g., “Black circle,” “Blue square”). Subtest 2 consists of five 3-word phrases with three critical elements—SIZE + COLOR + SHAPE (e.g., “Big green circle”). Subtest 3 contains five 5-word items; each item entails two 2-word
phrases combined by the conjunction AND, creating verbal stimuli with four critical elements—COLOR + SHAPE “AND” COLOR + SHAPE (e.g., “Green square and black square”).

Subtest 4 contains five 7-word items with each item comprising two 3-word phrases combined by the conjunction AND, creating verbal stimuli with six critical elements—SIZE + COLOR + SHAPE “AND” SIZE + COLOR + SHAPE (e.g., “Big black square and little red circle”). In addition to size, color, and shape, Subtest 5 and Subtest 6 contain spatial concept, such as “by,” “above,” “before,” “next to,” “behind,” “in front of,” “under,” and “below”, while Subtest 7 and Subtest 8 contain spatial concepts “to the left” and “to the right”.

Unlike Subtest 1 to Subtest 4, which consists of short phrases and combinations of phrases, Subtest 5 to Subtest 8 are comprised of grammatical sentences. Subtest 5 consists of five 8- to 9-word sentences with five critical elements—COLOR + SHAPE + LOCATION(1) + COLOR + SHAPE (e.g., “The black square is by the red circle.”).

Subtest 6 consists of five 10- to 12-word sentences with seven critical elements—SIZE + COLOR + SHAPE + LOCATION(1) + SIZE + COLOR + SHAPE (e.g., “The big red square is in front of the big white circle.”).

Subtest 7 contains five 11-word sentences with five critical elements—COLOR + SHAPE + LOCATION(2) + COLOR + SHAPE (e.g., “The black circle is to the left of the white square.”), and Subtest 8 contains five 13-word sentences with seven critical elements—SIZE + COLOR + SHAPE + LOCATION(2) + SIZE + COLOR + SHAPE (e.g., “The little green circle is to the left of the big red square.”).
subtests, verbal stimuli consist of modified phrases and combined phrases by the connector “AND.” By including the spatial concept in Subtest 5 through Subtest 8, verbal stimuli were presented with syntactic elements, such as grammar.

The MCTAC was designed to the level of language comprehension within controlled environment. The stimuli are neutral and free from pragmatic elements that can be found in conversational tasks such as, interest of a topic, knowledge of a topic, emotional factors, and familiarity with the conversational partner. Therefore, holistic aspects in conversational comprehension are not included in the current study.

For the purpose of this study, time course analysis was conducted on eye-tracking data of six out of eight MCTAC subtests. Subtests 5 and 6 were excluded from the current study. These two subtests yielded inconsistent findings across participants with and without aphasia in previous research conducted in the Neurolinguistics Laboratory at Ohio University. Both Subtest 5 and Subtest 6 consist of spatial concepts that are three-dimensional (i.e., “before,” “in front of,” and “behind”), which are difficult to depict in a two dimensional visual display. Table A1 in the Appendix shows the verbal stimuli for each subtest included in the current study, along with the foils in the visual display.

**Procedure**

**Experimental procedures.** Each participant sat in a comfortable chair and looked at the computer screen from a distance of 24-26 inches; a chin rest was offered to participants as an option in order to stabilize the head during the experiment. Because ocular motor deficit such as visual apraxia may be present among participants, all participants are not instructed to perform voluntary action by looking at the correct target
picture. Participants were instructed to “Look at the pictures in any way that comes naturally.”

During the experiment, visual and auditory stimulus items were presented simultaneously. Eye movements on the visual display were recorded from the onset of auditory stimulus until the end of the visual display presentation. Durations of visual display for each trial were calculated according to MCTAC subtests. The visual display duration for a MCTAC subtest is equal to the averaged duration of all five trials within a subtest, multiplied by two, rounded to the nearest second, plus two additional seconds (as proposed by Hallowell et al., 2002; Ivanova & Hallowell, 2012). The two additional seconds allowed an observation of eye movements within a time frame that is well above what is “typical.” By giving participants an ample time frame, any differences between control participants and PwA regarding the time frame of processing can be observed clearly. At the end of visual display, the computer automatically advanced to the next visual display. Recording was discontinued during visual display transitions.

**Data conversion.** The raw eye movement data, recorded during experiments, were converted to the text format in order to allow computation and numerical analyses. Data conversion was conducted using two programs, the iAnalyze and egConvert software. Conversion of raw data was performed for each item in all MCTAC subtests included in the current study. These converted data were documented based on time windows according to MCTAC subtests.

**Dependent measure.** In several previous studies, time-course analysis was conducted on eye-tracking data that include all eye movements (e.g., Allopenna et al.,
For example, in the study by Allopenna and colleagues (1998), eye movements were recorded at a rate of 30 frames per second, which corresponds to duration of 33.3 ms for each frame. The authors observed every single x/y coordinate associated with each frame, and did not base their analyses on actual eye fixations. Thus, the data analyzed included considerable noise, which is not associated with actual information processing.

The noise includes movements of the eyes during the transition from one fixation to another when the eyes were not stable enough for actual uptake of visual information (Ivanova & Hallowell, 2011). Time-course analysis based on raw x/y coordinates does not enable accurate interpretation of processing activity based on eye-tracking findings. The eyes must be stabilized at a point for a duration that is long enough to process visual information. A single fixation required stabilized eye position at a spot on the visual display for at least 100 ms (Hallowell & Lansing, 2004; Hannula & Ranganath, 2009). It was found that previous studies on attention, cognitive processing, and memory (e.g., Blair et al., 2009; Hannula & Ranganath, 2009; Hannula et al., 2007; Ivanova & Hallowell, 2012; Ryan, Hannula, & Cohen, 2007) utilized the proportion of fixations to analyze processing duration.

In the current study, proportion of fixation durations on the target (PFDT) was selected as the dependent variable in order to analyze online comprehension at phrase and sentence levels based on eye-tracking data. PFDT is the highest proportion of time during which the eyes are fixated on the target. PFDT was calculated by dividing the total duration of all fixations on the target with the total duration of all fixations recorded
on the visual display. PFDT is reliable and valid in determining the level of spoken language comprehension as evidenced in previous comprehension studies conducted on adults with and without language impairment (Hallowell, 1999; Hallowell et al., 2002; Ivanova & Hallowell, 2012).

In previous experiments in the Neurolinguistics Laboratory at Ohio University, PFDT had been calculated and correlated with data collected during the pointing task (Hallowell et al., 2002). In the pointing task, participants were required to perform physical activity by pointing to one out of four pictures presented on each visual display based on the verbal stimuli presented auditorily. Significant correlations were found between eye-tracking data and data from the experimental pointing method for PwA and control groups, even though PwA have lower correlations than the control group, and several PwA exhibited dissociations between pointing and eye-tracking tasks (Hallowell et al., 2002; Ivanova & Hallowell, 2012).

Eye-tracking data were found valid and reliable to differentiate performances by PwA and participants in the control group. According to Hallowell et al. (2002), typical auditory comprehension of words and phrases is accomplished within about twice the duration of the verbal stimulus. In previous studies conducted in the Neurolinguistics Laboratory at Ohio University, visual displays in each subtest of the MCTAC were presented within a predetermined length of time.

**Time windows.** PFDT was used to analyze data in each of the time windows expanded in 200 ms increments; 0 ms to 200 ms, 0 ms to 400 ms, 0 ms to 600 ms, and so
on for each stimulus, starting from the onset of the stimulus and continuing until the offset of the verbal stimulus, as depicted in Table 1.

Table 1

Duration of Time Windows for Analysis

<table>
<thead>
<tr>
<th>Time window</th>
<th>Duration included in analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>0-200 ms</td>
</tr>
<tr>
<td>T2</td>
<td>0-400 ms</td>
</tr>
<tr>
<td>T3</td>
<td>0-600 ms</td>
</tr>
<tr>
<td>T4</td>
<td>0-800 ms</td>
</tr>
<tr>
<td>T5</td>
<td>0-1000 ms</td>
</tr>
<tr>
<td>:</td>
<td>:</td>
</tr>
<tr>
<td>:</td>
<td>:</td>
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<tr>
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<tr>
<td>:</td>
<td>:</td>
</tr>
<tr>
<td>:</td>
<td>:</td>
</tr>
<tr>
<td>T50</td>
<td>0-10000 ms</td>
</tr>
</tbody>
</table>

Although the first time window (0-200 ms) is very brief, earlier studies had demonstrated that word recognition could occur as early as 150 ms after the onset of the stimulus (Mirman & Magnuson, 2009). A saccade and its subsequent eye fixation also require at least 200 ms to occur (Hallowell & Lansing, 2004). In the current study, data were analyzed within the time windows that were divided incrementally (e.g., 0-200 ms, 0-400 ms, 0-600 ms and so on), rather than successively (e.g., 0-200 ms, 200-400 ms, 400-600 ms and so on), because occurrence of eye fixations require at least 100 ms

If data are analyzed based on successive time windows, some data might be missed because parts of a fixation may take place in different time windows. In addition,
initial eye fixation could also be influenced by random factors other than word processing (Mirman & Magnuson, 2009). By analyzing data continuously, eye fixations occurring throughout the presentation of a stimulus were taken into account and the pattern of fixations on the target could be documented.

**Data cleaning and data analyses.** Before performing data analyses, data cleaning was conducted by deleting “bad data.” Two percent of data were deleted by experimenters based on their observations of participants’ eye movements. Data for a given trial were eliminated due to participants’ failure to fixate on the display, the lack of eye stability in meeting fixation criteria, or evidence of poor calibration for more than 50% of that trial. Data were excluded from data analyses in order to maintain data validity and reliability. The data cleaning process was performed before the analyses for both hypotheses.

Data analyses were performed to answer research hypotheses by using the PASW Statistics version 18 and version 20 (IBM Corporation, 2011). Descriptive analyses and independent-samples t-tests were conducted on demographic data. Because each MCTAC subtest consists of five trials, mean PFDT was calculated according to MCTAC subtests based on different time windows for each group. Pearson’s correlation analyses were conducted to compare the time window with the maximum mean PFDT for each MCTAC subtest and WAB-R AC total score of PwA. Bar graphs were also created using the PASW software.

For Hypothesis 1, bar graphs were created for PwA group and control group based on mean PFDT values at each time window. In order to compare language
comprehension indices between the two groups, PwA data shown include eye-tracking trials that corresponded to the correct responses in the MCTAC pointing version. In the MCTAC pointing version, participants’ language comprehension was assessed based on their ability to point to the target picture; while in the MCTAC eye-tracking version, participants were not instructed to intentionally engage in responses to indicate their ability to understand the verbal stimuli. Previous studies (e.g., Hallowell et al., 2002) demonstrated significant correlations between MCTAC pointing and eye-tracking versions following this method.

The highest mean PFDT was identified for every MCTAC subtest for each group. Time windows with the highest mean PFDT were compared between groups. Patterns of mean PFDT increments across time windows were also compared between PwA and control groups for every MCTAC subtest. Individual mean PFDT patterns were also created for all participants in both groups according MCTAC subtests. These individual mean PFDT patterns were qualitatively compared to the control group pattern by looking at differences of the mean PFDT slope.

Because individual variations are common among people with aphasia despite type of aphasia or specific symptoms, assessment must take into account individual variability (Caramazza et al., 2001; Light, 1999). According to Light (1999), analyses of individual data could validate the findings at the group level and could be used to determine the clinical significance of a study. Therefore, individual qualitative analyses were conducted on mean PFDT patterns to obtain information that could support or explain findings at the group level.
To address Hypothesis 2, Pearson’s correlation analyses were conducted to compare PwA performance in the WAB-R AC and the MCTAC eye-tracking version. For these analyses, participants’ WAB-R AC total scores were compared to the time windows with the highest mean PFDT. Because scores for WAB-R AC were derived from correct and error responses, mean PFDT was calculated using data that include all trials in the eye-tracking version (including trials corresponding to correct and incorrect responses in the MCTAC pointing version). Pearson’s correlation analyses were conducted according to MCTAC subtests included in the study. Patterns of mean PFDT across time windows were also observed individually for each participant according to their WAB-R AC total scores.
Chapter 4: Results

Descriptive Analysis of Demographic Data

As described earlier in the Method section, the current study involved data that were gathered from a total of 80 participants; 40 participants were individuals without language impairment, acting as the control group, while 40 others were people with aphasia, known as the PwA group. Demographic data of participants in these two groups are summarized in Table 2.

Table 2

*Background Information of Participants in the Participants with Aphasia and Control Groups*

<table>
<thead>
<tr>
<th>Background Information</th>
<th>PwA</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>24-82</td>
<td>23-88</td>
</tr>
<tr>
<td>Mean</td>
<td>55.65</td>
<td>52.68</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>13.55</td>
<td>19.51</td>
</tr>
<tr>
<td>Education (years)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>12-23</td>
<td>12-23</td>
</tr>
<tr>
<td>Mean</td>
<td>16.67</td>
<td>17.25</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>3.09</td>
<td>3.02</td>
</tr>
<tr>
<td>Gender</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>n = 25 (62.5%)</td>
<td>n = 16 (40%)</td>
</tr>
<tr>
<td>Female</td>
<td>n = 15 (37.5%)</td>
<td>n= 24 (60%)</td>
</tr>
<tr>
<td>Race</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caucasian</td>
<td>n = 32 (80%)</td>
<td>n = 40 (100%)</td>
</tr>
<tr>
<td>African American</td>
<td>n = 8 (20%)</td>
<td>n = 0 (0%)</td>
</tr>
</tbody>
</table>
Independent-samples t-tests were conducted to compare the means between the control group and PwA on two variables: age of participants and years of education. There were no significant differences between groups according to age of participants ($t[78] = -0.792; p = 0.431$) or years of education ($t[78] = 0.841; p = 0.403$).

**Additional background information of participants with aphasia.** CT scans or MRI results verifying presence of brain damage secondary to stroke in the left hemisphere at least one month post-onset were documented for participants with aphasia (PwA). All participants in the PwA group demonstrated characteristics of aphasia, which were diagnosed and verified by at least two SLPs. Detailed background information of PwA can be found in Table A2 in Appendix, which includes time post-onset, type of aphasia, and WAB-R Auditory Comprehension scores.

The average number of years for post-stroke duration of PwA is 6.33 years (standard deviation of 6.31, range from 1 year to 26 years post-stroke). The types of aphasia were determined by participants’ WAB-R performance (Kertesz, 2007). PwA in the current study consist of individuals with anomic aphasia ($n = 22$), Broca’s aphasia ($n = 9$), conduction aphasia ($n = 6$), conduction/anomic aphasia ($n = 2$), and Broca’s/transcortical motor aphasia ($n = 1$). PwA demonstrated mean WAB-R AC total scores of 167.65 (standard deviation of 35.76, range from 42 to 200). PwA also exhibited mean WAB-R AC standard scores of 8.54 (with standard deviation of 1.45, range from 4.2 to 10).
Data Analysis and Outcomes: Hypothesis 1

In Hypothesis 1, we have posited that PwA would reach the maximum PFDT at a later time window, as compared to the control group. As mentioned earlier, the trials corresponding to the incorrect responses in the MCTAC pointing version were excluded from PwA data. The number and percentages of the incorrect responses in the MCTAC pointing version from 40 PwA are summarized in Table 3 according to MCTAC subtests.

Table 3

Percentages and Total Number of Incorrect Response in Multiple Choice Test of Auditory Comprehension Pointing Version

<table>
<thead>
<tr>
<th>MCTAC Subtest</th>
<th>Incorrect responses in MCTAC pointing version according to test item</th>
<th>Percentages and total number of incorrect responses in MCTAC pointing version according to subtest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtest 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Item 1</td>
<td>7 (n = 40)</td>
<td>14.0% (28)</td>
</tr>
<tr>
<td>Item 2</td>
<td>3 (n = 40)</td>
<td></td>
</tr>
<tr>
<td>Item 3</td>
<td>6 (n = 40)</td>
<td></td>
</tr>
<tr>
<td>Item 4</td>
<td>5 (n = 40)</td>
<td></td>
</tr>
<tr>
<td>Item 5</td>
<td>7 (n = 40)</td>
<td></td>
</tr>
<tr>
<td>Subtest 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Item 1</td>
<td>7 (n = 40)</td>
<td>19.0% (38)</td>
</tr>
<tr>
<td>Item 2</td>
<td>8 (n = 40)</td>
<td></td>
</tr>
<tr>
<td>Item 3</td>
<td>8 (n = 40)</td>
<td></td>
</tr>
<tr>
<td>Item 4</td>
<td>5 (n = 40)</td>
<td></td>
</tr>
<tr>
<td>Item 5</td>
<td>10 (n = 40)</td>
<td></td>
</tr>
<tr>
<td>Subtest 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Item 1</td>
<td>11 (n = 40)</td>
<td>23.0% (46)</td>
</tr>
<tr>
<td>Item 2</td>
<td>13 (n = 40)</td>
<td></td>
</tr>
<tr>
<td>Item 3</td>
<td>7 (n = 40)</td>
<td></td>
</tr>
<tr>
<td>Item 4</td>
<td>7 (n = 40)</td>
<td></td>
</tr>
<tr>
<td>Item 5</td>
<td>8 (n = 40)</td>
<td></td>
</tr>
</tbody>
</table>
Mean PFDT for every time window for each group was calculated according to each MCTAC subtest. In Figure 1, bar graphs of mean PFDT for each time window are shown for each MCTAC subtest, comparing the findings for control group and PwA group. For each MCTAC subtest, the maximum mean PFDT was found at the final time window for both control group and PwA group. In addition to the maximum mean PFDT of each subtest, the slope of mean PFDT values over time was analyzed based on visual inspection; the slopes were not tested statistically.
Figure 1. Comparisons of mean proportion of fixation duration on the target for control group and participants with aphasia group according to Multiple Choice Test of Auditory Comprehension subtests.
Figure 1 (continued). Comparisons of mean proportion of fixation duration on the target for control group and participants with aphasia group according to Multiple Choice Test of Auditory Comprehension subtests.
Figure 1 (continued). Comparisons of mean proportion of fixation duration on the target for control group and participants with aphasia group according to Multiple Choice Test of Auditory Comprehension subtests. Bar graphs in each group indicate mean PFDT according to time windows with 200 ms increment. For PwA, analyses were only conducted on data corresponding to the correct trials in the pointing version of the MCTAC. The black lines at the bottom left of the bar graphs indicate average durations of verbal stimuli according to subtests (Subtest 1, $T = 983.8$ ms; Subtest 2, $T = 1318.0$ ms; Subtest 3, $T = 1994.2$ ms; Subtest 4, $T = 2811.2$ ms; Subtest 7, $T = 2982.4$ ms; and Subtest 8, $T = 3636.0$ ms). The duration of each verbal stimulus and the averaged duration for each subtest, stated as $T'$, are included in Appendix (Table A1).
Based on visual inspection, the control group demonstrated a rapid increase of mean PFDT after the completion of verbal stimuli for Subtest 1 and Subtest 2. In Subtest 3, Subtest 4, Subtest 7, and Subtest 8, the rapid increase of mean PFDT started before the verbal stimuli were even completed (these patterns are referred as the control pattern). The rapid increase of mean PFDT continued until the end of visual display for all MCTAC subtests.

PwA group also demonstrated increments of mean PFDT values across time windows. Although PwA demonstrated similarity of mean PFDT patterns (as compared to the control group) for Subtest 1 and Subtest 2, rapid increments of mean PFDT at the completion of verbal stimuli seemed to be less robust compared to the control patterns. In Subtest 3, Subtest 4, Subtest 7, and Subtest 8, mean PFDT increments seemed to be more subtle; no noticeable differences between mean PFDT in one time window and mean PFDT in the subsequent time window were observed at the completion of verbal stimuli.

In addition to the group comparison, the highest mean PFDT and the slopes of mean PFDT values across time windows were examined based on individual data. When data were examined individually, several mean PFDT patterns were found in addition to the patterns demonstrated by the control group. Examples for these patterns are shown in Figure 2. The slopes of mean PFDT across time windows were generated and individually examined for all participants in both groups according to the MCTAC subtests. Additional individual patterns that differed from the control pattern were observed visually; these slopes were also not statistically analyzed.
Figure 2. Examples of individual patterns for mean proportion of fixation duration on the target values across time windows. Above are the examples of Pattern A and Pattern B for PwA and control group. Although the Pattern A and Pattern B were generated using individual data for Subtest 1, the pattern was found across all MCTAC subtests in both groups. The black lines at the bottom left of the bar graphs indicate average durations of verbal stimuli.
Figure 2 (continued). Examples of individual patterns for mean proportion of fixation duration on the target values across time windows. Above are the examples of Pattern C and Pattern D for both groups. Participants IDs and the MCTAC subtests were indicated at the bottom of the graphs. The black lines at the bottom left of the bar graphs indicate average durations of verbal stimuli.
For participants with the highest mean PFDT in the final time window, two additional patterns were found for both control group and PwA group: (a) a rapid decline of mean PFDT value before rapid value increments near or after the completion of verbal stimuli to the highest mean PFDT at the final time window (Pattern A; see Figure 2) and (b) a gradual increment of mean PFDT without rapid increments of mean PFDT near or after the completion of verbal stimuli (Pattern B; see Figure 2).
Not all participants exhibited maximum mean PFDT at the final time window. In two patterns, participants demonstrated the maximum mean PFDT after the completion of verbal stimuli but not in the final time window. In Pattern C, a gradual decrease of mean PFDT values towards the final time window after reaching the maximum mean PFDT was observed (see Figure 2). In Pattern D, the highest mean PFDT was followed by a gradual decrease of mean PFDT value and an increment of the values toward the final time window (see Figure 2).

Several participants also demonstrated the highest mean PFDT in time windows before the completion of verbal stimuli. For all control participants and several PwA who demonstrated this pattern, the highest mean PFDT before completion of verbal stimuli were followed by a decrease of mean PFDT values before an increment toward the final time window, where mean PFDT values are close to the highest mean PFDT value observed in the earlier time windows (Pattern E; see Figure 2).

Other PwA, who demonstrated a maximum mean PFDT before the completion of verbal stimuli, exhibited a decrease of mean PFDT after the highest value and a plateau trend toward the end of visual display (Pattern F; see Figure 2). Pattern F was demonstrated exclusively by the PwA and not by any control participant. In addition to the examples of additional mean PFDT patterns, the number of participants exhibiting each pattern for control and PwA groups was also summarized in Table 4.
Table 4

The Number of Participants Exhibiting Mean Proportion of Fixation Duration on the Target Patterns According to Groups

Mean PFDT patterns across time windows

<table>
<thead>
<tr>
<th>MCTAC Subtest</th>
<th>PwA</th>
<th>C</th>
<th>PwA</th>
<th>C</th>
<th>PwA</th>
<th>C</th>
<th>PwA</th>
<th>C</th>
<th>PwA</th>
<th>C</th>
<th>PwA</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtest 1</td>
<td>14</td>
<td>17</td>
<td>11</td>
<td>18</td>
<td>7</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Subtest 2</td>
<td>9</td>
<td>16</td>
<td>9</td>
<td>18</td>
<td>10</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Subtest 3</td>
<td>5</td>
<td>13</td>
<td>8</td>
<td>23</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>0</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Subtest 4</td>
<td>8</td>
<td>14</td>
<td>8</td>
<td>18</td>
<td>6</td>
<td>3</td>
<td>6</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Subtest 7</td>
<td>7</td>
<td>15</td>
<td>9</td>
<td>18</td>
<td>8</td>
<td>3</td>
<td>6</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Subtest 8</td>
<td>4</td>
<td>6</td>
<td>7</td>
<td>27</td>
<td>5</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>47</td>
<td>81</td>
<td>52</td>
<td>122</td>
<td>43</td>
<td>14</td>
<td>26</td>
<td>16</td>
<td>14</td>
<td>2</td>
<td>12</td>
<td>4</td>
</tr>
</tbody>
</table>

Note. PwA–Aphasia group, C–Control group.
A total of 240 mean PFDT patterns were observed for the control group and 233 mean PFDT patterns were observed for PwA group. In the PwA group, mean PFDT patterns could not be observed for seven participants due to the exclusion of their incorrect responses in the MCTAC pointing version. These five participants provided incorrect responses for all trials in a MCTAC subtest (a participant for Subtest 3 and four participants for Subtest 8. Only Participant A11 provided incorrect responses for all trials in two subtests (Subtest 1 and Subtest 7).

For the control group, 50.83% of control participants demonstrated Pattern A and 33.75% control participants demonstrated mean PFDT patterns that were similar to the control group patterns. For the PwA group, Pattern A is also the most demonstrated mean PFDT pattern (exhibited by 22.32% of PwA), followed by mean PFDT patterns similar to the control group pattern (20.17%). Although none of the control participant demonstrated Pattern F, 16.31% of the PwA demonstrated this particular pattern.

Data Analysis and Outcomes: Hypothesis 2

In Hypothesis 2, we predicted that PwA with higher scores in the WAB-R AC would reach maximum PFDT at an earlier time window for each MCTAC subtest. It was anticipated that PwA with a higher WAB-R AC score would reach maximum PFDT earlier; thus, a negative correlation was predicted. In addressing Hypothesis 2, analyses were conducted only on PwA data, where comparisons were made between performance of PwA based on MCTAC eye-tracking version and WAB-R AC. As mentioned earlier, analyses were based on all eye-tracking data from PwA including data that corresponded to incorrect trials for the MCTAC pointing version.
After determining the time windows that contain the highest mean PFDT for all MCTAC subtests, mean values and standard deviations of time window which contain the maximum PFDT for every subtest were calculated. Correlation analyses were performed between the WAB-R AC total score for each participant and the time window where the participant demonstrated with highest mean PFDT. Means and standard deviations of time window with the maximum PFDT and Pearson’s correlation coefficient between the WAB-R AC total score and the time window with the maximum PFDT are shown in Table 5 according to MCTAC subtests.

Table 5

<table>
<thead>
<tr>
<th>MCTAC subtest</th>
<th>Mean and standard deviation for time windows with highest mean PFDT</th>
<th>Pearson’s correlation coefficient of WAB-R AC total scores and time windows with highest mean PFDT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtest 1</td>
<td>16.93 (5.10)</td>
<td>0.442** (0.004)</td>
</tr>
<tr>
<td>Subtest 2</td>
<td>18.18 (9.68)</td>
<td>0.650** (0.001)</td>
</tr>
<tr>
<td>Subtest 3</td>
<td>17.63 (12.51)</td>
<td>0.554** (0.001)</td>
</tr>
<tr>
<td>Subtest 4</td>
<td>29.20 (15.33)</td>
<td>0.430** (0.006)</td>
</tr>
<tr>
<td>Subtest 7</td>
<td>27.53 (15.69)</td>
<td>0.475** (0.002)</td>
</tr>
<tr>
<td>Subtest 8</td>
<td>21.38 (17.43)</td>
<td>0.034 (0.835)</td>
</tr>
</tbody>
</table>

Note. (**) indicates significant level, p<0.01.

Significant positive correlations, between WAB-R AC total score and the time window with maximum PFDT were found for all MCTAC subtests for data that include the incorrect responses in the MCTAC pointing version, except for Subtest 8. In post hoc
analyses, patterns of increment or decrease of mean PFDT across time windows were qualitatively and individually compared as WAB-R AC total scores increased.

According to Kertesz (2007), the WAB-R AC mean standard score is 5.7 with a standard deviation of 2.9. As stated earlier, PwA in the current study have WAB-R AC standard scores ranging between 4.2 and 10 with 50% of participants (n = 20) having scores at above +1 standard deviation (according to WAB-R). Therefore, different patterns of mean PFDT values were observed and compared against the WAB-R AC total score (rather than the standard score).

WAB-R AC total scores were calculated based on participants’ raw data, which all of the responses demonstrated by participants during the test. Several examples of the patterns are displayed in Figure 3 according to MCTAC subtests. Individual patterns of mean PFDT values were also compared to the trend of mean PFDT showed by the control group (control pattern), as discussed earlier for Hypothesis 1. In order to allow comparisons of mean PFDT patterns with the mean PFDT trends by control group, the bar graphs in Figure 3 were generated using data that include the incorrect responses in the MCTAC pointing version.

Based on observations of mean PFDT across time windows for each PwA, most PwA were found to reach the maximum mean PFDT at the final time window; many PwA with lower WAB-R AC total scores demonstrated the maximum mean PFDT at the final time window with lower mean PFDT values as compared to PwA with higher WAB-R AC scores. Although many PwA with higher WAB-R AC total scores demonstrated mean PFDT patterns across time windows that are similar to the trends
found in the control group (e.g., in Figure 3, bar graph from participant A09 in Subtest 1, participant A33 in Subtest 2, and participant A16 in Subtest 8), PwA with high WAB-R AC total scores also demonstrated other individual patterns that have been discussed earlier (e.g., in Figure 3, bar graphs from participant A33 in Subtest 1, participant A24 from Subtest 3, and participant A24 in Subtest 8).

As described earlier in Hypothesis 1, several PwA demonstrated a maximum mean PFDT at the first time window or several time windows before verbal stimuli were completed. In the example shown in Figure 3, participant A10, who has a WAB-R AC total score of 172 and a standard score of 8.6, demonstrated the time window with a maximum mean PFDT value at time window 3 before exhibiting decreased values towards the final time window in Subtest 3.

Maximum mean PFDT values at the first time window or several time windows before verbal stimuli were completed were demonstrated not only by PwA with low WAB-R AC total score, but also PwA with high WAB-R AC total scores; however, PwA with WAB-R AC total score of 168 and above demonstrated maximum mean PFDT values at the first time window or several time windows before the completion of verbal stimuli in two subtests or lesser, while PwA with WAB-R AC total score below 168 demonstrated maximum mean PFDT values at the first time window or several time windows before the completion of verbal stimuli in at least two MCTAC subtests. None of the PwA demonstrated maximum mean PFDT values at the first time window or during the time windows before verbal stimuli were completed in all MCTAC subtests.
**Subtest 1**

- Control group
- Participant A38 (WAB-R AC total score=42)
- Participant A11 (WAB-R AC total score=102)
- Participant A09 (WAB-R AC total score=192)
- Participant A24 (WAB-R AC total score=200)
- Participant A33 (WAB-R AC total score=200)

*Figure 3.* Patterns of mean proportion of fixation duration on the target across time for individual participants with aphasia according to Multiple Choice Test of Auditory Comprehension subtests.
Subtest 2

Control group

Participant A38
(WAB-R AC total score=42)

Participant A11
(WAB-R AC total score=102)

Participant A41
(WAB-R AC total score=171)

Participant A24
(WAB-R AC total score=200)

Participant A33
(WAB-R AC total score=200)

Figure 3 (continued). Patterns of mean proportion of fixation duration on the target across time for individual participants with aphasia according to Multiple Choice Test of Auditory Comprehension subtests.
Subtest 3

Control group

Participant A38
(WAB-R AC total score=42)

Participant A10
(WAB-R AC total score=172)

Participant A16
(WAB-R AC total score=198)

Participant A24
(WAB-R AC total score=200)

Participant A33
(WAB-R AC total score=200)

Figure 3 (continued). Patterns of mean proportion of fixation duration on the target across time for individual participants with aphasia according to Multiple Choice Test of Auditory Comprehension subtests.
Figure 3 (continued). Patterns of mean proportion of fixation duration on the target across time for individual participants with aphasia according to Multiple Choice Test of Auditory Comprehension subtests.
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Figure 3 (continued). Patterns of mean proportion of fixation duration on the target across time for individual participants with aphasia according to Multiple Choice Test of Auditory Comprehension subtests. The graphs are arranged horizontally according to participants’ WAB-R AC total scores.
Chapter 5: Discussion

Between-Group Comparisons of Mean Proportion of Fixation Duration on the Target Values and Patterns

To compare language comprehension ability as indexed by PFDT between the control and PwA groups, PwA data only included trials that corresponded with the correct responses in the pointing MCTAC. An increase in the number of excluded items across MCTAC subtests, based on the corresponding incorrect responses in the MCTAC pointing version, is likely to be due to the increased length and complexity across subtests. The difficulty to comprehend language increases among individuals with aphasia as the auditory input gets longer and more grammatical elements are embedded in the stimuli (Altmann & Kamide, 1999; Chambers et al., 2002).

In a formal assessment, such as the traditional MCTAC, participants are commonly given several seconds after the end of a language stimulus to point at one of the images on a visual display. The pressure to comprehend and respond to language stimuli within a limited time frame may increase participants’ responses to incorrect images, especially when participants are presented with longer and more complex sentences.

Group level. In the current study, maximum mean PFDT for control and PwA groups were identified at the final time window for all MCTAC subtests. Although both groups demonstrated the maximum mean PFDT at the final time window, qualitative differences regarding patterns of mean PFDT over time windows were observed between control and PwA.
Overall results support the use of visual display durations as prescribed by Hallowell and colleagues (2002) to capture comprehension indices for participants with and without aphasia. Trial durations utilized in the current study are long enough to enable people with aphasia to attend to the visual items and comprehend (if possible) the verbal stimuli, but not too long to induce boredom or attention loss in control participants.

Continuation of mean PFDT increments and the occurrence of the highest mean PFDT in the final time window support the conclusion made by Shapiro et al. (2003). Following their study, Shapiro and colleagues (2003) concluded that linguistic stimuli were continuously processed to reach final interpretation. In the current study, continuous increments of mean PFDT across presentation of verbal stimuli and after the offset of the verbal stimuli indicated that participants comprehended the verbal stimuli.

The lower value of mean PFDT in the earlier time windows might be due to scanning of the presented images on the visual display while processing the linguistic input. Language processing was found to occur not only at the ending of the linguistic input, but also at word and phrasal levels to reach the final interpretation (Altmann & Kamide, 1999; Altmann & Steedman, 1988). Continuous increments of mean PFDT towards the final time window might indicate the process of matching the verbal stimuli to a specific target image and locking of the selection based on the linguistic input.

As mentioned earlier, increments of mean PFDT were observed to be more rapid in the control group compared to PwA. The start of rapid increments of mean PFDT in the control group can be observed at the completion of verbal stimuli for Subtest 1 and
Subtest 2, and even before the completion of verbal stimuli for Subtest 3, Subtest 4, Subtest 7 and Subtest 8. Although the duration of verbal stimuli increases across MCTAC subtests (Subtest 1 consists of shortest verbal stimuli and Subtest 8 consists of the longest verbal stimuli), the control group demonstrated rapid changes of mean PFDT value at a relatively earlier point when presented with longer verbal stimuli.

In a study by Chambers et al. (2002), sentences were reported to be processed incrementally based on phrasal constraint, whereby the information provided by an earlier phrase predicts the following information. In the current study, Subtest 1 and Subtest 2 consist of a single noun phrase in each trial. Although the number of critical elements is increased from two elements (in Subtest 1) to three elements (in Subtest 2) and the feature of the images on each visual display is systematically manipulated to discriminate target from foil images, an individual still must listen to the entire verbal stimulus to identify the matching image. Starting from Subtest 3, phrase combinations in each trial lead to a constraint by the first phrase. For example in Subtest 3, when a participant is presented with the verbal stimuli “GREEN SQUARE and BLACK CIRCLE”, the first phrase “GREEN SQUARE” reduces participant’s choice from four images to two images, the target image and Foil 2 (designed to elicit “Green square and RED SQUARE”). The first word of the following phrase could be used to determine the correct target image based on the verbal stimulus. Participants might have differentiated the target based on the earlier phrase.

In addition, individuals without language impairment tend to predict the ending of a sentence after listening to the verb (Altmann & Kamide, 1999) or the spatial concept
(Chambers et al., 2002), thus, reducing the time required to understand a sentence. In the current study, Subtest 7 and Subtest 8 consist of the “left-right” concept. In an example from Subtest 7, an individual presented auditorily with a stimulus such as, “The BLACK CIRCLE is to the LEFT of the WHITE SQUARE,” could reduce the choice between the target image and the foil that may elicit “The black square is to the left of the RED square.” The first word that follows the spatial concept could discriminate the target from the foil image.

While the control group demonstrated earlier rapid increments at later subtests, PwA demonstrated rapid increments of mean PFDT only in Subtest 1 and Subtest 2. The increments of mean PFDT were more gradual in later subtests, which might indicate difficulties to comprehend sentences with increasing length and complexity. As the number of words in a sentence increases, duration to comprehend the input of spoken language also increases.

For the first hypothesis, we posited that mean PFDT would decrease after participants reached the maximum value, which could be due to low arousal during prolonged monotonous activity (Malkovsky, Merrifield, Goldberg, & Danckert, 2012); however, this trend was not seen in the current study. The existing data were gathered from experiments utilizing the pre-set duration where participants were presented with visual stimuli for twice the duration of the verbal stimuli plus two additional seconds and rounded up to the nearest whole second to allow extra processing time for individuals with aphasia (Hallowell et al., 2002; Ivanova & Hallowell, 2012). Although different time windows with the highest mean PFDT between groups were not seen, mean PFDT
patterns could still be utilized to track comprehension ability among people with and without aphasia.

**Individual level.** Based on individual data, not all participants in both groups reached the highest mean PFDT at the final time window. In contrast to the lower number of control participants who reached the highest mean PFDT before the final time window (a total of 22 out of 240 slopes for all MCTAC subtests), the number of PwA reaching the maximum mean PFDT before the final time window (90 out of 233 slopes) was relatively high. In addition, more than half of these PwA (55.56%) exhibited the highest mean PFDT at time windows before the completion of verbal stimuli, while in the control group, only four participants demonstrated the highest mean PFDT at time windows before the verbal stimuli were completed.

The results showed a greater variation of responses among people with aphasia as compared to individuals without language impairment in completing language comprehension tasks. The severity of language impairment for individuals with aphasia varies depending on individuals’ specific language skills and tasks (Johnson & Cannizzaro, 2009). Individual variations among participants with aphasia may elicit higher variability of responses in the current study as compared to control participants.

It is also important to take into consideration the non-linguistic factors, including memory and attention that might have some influence in language comprehension (Ivanova & Hallowell, 2012; Sung et al., 2009). Individuals with aphasia have greater distraction of visual attention toward competing images that are not consistent with the meanings of auditory input, thus, reducing their attention to target images especially in
longer and more complex sentences (Dickey, Choy, & Thompson, 2007; Heuer & Hallowell, 2012).

In addition to group data analyses, individual analyses of mean PFDT values were conducted on individual basis in order to explore the different trends of mean PFDT patterns. Qualitative case-by-case analysis might provide important information about the individual capacity and detailed comprehension ability of each participant (Damico, Simmons-Mackie, Oelschlaegers, Elman, & Armstrong, 1999; Tetnowski & Franklin, 2003). Variability of performance among individuals with aphasia might have significant effects on the findings of the study (Caramazza et al., 2001; Johnson & Cannizzaro, 2009).

As discussed earlier, when individually observed over time, six variations of mean PFDT pattern that differed from the control pattern were found, including a decline of mean PFDT at earlier time windows before a rapid increase at the completion of verbal stimuli, a gradual increase of mean PFDT across time without a rapid change at the completion of verbal stimuli, and the occurrence of the highest mean PFDT at time windows other than the final time window. In the control group, the individual mean PFDT patterns are more predictable than the PwA group. For example, control participants who demonstrated a specific pattern in a MCTAC subtest might exhibit a similar pattern in another subtest; however, most PwA usually exhibited different patterns across MCTAC subtests.

Five of the patterns generated from individual data (Pattern A, B, C, D, and E) were observed among participants from both the control and PwA groups, while Pattern F
was generated only from PwA data. Although these patterns differed from the control pattern (the pattern most typically demonstrated by the control group), it is difficult to determine the significance of these different patterns without any statistical analyses. A pattern similar to the control pattern can easily be mistaken for another pattern such as Pattern B (which show a gradual change across time) if the increments of mean PFDT value seemed less robust. However, if statistically tested, mean PFDT shifts over time and the level of mean PFDT value might demonstrate significant differences.

When data were observed at the group level, combining these patterns may lead to the lack of robustness of mean PFDT increments especially for the PwA group. Further exploration is needed to determine the factors that might affect patterns variation among participants. Analyses based on time windows of incrementally increased durations may be useful to index auditory comprehension by statistically comparing mean PFDT slopes and mean PFDT values to the control group.

**Comparisons of Mean Proportion of Fixation Duration on the Target Values and Patterns According to Western Aphasia Battery-Revised Scores**

The second hypothesis was that PwA with higher WAB-R AC scores would reach the maximum mean PFDT earlier than PwA with lower WAB-R AC scores. A negative correlation between the WAB-R AC scores and the time window was expected for every MCTAC subtest. Correlation analyses were performed between WAB-R AC total scores and PwA data that include trials corresponding with incorrect answers based on the traditional pointing version of MCTAC.
Significant positive correlations were found between the WAB-R AC total score and the time window with maximum PFDT for all MCTAC subtests included in the current study except for Subtest 8, when analyses were performed on data that include incorrect responses in MCTAC pointing version. For Hypothesis 2, we expected a negative correlation for each MCTAC subtest because individuals with better comprehension levels were found to comprehend auditory input more quickly compared to individuals with lower comprehension ability (Kertesz, 2007). In the current study, maximum mean PFDT mostly occurred in the final time window even among control participants. PWA with higher WAB-R AC total score might demonstrate maximum mean PFDT at the final time window, thus, influencing the positive correlations, where individuals with higher WAB-R AC total score reached the highest mean PFDT at later time windows compared to individuals with lower WAB-R AC total score.

The MCTAC was designed to tap varied levels of difficulty of language stimuli across subtests. The non-significant correlation for Subtest 8 might indicate similar performance among PwA regardless their WAB-R AC scores. Because Subtest 8 consists of the longest stimuli, the highest number of critical elements, and the greatest grammatical complexity, PwA with low or high WAB-R AC total scores may have difficulty understanding the stimuli as compared to the earlier subtests. The difficulties faced by PwA in Subtest 8 could have also been affected by cognitive factors, such as increased distractions to the multiple elements and grammatical aspects (Dickey, Choy, & Thompson, 2007; Heuer & Hallowell, 2012) that could affect their comprehension.
ability. Therefore, time windows with the highest mean PFDT may vary among participants, regardless their total WAB-R AC scores.

When individual mean PFDT patterns were observed for each MCTAC subtest, the number of PwA demonstrating the highest mean PFDT at the final time window decreased across MCTAC subtests. Exclusively for Subtest 8, the number of participants demonstrating mean PFDT patterns (as described earlier) was found to be similar with the highest number of PwA demonstrating Pattern F. These findings further support the variability of PwA performance in Subtest 8 despite different levels of WAB-R AC total scores.

In addition, individual mean PFDT patterns among PwA could not be predicted based on their WAB-R AC total scores. As described earlier, one of the trends demonstrated by PwA is the occurrence of the maximum mean PFDT at time windows before the completion of verbal stimuli that increased across MCTAC subtests (Pattern E and Pattern F). Comparing to their WAB-R AC total scores, the number of PwA with WAB-R AC total score of 168 and above demonstrating the maximum mean PFDT before the completion of verbal stimuli is low. In contrast, PwA with WAB-R AC total score below 168 demonstrated maximum mean PFDT at the time window before the completion of verbal stimuli in at least two MCTAC subtests. These findings may imply that the PwA with lower WAB-R AC scores tend to demonstrate the highest mean PFDT at a time window before the verbal stimuli were even completed. On the contrary, PwA with higher WAB-R AC scores often reached maximum mean PFDT at the final time window similarly to the pattern demonstrated by the control group.
Because the WAB-R AC subtest was designed to determine the degree of language comprehension ability, the findings may suggest that the gap of performance in language comprehension tasks could increase as the participants’ scores decrease. Nevertheless, it is important to consider non-linguistic factors embedded in the WAB-R and the MCTAC procedures, such as presentation of tasks and types of required responses that could induce the performance gap between individuals with aphasia across various degree of impairment severity.

Different language activity, assessment tasks, and required responses in WAB-R AC and MCTAC might influence language comprehension performance among PwA. For the WAB-R AC, participants are required to respond to three different tasks; Yes-No questions, word recognitions, and verbal commands. The MCTAC involves the identification of images based on verbal stimuli. Among the three tasks in WAB-R AC, Word Recognition component is the most similar to the MCTAC; however, the Word Recognition component includes different vocabulary types (e.g., nouns, verbs, prepositions, adjectives), while only three specific word types are utilized in the MCTAC (i.e., shapes, left-right concept, colors, sizes).

It is also important to consider the purpose and the nature of the standardized tools in comparing participants’ performance. WAB-R was designed to be used clinically to assess all modalities of language competence for people with aphasia and could be used to identify types of aphasia. The WAB-R AC component consists of a variety of tasks related to language comprehension including following commands, identifying words and sentences, and responding to yes-no questions. Unlike the WAB-R
AC, the MCTAC was systematically designed to identify PwA ability in understanding stimuli with increasing length and difficulty, free from any contextual or environmental cues.

Individuals with different types of aphasia may exhibit different pattern of mean PFDT due to specific features of language impairment. For example, individuals with Broca’s aphasia have marked agrammatism compared to other types of aphasia (Hallowell & Chapey, 2008). In the current study, visual inspection of mean PFDT patterns were completed according to the types of aphasia (based on the WAB-R). Based on comparisons of individual mean PFDT patterns based on the types of aphasia, no specific trend of mean PFDT shifts across time were seen within an aphasia type.

Due to the unequal number of participants according to the types of aphasia, these patterns were not statistically tested. Although aphasia affects all language modalities including language comprehension, the current study was focused on indexing language comprehension of PwA and not on the entire aphasia profile. In previous studies (e.g., Caramazza et al., 2001; Johnson & Cannizzaro, 2009), individual variations were found even among participants with the same type of aphasia. Therefore, in the current study, analyses of individual data were focused on rather than analyzing PwA data according to types of aphasia.
Conclusion

Increments of length and complexity of verbal stimuli lead to increase of performance gap as indicated by qualitative differences in responding over time between individuals with and without aphasia, based on the pattern and values of mean PFDT. The current study also confirmed the time length proposed by previous studies (e.g., Hallowell et al., 2002; Ivanova & Hallowell, 2012) in presenting visual stimuli during the study of language comprehension among individuals with aphasia. When an individual with or without aphasia, who is able to understand a verbal stimulus is given twice the time of the verbal input, plus two more seconds, and rounded up to the nearest whole second; message can be comprehended successfully without eliciting loss of attention. Trial durations based on this formula may be adequate to process verbal messages for individuals with and without aphasia.

The control and PwA groups demonstrated contrasting mean PFDT patterns including rapid increments of mean PFDT at the ending of verbal stimuli (for shorter stimuli) and several time windows before the completion of verbal stimuli (for longer stimuli) for the control group and rapid increments of mean PFDT only in Subtest 1 and Subtest 2 for the PwA. Although the rapid mean PFDT increments might indicate the point of time when participants started to comprehend the verbal stimuli, lack of statistical analyses on the mean PFDT shifts across time complicates the identification of the exact time window when participants begin to understand the stimuli.

Because rapid change in the mean PFDT slope may indicate the point when a person comprehends a language stimulus, identification of the time when a rapid change
in the slope occurs may also be useful to determine the duration needed by individuals with normal language ability as compared to individuals with aphasia to understand a specific length and type of phrase or sentence. Identification of the duration needed for understanding spoken language may also be used to guide clinicians in clinical settings to improve the validity of patients’ performance during auditory comprehension tasks, including individuals with aphasia.

Despite maximum mean PFDT at the final time window for PwA and control group in all MCTAC subtests that were included in the current study, group data generated different trends of mean PFDT over time, especially in later subtests. Testing for longer trial durations would allow further examinations of responses when participants are given greater amounts of time to look at visual displays. At some point in time, visual attention is likely to decrease due to prolonged presentation of the same images and mean PFDT value will decrease after the highest mean PFDT has been reached. Additional observations of mean PFDT over an extended period of time may elicit further discrepancy of performance between people with and without aphasia.

Another pertinent finding is related to the importance of case-by-case analysis that should accompany group data analyses. Each individual with and without aphasia is unique and may have different potential and specific difficulties that require additional attention. Relying solely on group data might not demonstrate the true performance of these individuals because data from one participant may influence the findings from another. Based on individual data analyses, participants in both groups demonstrated additional trends of mean PFDT pattern, which are different than the slopes discovered in
the group analyses. Especially among individuals with aphasia, various internal factors, such as type of language impairment, cognitive status, and post-onset duration, could further increase the gap of performance as compared to the control group.

From the PwA data, we also found that comparisons of language comprehension performance may not correlate directly between one assessment tools to another. Lack of correlations between the scores of different assessment tools may be due to differences of language skills that are tested and the responses that are required from the participants. In addition, different testing condition and environment may also affect participants’ performance in completing different assessment tools.

**Limitations and Future Research**

In using time course analysis to study language comprehension among individuals with aphasia, further experiments are needed to address limitations of the current study. Limitations of the current study include: (a) reliance on existing data, where maximum mean PFDT could only be observed within the limited time frame based on the pre-set durations and (b) lack of statistical analyses to compare mean PFDT slopes at group and individual levels.

Although the preset visual display duration is adequate to discriminate the performance of individuals with and without language impairment, further research is needed to study the point where reduction of fixation on the target following the maximum degree of fixation is elicited. According to Sarter, Givens, and Bruno (2001), duration of stimuli could influence a person’s attention. By increasing the durations for visual displays, different time windows with the highest mean PFDT may be observed.
and compared between control and PwA groups. Observations on the reduction of mean PFDT after the maximum mean value may indicate the time length that could elicit attention loss in people with and without aphasia. Therefore, we could identify the minimum and the maximum durations of visual display that should be used while assessing a person with aphasia in clinical settings.

In addition to observational comparison between the patterns of the mean PFDT increments for both groups in the study, future statistical comparisons between the slopes for each group and individual data should be conducted to determine the significant differences between the mean PFDT patterns. According to Mirman, Dixon, and Magnuson (2008), growth curve analysis is beneficial to: (a) study participants’ responses over time without losing the information in the curvature of the graphs and (b) examine individual performances across time.

Another way to study time course analysis may be related to the focus of PFDT pattern after the completion of verbal stimuli and taking into consideration the level of fixation probability on the target images. Generally, PwA demonstrated a lower height of mean PFDT slope as compared to the control group. In addition to the duration between the onset of visual display and the significant change of slope pattern, comparisons between mean PFDT values itself might indicate further differences between control participants and PwA in comprehending linguistic stimuli.
References


## Appendix: Supplemental Data

Table A1

*Verbal Stimuli, Visual Foils, Duration of Verbal Stimuli, and Duration of Stimuli and Visual Displays in the Multiple Choice Test of Auditory Comprehension*

<table>
<thead>
<tr>
<th>Subtest</th>
<th>Target phrase/sentence</th>
<th>Foil 1</th>
<th>Foil 2</th>
<th>Foil 3</th>
<th>(T) of verbal stimulus</th>
<th>Average (T) for Subtest</th>
<th>(T) of visual display</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtest 1</td>
<td>i. Black Circle (UR)</td>
<td>Black Square (LL)</td>
<td>White Circle (UL)</td>
<td>White Square (LR)</td>
<td>872 ms</td>
<td>983.8 ms</td>
<td>4000 ms</td>
</tr>
<tr>
<td></td>
<td>ii. Red Circle (UR)</td>
<td>Red Square (LL)</td>
<td>Green Circle (LR)</td>
<td>Green Square (UL)</td>
<td>984 ms</td>
<td>984 ms</td>
<td></td>
</tr>
<tr>
<td></td>
<td>iii. Blue Square (LR)</td>
<td>Green Square (UR)</td>
<td>Blue Circle (LL)</td>
<td>Green Circle (UL)</td>
<td>984 ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>iv. Green Square (UL)</td>
<td>Green Circle (LR)</td>
<td>Red Square (UR)</td>
<td>Red Circle (UL)</td>
<td>1095 ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>v. White Circle (UL)</td>
<td>White Square (LR)</td>
<td>Black Circle (LL)</td>
<td>Black Square (UR)</td>
<td>984 ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtest 2</td>
<td>i. Big Green Circle (UL)</td>
<td>Little Green Circle (LR)</td>
<td>Big Blue Circle (UR)</td>
<td>Big Green Square (LL)</td>
<td>1281 ms</td>
<td>1318.0 ms</td>
<td>5000 ms</td>
</tr>
<tr>
<td></td>
<td>ii. Big Black Circle (LR)</td>
<td>Little Black Circle (UR)</td>
<td>Big White Circle (UL)</td>
<td>Big Black Square (LL)</td>
<td>1318 ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>iii. Little Blue Square (UR)</td>
<td>Big Blue Square (LR)</td>
<td>Little Green Square (LL)</td>
<td>Little Blue Circle (UL)</td>
<td>1355 ms</td>
<td></td>
<td></td>
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<td></td>
<td>iv. Big Red Square (UL)</td>
<td>Little Red Square (UR)</td>
<td>Big Blue Square (LL)</td>
<td>Big Red Circle (LR)</td>
<td>1244 ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>v. Little Red Circle (UL)</td>
<td>Big Red Square (LL)</td>
<td>Little Green Square (UR)</td>
<td>Little Red Circle (LR)</td>
<td>1392 ms</td>
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<tr>
<th>Subtest 3</th>
<th>Condition 1</th>
<th>Condition 2</th>
<th>Condition 3</th>
<th>Time (ms) 1</th>
<th>Time (ms) 2</th>
<th>Time (ms) 3</th>
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<tr>
<td>i. Green Square and Black Square (LL)</td>
<td>Green Circle and Black Square (UR)</td>
<td>Green Circle and Red Square (LR)</td>
<td>Red Square and Black Circle (UL)</td>
<td>1912 ms</td>
<td>1994.2 ms</td>
<td>6000 ms</td>
</tr>
<tr>
<td>ii. Blue Circle and Green Square (LL)</td>
<td>Blue Square and Green Square (LR)</td>
<td>Blue Circle and Black Square (UL)</td>
<td>Black Circle and Green Circle (UR)</td>
<td>1987 ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>iii. White Circle and Blue Square (UL)</td>
<td>White Square and Blue Square (LL)</td>
<td>White Circle and Black Square (LR)</td>
<td>Black Circle and Blue Circle (UR)</td>
<td>1987 ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>iv. Black Circle and White Square (UR)</td>
<td>Black Square and White Square (LL)</td>
<td>Black Circle and Red Square (UL)</td>
<td>Red Circle and White Circle (LR)</td>
<td>1987 ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>v. Green Circle and Red Square (UL)</td>
<td>Green Square and Red Square (UR)</td>
<td>Green Circle and White Square (LR)</td>
<td>White Circle and Red Circle (LR)</td>
<td>2098 ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtest 4</td>
<td>i. Big Green Square and Little Black Square (UR)</td>
<td>Big Green Square and Big Black Square (LR)</td>
<td>Big Green Square and Little Black Square (UL)</td>
<td>Big Blue Square and Little Black Circle (LL)</td>
<td>2915 ms</td>
<td>2811.2 ms</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------------------------------------------</td>
<td>-------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>---------</td>
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</tr>
<tr>
<td>ii. Big Black Square and Little Red Circle (LL)</td>
<td>Big Black Square and Big Red Circle (UL)</td>
<td>Big Black Circle and Little Red Circle (LR)</td>
<td>Big Green Square and Little Red Square (UR)</td>
<td>Big White Circle and Little Red Square (UL)</td>
<td>2804 ms</td>
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</tr>
<tr>
<td>iii. Big Blue Circle and Little Green Square (UL)</td>
<td>Big Blue Circle and Big Green Square (UR)</td>
<td>Big Blue Circle and Little Green Square (LL)</td>
<td>Big White Circle and Little Green Circle (LR)</td>
<td>Big White Circle and Little Green Circle (LR)</td>
<td>2618 ms</td>
<td></td>
</tr>
<tr>
<td>iv. Big White Circle and Little Blue Square (LL)</td>
<td>Big White Circle and Big Blue Square (LR)</td>
<td>Big White Circle and Little Blue Circle (UR)</td>
<td>Big Green Circle and Little Blue Circle (UL)</td>
<td>Big White Circle and Little Blue Circle (UL)</td>
<td>2841 ms</td>
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</tr>
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<td>v. Little Blue Square and Big Black Square (UR)</td>
<td>Little Blue Square and Little Black Square (UL)</td>
<td>Little Blue Circle and Big Black Square (LL)</td>
<td>Little Green Square and Big Black Circle (LR)</td>
<td>Little Green Square and Big Black Circle (LR)</td>
<td>2878 ms</td>
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<table>
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<th>Subtest 7</th>
<th>The black circle is to the left of the white square (LL)</th>
<th>The black circle is to the right of the white square (LR)</th>
<th>The black circle is to the left of the white square (UR)</th>
<th>The black circle is to the left of the red square (UL)</th>
<th>3064 ms</th>
<th>2982.4 ms</th>
<th>8000 ms</th>
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<tbody>
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<td>i.</td>
<td>The red square is to the left of the white circle (UR)</td>
<td>The red square is to the left of the white circle (LL)</td>
<td>The red square is to the left of the white circle (LL)</td>
<td>The red square is to the left of the white circle (LL)</td>
<td>3027 ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ii.</td>
<td>The black square is to the right of the red circle (LR)</td>
<td>The black circle is to the right of the red circle (LR)</td>
<td>The black circle is to the right of the red circle (LR)</td>
<td>The black circle is to the right of the red circle (LR)</td>
<td>2730 ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>iii.</td>
<td>The blue circle is to the left of the green square (LR)</td>
<td>The blue circle is to the left of the green square (LR)</td>
<td>The blue circle is to the left of the green square (LR)</td>
<td>The blue circle is to the left of the green square (LR)</td>
<td>3027 ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>iv.</td>
<td>The green circle is to the right of the red square (LL)</td>
<td>The green square is to the right of the red square (UR)</td>
<td>The green square is to the right of the red square (LR)</td>
<td>The green square is to the right of the red square (LR)</td>
<td>3064 ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>v.</td>
<td>The black square is to the left of the white square (UL)</td>
<td>The black square is to the left of the white square (UR)</td>
<td>The black square is to the left of the white square (UR)</td>
<td>The black square is to the left of the white square (UR)</td>
<td>3064 ms</td>
<td></td>
<td></td>
</tr>
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</table>
### Table A1: continued

| Subtest  | i. The little green circle is to the left of the big red square (LR) | ii. The big white circle is to the right of the little blue square (LR) | iii. The big green square is to the right of the little black square (UL) | iv. The little white square is to the right of the big green circle (UL) | v. The big red square is to the left of the big white circle (LR) | The little green circle is to the right of the big red square (UR) | The big white circle is to the left of the big blue square (LL) | The big green circle is to the left of the little black square (UL) | The little white square is to the right of the big green circle (LL) | The big red square is to the left of the little white circle (UR) | The big white circle is to the right of the big blue square (LR) | The little green circle is to the left of the big red square (UL) | The big white circle is to the left of the little blue square (UR) | The big green circle is to the right of the little black square (LR) | The little white circle is to the right of the big green circle (UR) | The big red square is to the left of the big white circle (LL) | The big white circle is to the right of the big blue circle (UR) |
|----------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
|          | The little green circle is to the right of the big red square (UR) | The big white circle is to the left of the little blue square (LL) | The big green circle is to the right of the little black square (UL) | The little white square is to the right of the big green circle (LR) | The big red square is to the left of the big white circle (LR) | The little green circle is to the right of the big red square (UR) | The big white circle is to the left of the little blue square (LL) | The big green circle is to the right of the little black square (UL) | The little white square is to the right of the big green circle (LL) | The big red square is to the left of the big white circle (LR) | The big white circle is to the right of the big blue square (LR) | The little green circle is to the right of the big red square (UR) | The big white circle is to the left of the little blue square (LL) | The big green circle is to the right of the little black square (UL) | The little white square is to the right of the big green circle (LR) | The big red square is to the left of the little white circle (UR) | The big white circle is to the right of the big blue square (LR) |
|          | 3584 ms                                         | 3844 ms                                         | 3584 ms                                         | 3584 ms                                         | 3844 ms                                         | 3584 ms                                         | 3584 ms                                         | 3584 ms                                         | 3584 ms                                         | 3844 ms                                         | 3584 ms                                         | 3584 ms                                         | 3584 ms                                         | 3584 ms                                         | 3584 ms                                         | 3584 ms                                         | 3584 ms                                         |


### Table A2

**Demographic Data of Participants with Aphasia**

<table>
<thead>
<tr>
<th>Participant</th>
<th>Gender</th>
<th>Age (years)</th>
<th>Duration of education (number of years)</th>
<th>Race</th>
<th>Event of CVA (calendar year)</th>
<th>Aphasia type (per WAB)</th>
<th>WAB-R Auditory Comprehension subtest score</th>
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<tbody>
<tr>
<td>A01</td>
<td>Male</td>
<td>61</td>
<td>20.00</td>
<td>Caucasian</td>
<td>1985</td>
<td>Conduction</td>
<td>168 8.4</td>
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<tr>
<td>A03</td>
<td>Male</td>
<td>57</td>
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<td>2005</td>
<td>Anomic</td>
<td>190 9.5</td>
</tr>
<tr>
<td>A04</td>
<td>Male</td>
<td>49</td>
<td>12.00</td>
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<td>1978</td>
<td>Anomic</td>
<td>191 9.6</td>
</tr>
<tr>
<td>A05</td>
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<td>65</td>
<td>16.00</td>
<td>Caucasian</td>
<td>2005</td>
<td>Conduction</td>
<td>153 7.7</td>
</tr>
<tr>
<td>A06</td>
<td>Female</td>
<td>48</td>
<td>16.00</td>
<td>African American</td>
<td>2005</td>
<td>Broca's</td>
<td>194 9.7</td>
</tr>
<tr>
<td>A07</td>
<td>Male</td>
<td>56</td>
<td>18.50</td>
<td>Caucasian</td>
<td>2005</td>
<td>Anomic</td>
<td>197 9.85</td>
</tr>
<tr>
<td>A08</td>
<td>Male</td>
<td>67</td>
<td>17.50</td>
<td>Caucasian</td>
<td>2010</td>
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</tr>
<tr>
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<td>Male</td>
<td>72</td>
<td>20.00</td>
<td>Caucasian</td>
<td>2003</td>
<td>Anomic</td>
<td>192 9.6</td>
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<td>Anomic</td>
<td>172 8.6</td>
</tr>
<tr>
<td>A11</td>
<td>Male</td>
<td>59</td>
<td>19.50</td>
<td>Caucasian</td>
<td>2010</td>
<td>Broca's</td>
<td>102 5.1</td>
</tr>
<tr>
<td>A12</td>
<td>Male</td>
<td>43</td>
<td>16.00</td>
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<td>2005</td>
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<td>159 7.95</td>
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<td>A19</td>
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