Introduction

Deficits in working memory (WM) are a critical subset of non-linguistic impairments in aphasia (Caspari, Parkinson, LaPointe, & Katz, 1998; Murray, Ramage, & Hooper, 2001; Tompkins, Bloise, Timko, & Baumgaertner, 1994; Wright & Shisler, 2005). Further study of the role of WM in aphasia is important for improving understanding of non-linguistic aspects of aphasia, developing valid and reliable assessment methods, and providing optimal treatment while taking non-linguistic factors into account. Despite recent advances in WM research in general and in research specifically addressing aphasia (e.g., Fergadiotis, Wright, Katz, Ross, & Shapiro, 2009; Sung et al., 2008; Wright, Downey, Gravier, Love, & Shapiro, 2007), tasks used to measure WM in individuals with aphasia have substantial methodological limitations. Alternative methods that allow for reduction of the many confounds of existing WM tasks and measures are needed. Eye-tracking methods have been successfully used to assess linguistic comprehension (Hallowell, 2010; Hallowell, Kruse, Shklovsky, Ivanova, & Emeliyanova, 2006; Hallowell, Wertz, & Kruse, 2002) and attention processing (Heuer & Hallowell, 2009) in individuals with and without aphasia. They hold promise for developing alternative WM tasks and measures as well. Compared to traditional complex span tasks eye-movement tasks have the following advantages:

1) Reduce reliance on comprehension of complex task instructions;
2) Provide a naturalistic way to assess processing of linguistic stimuli;
3) Do not require verbal responses or intentional motor responses; and
4) Yield online processing measures.

An eye-movement method to index WM capacity in adults with and without aphasia was developed and tested.

Methods

Experimental data were collected from individuals with aphasia (n=28) and individuals without language, cognitive, or neurological impairments (n=32). Detailed inclusion/exclusion and screening criteria for both groups, the operational definition of aphasia used, and detailed participant descriptions will be given.

Following screenings, and a brief health history, people without aphasia were administered the Mini Mental Status Examination (MMSE; Folstein, Folstein, & McHugh, 1975) and people with aphasia were administered the Western Aphasia Battery-Revised (WAB-R; Kertesz, 2007). Then two WM tasks were administered: (a) a modified listening span (MLS) task (Ivanova & Hallowell, 2009) to serve as a comparison with the new method; and (b) a novel eye-movement WM task. In the MLS task participants were asked to listen to short (4- to 6-word) and simple active sentences that were semantically and syntactically plausible and also remember a separate set of words for subsequent recognition. Prerecorded sentences and multiple-choice image arrays were presented simultaneously. Each array consisted of four pictures: one target (corresponding to the presented sentence) and three foils. For the processing component participants were asked to point to the image best matching the sentence. Items to be remembered were separate words presented after each sentence. At the end of each sentence set a picture set was presented for recognition; participants had to point to pictures representing words to be remembered. An example of a stimulus set is provided in Figure 1.

In the eye-movement WM task, the comprehension-processing component included four-picture multiple-choice arrays accompanied by a verbal stimulus corresponding to one of the pictures while participants' eye movements were monitored and recorded at 60 Hz using an LC

Technologies Eyegaze remote pupil center/corneal reflection system. The efficacy of this method of indexing comprehension has been demonstrated (Hallowell, 2010; Hallowell, Kruse, Shklovsky, Ivanova, & Emeliyanova, 2006; Hallowell, Wertz, & Kruse, 2002). It does not require metalinguistic judgments and can be regarded as natural in terms of everyday language use. Verbal stimuli were short active declarative sentences, similar to those used in the MLS task. This task was presented prior to the MLS task, so that participants were not aware that there was a particular visual target to be found and so they would not look at the images in a consciously predetermined manner. Following each multiple-choice array an item to be remembered was presented in a separate display. Storage items were abstract symbols for half of the sets and color boxes for the other half. Multiple-choice arrays, each one followed by a display with an item to be remembered, were presented in a sequence of 2 to 6 sets. At the end of each sequence a "recognition screen" was presented. This was also a multiple-choice array; instead of pictures it had different combinations of symbols or colors in each quadrant. One of the combinations (the target) corresponded to the combination of all of the symbols/colors presented previously within a given set. Participants were instructed to look at the quadrant that contained the colors/symbols they just saw. Performance was also monitored via eye movements. An example of a set of stimuli is provided in Figure 2. Set sizes of 2 to 6 were presented in ascending order with two sets of each size. The following WM scores were used to index performance:

1. MLS task
    a. Storage score: Mean proportion of correctly recalled/recognized elements per set (Conway et al., 2005).
    b. Processing score: Mean proportion of items for which the target picture was correctly selected.
2. Eye-movement WM task
    a. Storage score: Mean proportion of fixation duration (PFD) on the target images across recognition screens
    b. Processing score: Mean PFD on the target images across multiple-choice arrays.

Results

Results of correlational analyses indexing the relationship between eye-movement WM and MLS task performance are presented in Table 1.

Correlations analyses for processing and storage WM scores from the MLS and the eye-movement WM tasks with subtest scores of the WAB-R (Kertesz, 2007) are given in Table 2. Space permitted here does not allow mention of additional relevant analyses.

Participants without aphasia performed less accurately on trials requiring recall of symbols compared to trials with colors (t (31) = 6.683, $p < .001$); a similar difference was observed for individuals with aphasia (t (27) = 3.175, $p = .004$).

Results of univariate general linear model analysis, with age and years of education as covariates (see Table 3), indicate that participants with aphasia obtained significantly lower WM scores compared to participants without aphasia across the two WM tasks.

Discussion

A significant relationship was observed between performance on the MLS and eye-movement WM tasks. Storage scores demonstrated a particularly strong association. Recall of symbols was significantly worse than colors for both groups. No consistent relationship was observed between WM scores and scores on subtests of the WAB-R (Kertesz, 2007). When data were analyzed separately for individuals with mild/moderate aphasia, no significant correlations between storage scores and WAB-R subtest scores were detected.

Participants without stroke or brain injury obtained higher scores on storage and processing components of the two tasks than participants with aphasia. While significant differences in processing scores can be attributed to language comprehension difficulties intrinsic to aphasia, differences in storage scores cannot be ascribed to specific linguistic deficits as indexed via the WAB-R. Observed differences in performance on the recall components supports the interpretation that, apart from language impairment, WM capacity is reduced in individuals with aphasia. Thus, individuals with aphasia exhibit both specific linguistic deficits and general reductions in processing resources, or limited controlled processing capacity, consistent with McNeil, Odell, and Tseng (1991) McNeil and Pratt, 2001, and Murray (1999). Results support the validity of the new method to assess WM capacity in adults with and without aphasia.

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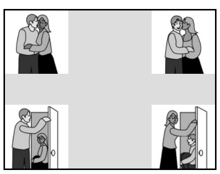
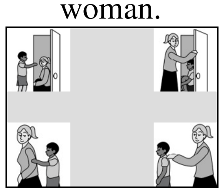
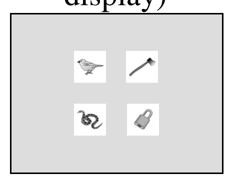
Verbal stimuli	The woman is kissing the man.	*Bird*	The boy is finding the woman.	*Lock*	- (recognition display)
Visual stimuli		Blank screen		Blank screen	
Duration of presentat ion	Until participant gives a response (points to a picture)	2 sec.	Until participant gives a response (points to a picture)	2 sec.	Until participant gives a response (points to images)

Figure 1. Example of a set from the modified listening span task (set size two).

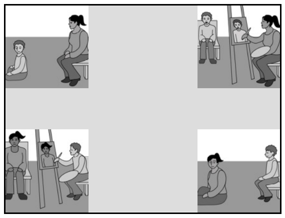
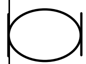
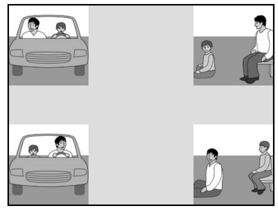
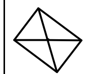
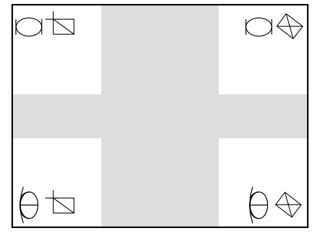
Verbal stimuli	The boy is watching the woman.	-	The man is driving the boy.	-	- (recognition display)
Visual stimuli					
Duration of presentation	Twice the duration of the verbal stimuli plus two seconds	2 sec.	Twice the duration of the verbal stimuli plus two seconds	2 sec.	Number of items to be recalled times 2.5 seconds (in this case 5 seconds)

Figure 2. Example of a sequence of multiple-choice arrays in the eye-movement working memory task (set size two, symbols).

Table 1

Correlations between Working Memory Scores on the Eye-movement Working Memory Task and the Modified Listening Span Task for Participants With and Without Aphasia

		Modified listening span	
	WM scores	Participants without aphasia	Participants with aphasia
Eye-movement WM task	ST	.557**	.644**
	PR	.044	.541**

Note. WM scores: ST=storage score; PR=processing score.
* $p < .05$, ** $p < .01$.

Table 2

Correlations Between WAB-R and Working Memory (WM) Scores for Participants With Aphasia

	WM scores	Spontaneous speech	Auditory verbal comprehension	Repetition	Naming	AQ
Modified listening span	ST	.075	.163	-.086	.227	.090
	PR	.515**	.719**	.802**	.548**	.689**
Eye-movement WM task	ST	.400*	.355	.164	.435*	.378*
	PR	.190	.463*	.260	.407	.325

Note. WM scores: ST=storage score; PR=processing score; C=combined score.
* $p < .05$, ** $p < .01$.

Table 3

Univariate General Linear Model Analysis of Working Memory Scores between Participants with and without Aphasia with Age and Years of Education as Covariates

	WM scores	*df*	*MS*	*F*	*p*-value	η^2
Modified listening span task	ST	1, 56	.495	55.721	<.001	.499
	PR	1, 56	.404	33.158	<.001	.372
Eye-movement WM task	ST	1, 56	.667	68.242	<.001	.549
	PR	1, 56	.324	13.896	<.001	.199

Note. WM scores: ST=storage score; PR=processing score.