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Validity of an eye-tracking method to index working memory in people with and without aphasia

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Background: Working memory (WM) is essential to auditory comprehension; thus understanding of the nature of WM is vital to research and clinical practice to support people with aphasia. A key challenge in assessing WM in people with aphasia is related to the myriad deficits prevalent in aphasia, including deficits in attention, hearing, vision, speech, and motor control of the limbs. Eye-tracking methods augur well for developing alternative WM tasks and measures in that they enable researchers to address many of the potential confounds inherent in tasks traditionally used to study WM. Additionally, eye-tracking tasks allow investigation of trade-off patterns between storage and processing in complex span tasks, and provide on-line response measures.
Aims: The goal of the study was to establish concurrent and discriminative validity of a novel eye movement WM task in individuals with and without aphasia. Additionally we aimed to explore the relationship between WM and general language measures, and determine whether trade-off between storage and processing is captured via eye-tracking measures.
Methods & Procedures: Participants with ($n = 28$) and without ($n = 32$) aphasia completed a novel eye movement WM task. This task, incorporating natural response requirements, was designed to circumvent potential confounds due to concomitant speech, motor, and attention deficits. The task consisted of a verbal processing component intermixed with presentation of colours and symbols for later recall. Performance on this task was indexed solely via eye movements. Additionally, participants completed a modified listening span task that served to establish concurrent validity of the eye-tracking WM task.

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Outcomes & Results: Performance measures of the novel eye movement WM task demonstrated concurrent validity with another established measure of WM capacity: the modified listening span task. Performance on the eye-tracking task discriminated effectively between participants with and without aphasia. No consistent relationship was observed between WM scores and Western Aphasia Battery aphasia quotient and subtest scores for people with aphasia. Additionally, eye-tracking measures yielded no trade-off between processing and storage for either group of participants.
Conclusions: Results support the feasibility and validity of employing a novel eye-tracking method to index WM capacity in participants with and without aphasia. Further research is required to determine the nature of the relationship between WM, as indexed through this method, and specific aspects of language impairments in aphasia.

Keywords: Working memory; Working memory assessment; Eye-tracking; Aphasia; Cognitive processing; Complex span tasks.

To understand spoken language one must have sufficient working memory (WM) to enable the interpretation of ongoing verbal stimuli. Given that WM is paramount to auditory comprehension, understanding of the nature of WM is vital to research and clinical practice to support people with aphasia (PWA) (Friedmann & Gvion, 2003; Laures-Gore, Marshall, & Verner, 2011; Murray, Ramage, & Hooper, 2001; Sung et al., 2009; Wright, Downey, Gravier, Love, & Shapiro, 2007; Wright & Shisler, 2005). Also, better understanding of WM is essential to resolving equivocation among aphasiologists regarding whether WM deficits are inherent in (versus concomitant with) aphasia, and whether severity of WM deficits are causally linked with the severity of comprehension deficits in PWA. A key challenge in assessing WM in PWA is related to the myriad deficits especially prevalent in PWA, including deficits in attention, hearing, vision, speech, and motor control of the limbs (Hallowell, 2008; Murray, 1999, 2004; Murray & Clark, 2006). Any such deficit may interfere with performance on tasks used to study WM.

WM can be broadly defined as the capacity to engage simultaneously in processing and storage of information. Thus the tasks used to evaluate WM capacity require a dual-task condition when two tasks—one involving storage and one processing—are performed concurrently. WM tasks must be carefully designed and the psychometric properties of associated performance measures must be established prior to making inferences regarding WM limitations in clinical populations.

Among a wide array of WM tasks, complex span tasks (often referred to as WM span tasks) are among the most widely used measures of WM (for a review see Conway et al., 2005; Waters & Caplan, 2003). In a typical complex span task a processing task (e.g., sentence reading, arithmetic problem solving, or visual-spatial tracking) is given along with a set of stimuli (e.g., letters, words, or shapes) to be remembered for later recall. There are two primary types of complex span tasks: verbal and nonverbal (or visual-spatial). Among the verbal span tasks the reading and listening span tasks are the most common. In the initial reading span task (Daneman & Carpenter, 1980) participants were required to read aloud sentences presented in sets of two to six (processing component), and at the same time remember the last word of each sentence (storage component); three sets of each size were presented. At the end of each sentence set participants were asked to recall the sentence-final words in the order in which they were presented. A participant's WM score was defined as the highest level (largest set size) at which he or she correctly recalls the words for all the sets. Since the Daneman and Carpenter study, complex span tasks have undergone numerous modifications. Different types of linguistic tasks have been embedded within the processing component. A variety of items have been used for storage. Also new variants of verbal span tasks, such as the operation span (Turner & Engle, 1989) and counting span (Case, Kurland, & Goldberg, 1982) tasks have been developed. Still, the general structure of the complex span tasks where processing items are intermixed with items for subsequent recall have remained unchanged.

Various theories of WM regard performance on complex span tasks as valid indices of WM, even though different explanations have been offered as to why a span score represents WM capacity (Baddeley, 2000; Case, 1985; Cowan, 1999; Engle, Kane, & Tuholski, 1999; Just & Carpenter, 1992; MacDonald & Christiansen, 2002; Towse, Hitch, & Hutton, 2000; Zacks & Hasher, 1993). Thus complex span tasks have become a fairly standard means of measuring WM. However, WM tasks developed for individuals without any history of neurological, cognitive, or language impairments cannot be directly applied to individuals with neurogenic language disorders (Wright & Shisler, 2005). Problems with WM complex span tasks and associated performance measures used in studies with PWA include: the assumption that PWA can comprehend task instructions and stimulus sentences used as processing components of complex span tasks (Tompkins, Bloise, Timko, & Baumgaertner, 1994); reliance on expressive language performance for recall tasks (Caspari, Parkinson, LaPointe, & Katz, 1998); the lack of methodical control for the difficulty of the processing component; the lack of methodical control for the effects of length versus complexity of verbal stimuli (Ivanova & Hallowell, 2011); the lack of clear means of indexing processing and storage components of WM tasks; use of off-line tasks for which any conclusions about processing must be inferred based on later performance; and the assumption that metalinguistic judgements of PWA are appropriate as means of monitoring performance on the processing component of WM tasks, as in the case of true/false decisions and comprehension questions. Additionally, many of the variations of complex span tasks used to assess WM in PWA have not been tested for construct and concurrent validity prior to being used as the basis for making claims about the nature of WM itself. In summary, further modification and development of suitable WM tasks and associated performance measures is needed.

Eye-tracking methods augur well for developing alternative WM tasks and measures in that they enable researchers to address many of the potential confounds listed above. They may reduce reliance on comprehension of complex task instructions and provide a naturalistic way to assess processing of linguistic stimuli as participants simply listen to verbal input and look at visual arrays. Eye tracking can be implemented during natural language processing tasks and offers a response mode that requires no additional verbal, gestural, or limb-motor responses (Hallowell, 1999; Hallowell, & Lansing, 2004; Hallowell, Wertz, & Kruse, 2002). Additionally, eye-tracking tasks yield online processing measures that allow investigation of potential trade-off patterns between processing and storage as memory load increases.

Myriad studies show the applicability of using eye movements to index of a wide variety of cognitive processes and to differentiate aspects of cognitive and linguistic functioning (for reviews see Henderson & Ferriera, 2004; van Gompel, Fischer, Murray, & Hill, 2007). Eye-tracking methods have been successfully used to assess language comprehension (Hallowell, 1999, 2011; Hallowell, Kruse, Shklovsky, Ivanova, & Emeliyanova, 2006; Hallowell et al., 2002), to study different aspects of linguistic processing (Allopenna, Magnuson, & Tanenhaus, 1998; Cooper, 1974; Dickey, Choy, & Thompson, 2007; Dickey & Thompson, 2009; Tanenhaus, Magnuson, Dahan, & Chambers, 2000; Tanenhaus & Spivey, 1996) and spoken language production (Choy

& Thompson, 2005; Griffin, 2004; Meyer, 2004) and attention (Heuer & Hallowell, 2009a) in individuals with and without aphasia.

To assess linguistic comprehension Hallowell and colleagues (1999, 2002, 2006, 2011) presented visual and verbal stimuli simultaneously while tracking participants' eye fixations. Verbal stimuli ranged from single words to sentences of varying length and complexity. Each verbal stimulus corresponded to one of the images in an image array of three or four images. Evidence from adults with and without aphasia indicates that the proportion of fixation duration (PFD) on the target image (defined as the proportion between the total fixation duration allocated to the target image and the total fixation duration) within an array is a valid and a reliable measure of comprehension ability (Hallowell, 1999, 2011; Hallowell et al., 2002). In individuals without cognitive, language, and neurological impairments PFD on the target has been shown to be significantly greater than on non-target foils (Hallowell et al., 2002). That is, when a person understands the verbal stimulus, he or she naturally attends for a proportionately longer time to a corresponding image than to other images.

For the current study we developed a new eye-tracking method to index WM capacity in participants with and without aphasia. Given the robust and online nature of eye-tracking indices of comprehension we reasoned that it would be logical to incorporate a language comprehension task, requiring no overt response, as the processing component of a novel eye movement-based WM task. Sentences were used as comprehension stimuli for the processing component of the task, not for the purpose of investigating the role of WM in sentence comprehension. Rather than requiring an overt pointing or verbal response to indicate items recalled or for the selection of a correct recognition display, we reasoned that it would be logical to have participants simply look at a multiple-choice set of possible recall items and select a set of items corresponding to images they recall from any given trial. By integrating the two comprehension and recall tasks into a dual task and recording eye fixations throughout it is possible to generate separate online indices for processing and storage. Building on prior work on the development of a modified listening span (MLS) task (Ivanova & Hallowell, 2011), methodical control for length and complexity of verbal stimuli was also incorporated into the development of the new method.

There were three primary goals. The first goal was to establish the concurrent and discriminative validity of the eye movement working memory (EMWM) method in individuals with and without aphasia. The second was to study the relationship between WM capacity as indexed by EMWM measures and standardised language assessment scores from the Western Aphasia Battery-Revised (Kertesz, 2007) of PWA. One would expect to find a significant relationship between experimental WM measures and standardised language assessment scores (especially comprehension subscores) if the degree of WM deficit contributes to language impairment in aphasia. If, however, EMMW task performance is not correlated with comprehension scores or overall language performance measures, this may suggest a dissociation between the severity of WM deficits and language deficit severity in aphasia. In either case, findings will help to inform further methodological developments in using eye tracking to index WM. The third goal was to explore whether EMWM results may be used to index possible trade-off effects between processing and storage as storage load increases. We expected to see a trade-off between processing and storage performance. That is, as storage demands increased, we anticipated that the resources allocated to processing would decrease.

METHOD

Participants

The study was approved by the Institutional Review Board of Ohio University. A total of 32 adults without aphasia and 28 PWA participated. General inclusion criteria for all participants were: (a) chronological age from 21 to 90 years; (b) status as a native speaker of American English; (c) intact near visual acuity for 100% accuracy for 20/250 vision using the Lea Symbols Line test (Precision Vision) (Hyvärinen, Näsänen, & Laurinen, 1980); and (d) hearing acuity screened at 500, 1000, and 2000 Hz at 40 dB SPL. Additionally, intactness of visual fields was documented through use of the Amsler grid, a confrontation finger counting test, an extraocular motor function screening, and pupil reflex examination (Hallowell, 2008).

Participants without language impairment. Additional inclusion criteria for individuals without aphasia were: (a) no reported history of speech, language, or cognitive impairment; (b) no reported history of neurological impairment; and (c) performance within the normal range on the Mini-Mental Status Examination (MMSE; Folstein, Folstein, & McHugh, 1975). See Table 1 for participant characteristics.

Participants with aphasia. Additional inclusion criteria for PWA were: (a) diagnosis of aphasia due to stroke as indicated in a referral from a neurologist or a speech-language pathologist and confirmation via neuroimaging data; (b) no reported history of speech, language, or cognitive impairment prior to aphasia onset; and (c) post-onset time of at least 2 months to ensure reliability of testing results through traditional and experimental means.

Aphasia in this study was defined as "an acquired communication disorder caused by brain damage, characterised by an impairment of language modalities: speaking, listening, reading, and writing; it is not the result of a sensory deficit, a general intellectual deficit, or a psychiatric disorder" (Hallowell & Chapey, 2008, p. 3). Only individuals who had aphasia following stroke were recruited. See Table 1 for overall group characteristics. Detailed characteristics of PWA can be found in the Appendix. All PWA were right-handed. There were no significant differences in age or years of post-high-school education between participants with and without aphasia: age: $t(56.3) = -0.501$, $p = .6$; education: $t(58) = 1.237$, $p = .221$.

Six PWA had some degree of visual field deficit; one of them also reported a history of visual neglect. This did not appear to influence performance on any of the

TABLE 1
Demographic characteristics of the participants with and without aphasia

	Participants without aphasia (*n = 32*)	*Participants with aphasia* (*n = 28*)
Age	$M = 54.6$, $SD = 16.6$ (22–80)	$M = 56.4$, $SD = 12.1$ (22–78)
Years of post-high-school education	$M = 5.7$, $SD = 3.1$ (2–14)	$M = 4.8$, $SD = 2.7$ (0–9)
Female / Males	23 / 9	11 / 17
Post onset (months)	–	$M = 64.1$ $SD = 56.6$ (10–275)

experimental tasks in that all of them passed the calibration procedure for the eye movement task and consistently pointed to images in all four quadrants.[1]

PWA were administered the Aphasia Quotient (AQ) components of the Western Aphasia Battery-Revised (WAB-R; Kertesz, 2007). AQ scores ranged from 45.1 to 99.4 ($M = 77.13$, $SD = 15.57$). WAB-R spontaneous speech scores ranged from 8 to 20 ($M = 14.57$, $SD = 3.37$); auditory verbal comprehension from 5.4 to 10 ($M = 8.7$, $SD = 1.25$); repetition from 1.7 to 10 ($M = 7.62$, $SD = 2.21$); and naming and word finding from 3.7 to 10 ($M = 7.67$, $SD = 1.8$). According to the scores on the AQ of the WAB-R 15 PWA were classified as mild, 11 as moderate, and 2 as severe.

WM tasks

Two WM tasks—the modified listening span (MLS) task and the eye movement working memory (EMWM) task—were presented to participants with and without aphasia.

Modified listening span (MLS) task. Participants completed the short and simple condition of the MLS task (for a detailed description of the task see Ivanova & Hallowell, 2011). Participants were asked to listen to sentences and remember words presented after each sentence for subsequent recognition at the end of the set. All sentences in the task were composed of six to seven words. Sentences were active, semantically and syntactically plausible, and semantically reversible (e.g., The boy is pushing the girl). Along with auditory presentation of each sentence, multiple-choice image arrays were presented. Each array consisted of four pictures: one target and three foils. Pictures used in the multiple-choice arrays were created by a graphic artist, applying careful strategies to reduce effect of visual image characteristics on the allocation of visual attention (Heuer & Hallowell, 2007, 2009a). Participants were asked to point to the image that best matched the sentence. Items to be remembered were separate words presented after each sentence. At the end of each sentence set an array of pictures, including the target (representing words to be remembered) and non-target foil images (equal to the number of target pictures), was presented for recognition. As the number of items to be remembered increased the number of foil pictures increased proportionately. In Figure 1 an example of a set from the task is provided.

Sentences were presented in sets of two to six in ascending order. Verbal stimuli were pre-recorded and digitised. Experimental stimuli were presented on the computer screen. The following measures were used to index MLS task performance:

- Storage scores were based on a partial credit unit scoring scheme (Conway et al., 2005). Items were scored as proportion of correctly recognised elements per set; for the final score a mean of these proportions was calculated. The order in which items were recognised was not taken into account.
- Processing scores were expressed as the proportion of items for which the target picture was correctly selected.

[1] We performed all the primary analyses described in the results section with and without participants with visual field deficits. All the results remained unchanged.

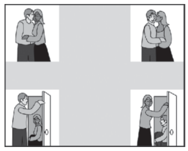
Verbal stimuli	The woman is kissing the man.	*Bird*	The boy is finding the woman.	*Lock*	– (recognition display)
Visual stimuli		Blank screen		Blank screen	
Duration of presentation	Until participant gives a response (points to a picture)	2 seconds	Until participant gives a response (points to a picture)	2 seconds	Until participant gives a response (points to images or says the words)

Figure 1. Example of a set from the modified listening span task (set size 2).

Previous research (Ivanova & Hallowell, 2011) has shown the concurrent validity of this simplified version of a complex span task with a traditional measure of WM—the listening span task—for participants without aphasia.

Eye movement working memory (EMWM) task. This task was an eye-tracking version of the MLS task. Participants were required to look at the computer screen during presentation of visual and verbal stimuli while their eye movements were recorded via a remote eye-tracking system. Participants were not required to respond to the presented items with a gesture or a verbal expression; their performance on the task was monitored solely via eye movements.

The comprehension-processing component of this task included multiple-choice picture arrays accompanied by a verbal stimulus corresponding to one of the images in the array. The verbal stimuli were short active declarative sentences, similar in terms of linguistic characteristics to the stimuli used in the MLS task. Verbal stimuli were prerecorded and digitised. A total of 20 multiple-choice arrays, the same as in the MLS task (although accompanied by a different verbal stimulus), were presented twice, each time with a different verbal stimulus. The EMWM 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 any consciously predetermined manner (i.e., their response would be as natural as possible). Following each multiple-choice array an item to be remembered was presented within a separate display. Storage items in this task were abstract symbols (for half of the sets) or colour boxes (for the other half). Several multiple-choice arrays, each one followed by a display with an item to be remembered (colour or symbol), were presented in a sequence. A sequence was composed from two to six multiple-choice arrays depending on the set size. 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 colours in each quadrant. One of the combinations (the target) corresponded to the combination of all of the symbols/colours presented previously within a given set. Participants were instructed to look at the colours or symbols they had just seen. See Figure 2 for an example of a set of stimuli from the EMWM task.

In this task the visual stimuli were presented on a 17-inch computer screen. The visual and the verbal stimuli were presented simultaneously. The multiple-choice

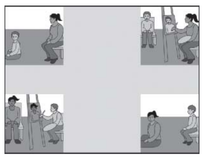
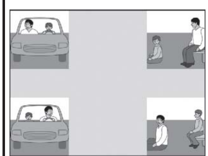
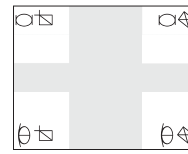
Verbal stimuli	The boy is watching the woman.	–	The man is driving the boy.	–	– (recognition display)
Visual stimuli					
Duration of presentation	Twice the duration of the verbal stimuli plus 2 seconds	2 seconds	Twice the duration of the verbal stimuli plus 2 seconds	2 seconds	Number of items to be 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 2, symbols).

arrays were displayed for twice the duration of the auditory stimuli plus 2 seconds rounded to the nearest second. Previous studies have shown that this duration provides sufficient time for recognising and finding the correct image in cases of mild to severe comprehension deficits (Hallowell, 2011), yet is not so long as to lose a comprehension effect for individuals without such deficits. Displays with storage items were presented for 2 seconds each. Recognition arrays were presented from 5 to 15 seconds each; duration of the recognition screen was determined by the number of items to be recalled times 2.5 seconds (for instance, recognition arrays for set size 4 lasted 10 seconds: 4 items multiplied by 2.5 seconds). Recognition arrays were not accompanied by verbal stimuli.

Participants were given the following instructions at the beginning of the experiment: “You will see pictures and hear sentences. Listen to the sentences and look at the pictures. Remember the colours or shapes that you see. Then look at the corner with the colours or shapes you just saw.” Practice trials were administered to assure comprehension of task instructions. Multiple-choice arrays were shown in sets of two to six in ascending order; two sets of each size were presented. For half of the sets the storage items were abstract symbols while in the other half the storage items were colours. All participants were administered all sets of all sizes.

Participants’ eye movements were monitored and recorded at 60 samples per second using an LC Technologies Eyegaze (Fairfax, VA, USA) remote pupil centre/corneal reflection system. An automatic calibration procedure, which involved looking sequentially at nine black dots on a white screen from a distance of 24 inches, was completed prior to stimulus presentation. A chin rest was used to restrict participants’ head movements during the calibration and the experimental task. Custom analysis software was used to determine fixation location and duration, and to eliminate blink artefact. Fixation was defined as a stable position of the eye (with six pixels horizontal and four pixels vertical tolerance) for at least 100 ms. Important strengths of these temporal and spatial parameters are that they have been shown to (a) effectively distinguish true fixations from noise in the raw data associated with ocular movements, and (b) validly index performance during cognitive tasks (Manor & Gordon, 2003). Eye-tracking data were summarised in terms of PFD on the target image, which was defined as the total fixation duration allocated to the quadrant with the target image divided by total fixation duration on the screen (total presentation of the stimuli minus blink artefact and duration of saccadic eye movements). The target image was defined as the image corresponding to the verbal stimulus (for processing trials) or the image containing all the items to be recalled (for the recognition screens). Previous research has shown that PFD on target is a valid measure for indexing linguistic comprehension (Hallowell, 2011; Hallowell et al., 2002, 2006) and other cognitive abilities (Heuer & Hallowell, 2009b; Odekar, Hallowell, Kruse, Moates, & Lee, 2009). Data from PWA further support the sensitivity of PFD on the target to reflect characteristics of linguistic impairment (Hallowell, 2011; Hallowell et al., 2006). When PWA were given a printed version of the same visual arrays as in a parallel eye-tracking condition and asked to point to the image that best corresponds to the spoken stimuli, their multiple-choice pointing scores were significantly correlated with their PFD on the target. Further, when PFD on the target was compared between correct trials (trials where participants provided correct responses in the pointing version) and incorrect trials (trials for which incorrect responses were provided) significant differences emerged. PFD on the target for correct trials was significantly larger compared to incorrect trials. These findings support the use of the PFD on the target as a fine-grained index of receptive abilities of individuals with and without aphasia. Also, PFD on the target has been shown to be a valid measure for indexing semantic priming effects (Odekar et al., 2009) and allocation of attention (Heuer & Hallowell, 2009b).

Storage and processing scores were determined for the EMWM task. Storage scores were the mean PFD on the target images across recognition screens. Processing scores were mean PFD on the target images across multiple-choice arrays.

RESULTS

Descriptive statistics

Descriptive statistics (mean, standard deviation, minimum, and maximum) and internal reliability (Cronbach's alpha) for the WM scores (storage and processing) on the MLS and the EMWM tasks for participants with and without aphasia are presented in Table 2. Internal reliability was computed for each score across sets for the two groups of participants. Individual processing and storage Z-scores for the EMWM task for PWA can be found in the Appendix.

PFD on target was significantly greater than PFD on all of the foils in storage and processing trials for both groups as indicated by a series of paired *t*-tests between PFD on target and foils (see Table 3).

Performance on trials with colours was compared to trials with symbols for both participants with and without aphasia. Participants without aphasia performed worse on trials requiring recall of symbols (as indexed by lower PFD on the target) compared to trials with colours, $t(31) = 6.683$, $p < .001$; a similar difference was observed for PWA, $t(27) = 3.175$, $p = .004$. No differences were observed in performance on the processing trials between the two conditions for individuals without aphasia, $t(31) = 1.443$, $p = .159$, or for PWA, $t(27) = -.77$, $p = .448$.

Relationship between performance on the eye movement working memory and the modified listening span tasks

To investigate the relationship between performance on the EMWM and MLS tasks storage and processing scores for these two tasks were correlated within groups of

TABLE 2
Descriptive statistics and internal reliability measures (Cronbach's alpha) for working memory scores on the on the modified listening span and the eye movement working memory tasks

		Participants without aphasia ($N = 32$)				*Participants with aphasia* ($N = 28$)				
WM tasks	*WM scores*	M	SD	*Min*	*Max*	M	SD	*Min*	*Max*	*IR*
MLS task	ST	.93	.08	.71	1.00	.73	.13	.46	.97	.867
	PR	1.00	.01	.95	1.00	.83	.16	.40	1.00	.831
Conditions of the EMWM task										
Colours only	ST	.73	.16	.32	.95	.46	.13	.21	.68	.718
	PR	.61	.17	.28	.82	.46	.12	.27	.69	.922
Symbols only	ST	.59	.13	.28	.83	.40	.10	.15	.64	.608
	PR	.60	.19	.22	.81	.46	.11	.31	.71	.915
Overall	ST	.66	.13	.34	.89	.43	.10	.22	.56	.823
	PR	.61	.18	.26	.82	.46	.11	.29	.70	.958

IR = internal reliability. WM scores: ST = storage score; PR = processing score. For the MLS task storage scores are proportions of correctly recognised elements per set; processing scores indicate accuracy rates. For the EMWM task storage and processing scores are expressed as PFD on target.

participants with and without aphasia (see Table 4). Prior to conducting the correlation analyses, scatter plots were examined for presence of outliers and influential cases. No such cases were found; all data points were included in the analyses. After the Holm correction to control for familywise alpha was applied, all the correlations between WM scores on the two tasks remained significant except the storage scores for the symbols condition of the EMWM task for PWA. Results of these correlational analyses demonstrated that a significant relationship exists between WM storage scores on these tasks for both groups of participants. Additionally, for PWA a significant relationship between processing scores was observed. Positive correlations between scores on these two WM tasks indicate that higher accuracy rates on the MLS task (for both processing and storage) correspond to greater PFD on target on the EMWM task.

Comparison of performance between participants with and without aphasia

Differences in WM scores on the EMWM task between participants with and without aphasia were explored using univariate general linear model analysis, with age and years of higher education taken as covariates (see Table 5). Results of this analysis indicated that PWA obtained significantly lower WM scores compared to participants without aphasia.

An additional analysis with independent samples t-tests was done to compare performance of individuals with very mild aphasia (WAB-R AQ of 90 to 100) to individuals without aphasia on the EMWM task. A total of eight PWA were included in this analysis. Differences in the overall storage, $t(38) = 3.56$, $p = .001$, and processing scores, $t(38) = 2.16$, $p = .037$, were significant.

TABLE 3
Proportion of fixation duration on target and foil images for the processing and storage trials of the eye movement working memory task

		Participants without aphasia				*Participants with aphasia*			
		Mean PFD (SD)	*Min–Max*	*t*	*p*	*Mean PFD (SD)*	*Min–Max*	*t*	*p*
Storage trials	Target	.66 (13)	.34−.89	–	–	.43 (.1)	.22−.56	–	–
	Foil 1	.16 (07)	.05−.37	14.56	< .001	.24 (.05)	.18−.40	7.99	<.001
	Foil 2	.09 (05)	.02−.25	18.45	< .001	.19 (.06)	.08−.32	8.65	<.001
	Foil 3	.08 (04)	.02−.21	18.7	< .001	.14 (.06)	.08−.28	10.39	<.001
Processing trials	Target	.61 (18)	.26−.82	–	–	.46 (.11)	.29−.70	–	–
	Foil 1	.15 (05)	.07−.26	11.14	< .001	.27 (.07)	.13−.41	5.96	<.001
	Foil 2	.12 (07)	.06−.31	11.16	< .001	.13 (.04)	.06−.26	12.06	<.001
	Foil 3	.11 (06)	.03−.27	11.61	< .001	.14 (.04)	.08−.27	12.15	<.001

t = paired t-test between PFD on target and on corresponding foil.

TABLE 4
Correlations between working memory scores on the eye movement working memory and the modified listening span tasks

		MLS task	
EMWM task	*WM scores*	*Participants without aphasia*	*Participants with aphasia*
Colours only	ST	.477**	.654**
	PR	.011	.538**
Symbols only	ST	.558**	.449*
	PR	.073	.518**
Overall	ST	.557**	.644**
	PR	.044	.541**

WM scores: ST = storage score; PR = processing score. For the MLS task storage scores are proportions of correctly recognised elements per set; processing scores indicate accuracy rates. For the EMWM task storage and processing scores are expressed as PFD on target.
*$p < .05$, **$p < .01$.

TABLE 5
Univariate general linear model analysis of working memory scores between participants with and without aphasia with age and years of education as covariates

EMWM task	*WM scores*	df	MS	F	*p-value*	η^2
Colours only	ST	1, 56	.850	59.558	<.001	.515
	PR	1, 56	.383	16.366	<.001	.226
Symbols only	ST	1, 56	.506	43.185	<.001	.435
	PR	1, 56	.270	10.825	<.001	.162
Overall	ST	1, 56	.667	68.242	<.001	.549
	PR	1, 56	.324	13.896	<.001	.199

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

Association between working memory capacity and language abilities

To examine the relationship between WM capacity and general language abilities, correlations analyses for processing and storage WM scores from the EMWM tasks with subtest scores of the WAB-R (Kertesz, 2007) were performed (see Table 6). After the Holm correction to control for familywise alpha was applied, none of the correlations between WM and subtest scores, including those specific to auditory comprehension, remained significant.

Trade-off between processing and storage

To explore trade-off patterns between processing and storage, processing scores of items with low memory load were compared to processing scores of items with high memory load. First we compared processing scores for items from sets size 2 and 3 (low memory load) to items from set size 5 and 6 (high memory load). No significant differences in processing scores were observed for either group: participants without aphasia, $t(31) = -0.475$, $p = .638$; PWA, $t(27) = -0.99$, $p = .331$. When storage scores from sets size 2 and 3 were contrasted with storage scores from set size 5 and 6, significant differences were found for PWA, $t(27) = 2.219$, $p = .035$. No significant

TABLE 6
Correlations between WAB-R and working memory scores for participants with aphasia

	WM scores	*Spontaneous speech*	*Auditory verbal comprehension*	*Repetition*	*Naming*	*AQ*
EMWM task	ST	.400*	.355	.164	.435*	.378*
	PR	.190	.463*	.260	.407	.325

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

differences were observed for participants without aphasia, $t(31) = 1.1.21$, $p = .271$. To further examine potential trade-off effects, processing scores for the initial two multiple-choice items at the beginning of the set (low memory load) for set sizes 5 and 6 were compared to processing scores for the final two items at the end of these sets (high memory load). No significant differences in processing scores for either group were detected: participants without aphasia, $t(31) = 1.853$, $p = .073$; PWA, $t(27) = -0.24$, $p = .812$.

DISCUSSION

Concurrent validity of the eye movement working memory task

A significant relationship was demonstrated between WM scores on the EMWM and the MLS tasks. Medium-size correlations between the two tasks were observed within groups of participants with and without aphasia. The association in overall storage scores between the two tasks for participants without aphasia accounted for 31% of the variance; for PWA the association was stronger, accounting for 41% of variance. These associations were observed even though different items (words vs colours/symbols) had to be remembered and recall performance was indexed differently for the two tasks.

Identical sentence stimuli were used in the MLS and in the EMWM tasks. However, the two tasks had different temporal requirements and used different measures of processing accuracy. These divergences likely underlie the mere moderate correlation between processing scores on the two tasks for PWA. In the EMWM task each trial lasted for a predetermined amount of time, while in the MLS task participants were given as much time as they needed to respond to each item. In addition, responses in the processing component of the MLS task were binary (correct/incorrect), while scores were continuous in the EMWM task providing a more fine-grained measure of comprehension ability. Finally, in the EMWM task participants were not explicitly instructed to look at the correct image, while in the MLS task participants were trained to point to the image that corresponded to the sentence. Although it is a natural response to look at what is being mentioned (Hallowell et al., 2002), some of the participants spontaneously reported that they had consciously limited the amount of time they looked at the target image while focusing on rehearsal of items to be remembered. The tendency to do this was confirmed via online observations of eye movement patterns. These factors might have led to an underestimation of participants' comprehension abilities, and thus a weaker correlation than might otherwise have been obtained between processing components of the two tasks. For individuals without aphasia there was no association between processing scores on the two tasks. This is likely due to the factors described above, as well as the prevalent ceiling effect in performance on the processing component of the MLS task.

Notably, recall of symbols was significantly worse than colours for both groups. After the completion of the task, most participants (both with and without aphasia), when asked about their experience, reported that symbols were more difficult to remember because they were more difficult to verbalise. This suggests that PWA, despite their language deficits, encode items in memory in similar manner (i.e., using verbal labels) to that of individuals without language or cognitive deficits. Alternatively, it is possible that recall of colours was better than shapes because the set of 12 easily distinguishable colours was limited relative to the 40 abstract symbols used as shapes. The smaller number of alternatives in recall of colours might have simplified the task for both groups of participants.

Overall, findings demonstrate concurrent validity of a novel EMWM task to measure WM capacity in individuals with and without aphasia. A significant association between storage scores across the two methods was observed even though (a) no explicit instructions were given regarding the processing component of the EMWM task, in contrast to overt sentence–picture matching requirements in the MLS task, and (b) the two tasks included different items to be remembered and used different means of indexing performance.

Discriminative validity of the eye movement working memory task

Participants without language impairment obtained significantly higher scores on storage and processing components of the EMWM task than PWA (with age and years of higher education controlled for). Significant differences in processing scores on the EMWM tasks reflect linguistic comprehension deficits characteristic of aphasia. That is, PWA attended to the target images in the processing component of the task for a shorter duration of time than individuals without aphasia. These results mirror differences in performance observed in previous studies investigating language comprehension via eye tracking (Hallowell, 2011; Hallowell et al., 2006). At the same time, differences in storage scores cannot be easily explained as being due to purely linguistic aspects of aphasia. The lack of trade-off between processing and storage (see detailed discussion below) suggests that processing did not require more resources (i.e., was not more effortful) for PWA. Furthermore, PWA experienced difficulties in remembering both colours and symbols, even though symbols are more difficult to encode verbally. Therefore differences in performance on the recall component support the interpretation that, regardless of the severity of linguistic deficits, WM capacity is reduced in PWA. Similar differences in recall performance between people with and without aphasia were previously demonstrated for the MLS task (Ivanova & Hallowell, 2011). Thus PWA exhibit both specific linguistic deficits and general reductions in processing resources, or limited controlled processing capacity, consistent with Hula and McNeil (2008), McNeil, Odell, and Tseng (1991), McNeil and Pratt, 2001, Murray (1999, 2004), Tompkins et al. (1994), and Sung et al. (2009). In contrast to previous studies demonstrating differences in WM measures between people with and without aphasia, the differences in performance on the EMWM task cannot be easily ascribed to other concomitant deficits in aphasia or to performance requirements of the tasks, given that the EMWM task circumvented most potential task confounds. It is important to point out that even individuals with very mild aphasia (as indicated by a WAB-R

AQ greater than 90) still demonstrated significantly lower performance on the storage (recall) component compared to the control group. Moreover, differences in storage scores were more pronounced than the differences in processing scores for people with very mild aphasia. That is, decreased WM capacity or deficits in overall processing resources are present even in individuals with relatively mild language impairment.

Association between working memory capacity and language abilities

No consistent significant association was observed between WM scores on the EMWM task and scores on subtests of the WAB-R (Kertesz, 2007). This may be interpreted to suggest that a reduction in WM capacity, as indexed using the EMWM method, is an additional concomitant impairment in aphasia above and beyond basic linguistic deficits indexed by the WAB-R. If substantiated through further research, such findings would highlight that it is vital to specifically assess WM in aphasia in addition to basic language abilities because WM capacity cannot be inferred from scores on traditional standardised language tests. These results are in accordance with previously reported data on the MLS task, where no relationship between WM storage scores and scores on subtests of the WAB-R was observed either (see Ivanova & Hallowell, 2011, for a detailed explanation of this finding). However, these findings alone are not sufficient to assert that reduction in WM capacity in aphasia is unrelated to language abilities (such a relationship has been consistently reported in other studies, cf. Martin & Ayla, 2004; Sung et al., 2009; Wright et al., 2007). It may be that, if more complex linguistic stimuli were used, then a significant association between scores on the EMWM task and languages measures would be observed. The relationship between WM capacity limitations and more detailed measures of language processing (in particular, linguistic comprehension) should be explored further. Further developments of the eye-tracking method validated in this study has the potential to become especially helpful in future studies of the degree to which severity of WM capacity limitations is predictive of severity of language deficits, and vice-versa.

Trade-off between processing and storage

No trade-off between processing and storage for either group of participants was observed using the novel eye-tracking method, since change in one aspect of the task (storage) did not affect the other component (processing) of the task. If increasing the memory load (from short to long set sizes or from items at the beginning of the set to items later in the set) led participants to allocate more common resources to maintenance or rehearsal of items in memory, then we should have observed a reduction in processing efficiency and accuracy (i.e., decrease in PFD on target in processing trials). However, we detected no difference between processing scores for items with high versus low memory load. Additionally, even though remembering symbols was more difficult compared to remembering colours (as demonstrated by differences in storage scores for both groups), no differences were observed between processing scores for the two types of sets. Finally, even though PWA had higher storage scores on the short set sizes compared to long set sizes (meaning that remembering longer sets was more difficult for them) no differences in processing scores were found. Thus, in several instances (short vs long set sizes, colours vs symbols), as storage demands increased additional resources were not deployed from the processing component of the task to support execution of the recall component of the task. Taken together these results lead to the conclusion that no trade-off was observed between storage and processing performance in this instance. Similar results concerning the lack of interaction between processing and storage resources were observed in another study where increasing difficulty of the processing component of a complex span task had no impact on storage capacity of PWA (Ivanova & Hallowell, 2011).

The method tested here is promising in terms of its potential to elucidate the nature of processing versus storage deficits through online data. The observed lack of trade-off speaks against a common pool of resources for both storage and processing as proposed by Just and Carpenter (1992). Although it remains possible that participants adopted a fixed resource allocation strategy between processing and storage that they later did not adapt to changing task demands. While this explanation might be feasible for PWA who experience difficulty monitoring task demands and accordingly flexibly distributing resources (Murray, Holland, & Beeson, 1997; Tseng, McNeil, & Milenkovic, 1993), this seems relatively unlikely for people without language and cognitive impairment. It is possible that two different non-interchangeable pools of resources are involved in on-line sentence processing and storage of items, as suggested by Caplan and Waters (1999). Alternatively, it is possible that WM capacity is determined by a more general attentional mechanism—like the ability to allocate attention between two components of a given task, keeping relevant information activated despite possible ongoing interference (Engle et al., 1999; Kane et al., 2004), or efficient constant attention switching (Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Towse et al., 2000). Future research is required to disentangle these possible alternative explanations.

The eye movement working memory task as a measure of working memory capacity in aphasia

Results support the feasibility and validity of employing a novel eye-tracking method to index WM capacity in participants with and without aphasia. WM scores derived from performance on the EMWM demonstrated concurrent validity with another established measure of WM capacity—the MLS task (Ivanova & Hallowell, 2011). Performance on the task discriminated effectively between participants with and without aphasia. The use of such tasks overcomes performance confounds inherent in more traditional WM tasks that require overt motor and/or verbal responses, which are especially problematic for PWA. The EMWM task also incorporated a more natural linguistic processing component compared to other traditional WM tasks that involve metalinguistic judgements or comprehension questions. Like other eye-tracking methods, the EMWM method is also advantageous in that it minimises reliance on comprehension of complex task instructions and yields online processing measures (Hallowell, 2011; Hallowell et al., 2002). The EMWM task is easier to explain to participants compared to other WM tasks; it entails minimal instructions and all PWA in this study were able to pass the training for the task.

Current limitations and future objectives

In the current study only two sentence sets of each size (one with colours and one with symbols as items for recall) were presented in the EMWM task. Inclusion of more sets in WM tasks may reduce unsystematic variability and help detect more subtle patterns of performance.

The lack of in-depth auditory comprehension testing of participants with aphasia precludes extensive analyses of the relationship between WM and language processing abilities most likely to be influenced by WM limitations. Administering a more extensive language test or several language comprehension tasks would allow (a) analysis of performance on WM tasks by more detailed language profiles, and (b) examination of the relationship between WM capacity and linguistic abilities in greater detail.

In the current study we included PWA that greatly varied in age, type of aphasia, and aphasia severity. This was done because the primary goal was to test the validity of the EMWM as a measure of WM for individuals with various types and severity of aphasia. However, such a heterogeneous sample limits specific inferences that can be made regarding the role of WM in aphasia language performance. In future studies larger samples of PWA with certain symptom constellations should be recruited, so that specificity of WM impairments to certain syndromes of aphasia can be determined. Also, time course analysis of eye movement data may yield additional information related to individual differences among PWA with different language profiles. Additionally, WM of individuals with stroke but no aphasia (such as people with right hemisphere brain injury) should be explored to elucidate the relationship between WM and linguistic versus non-linguistic impairments.

Further development of the method described here may be especially applicable to future investigations of whether WM capacity limitations in aphasia are domain-general or specific to linguistic processing. Results of the current study and the study on the MLS task suggest that observed limitations in WM capacity are not specific to particular linguistic stimuli or task requirements. However, further empirical evidence is needed to support this claim. Impact of varying linguistic stimuli (syntactic, semantic, and phonological) on performance should be explored. Additionally, spatial span tasks (Kane et al., 2004) or their variants incorporating nonverbal stimuli should be employed to determine whether limitations in WM capacity transcend different domains.

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APPENDIX

TABLE A1
Characteristics of participants with aphasia

#	A	G	Number of CVAs	Onset	Paresis/ Paralysis	AOS/ Dysarthria	Neuroimaging information	Aphasia type	Scores on the WAB-R subtests: SS	AVC	R	NaWF	AQ	Z-scores on EMWM task: ST	PR
1	78	m	2	130	No	No	Left MCA infarct Left anterior temporal lobe, temporal operculum, posterior insular cortex, posterior frontal, parietal operculum	Anomic	15	9.5	8.8	8.5	83.5	−1.99	−1.12
2	67	f	1	110	No	No	n/a	Anomic	19	9.6	9.1	9.4	94.2	−0.07	0.82
3	72	m	1	11	No	AOS	n/a	Anomic	18	9.3	8.0	9.9	90.3	−0.8	0.38
4	22	m	1	22	No	No	n/a	Anomic/ Conduction	12	7.2	6.2	7.1	65.0	0.06	−0.87
5	53	f	2	64	R side paralysis	AOS	n/a	Anomic	14	8.6	8.6	6.6	75.6	−1.32	−0.64
6	51	f	1	98	No	No	n/a	Anomic	19	9.6	7.2	9.3	90.1	−0.36	−1.5
7	46	m	1	35	R side hemiparesis	AOS	n/a	Transcortical motor	13	9.4	7.4	7.8	75.2	0.03	0.99
8	62	m	1	30	R side hemiparesis	No	n/a	Anomic	14	9.6	8.8	7.3	78.5	−1.62	−0.08
9	64	f	1	32	R side hemiparesis	AOS	Left MCA infarct Left frontalparietal	Transcortical motor	9	7.9	8.2	6.0	62.2	−1.96	−1.08
10	60	f	1	50	R hemiparesis	AOS	n/a	Broca's	8	5.4	5.7	3.7	45.6	−1.2	−1.17
11	63	f	1	42	R leg mild paresis	AOS	n/a	Conduction	12	7.4	2.8	5.0	54.4	−0.85	−0.41
12	67	m	1	18	No	No	Left embolic CVA Left temporoparietal	Anomic	20	10.0	9.8	9.9	99.4	−0.4	0.25
13	55	m	1	45	R paralysis	AOS	Left MCA infarct	Anomic	14	9.9	9.6	8.2	83.4	−0.54	0.09
14	62	m	1	59	R paralysis/ hemiparesis	Dysarthria, poor breath control and voice quality	n/a	Anomic	15	10.0	9.4	10.0	88.8	−0.34	−0.26

15	46	m	2	151	R hemiparesis	AOS	Left large MCA infarct Left frontal, temporal and parietal	Anomic	19	9.1	9.1	8.4	91.2	0.07	−1.49
16	45	f	1	10	R side paresis	AOS	Left MCA haemorrhage Left inferior frontal, inferior parietal, anterior temporal (gliosis and encephalomalacia)	Anomic	16	7.3	8.6	5.6	75.0	−1.19	−0.71
17	60	m	1	125	R side paresis	No, phonation problems	Had a left CVA infarct following removal of a tumor that extended from his neck to the top of his head Left basal ganglia/ insula infarct, also extends to the inferior frontal lobule with middle frontal gyrus white matter change	Anomic	18	10.0	9.9	8.9	93.6	0.05	−0.91
18	59	m	1	74	R leg paresis, R arm paralysis	AOS	Left carotid artery occlusion	Transcortical motor	13	9.0	7.6	7.7	74.5	−0.83	0.27
19	57	m	1	35	R paresis	dysarthria	n/a	Anomic	15	9.4	9.0	9.3	85.4	−1.25	−0.33
20	66	m	1	15	No	No	n/a	Anomic	19	9.1	9.3	8.7	92.1	−0.9	−0.8
21	58	f	2	101	R leg paresis, R arm paralysis	AOS	n/a	Broca's	9	6.9	1.7	5.0	45.1	−1.58	−0.89
22	70	m	1	66	No	Dysarthria	CVA following carotid artery endectomy	Anomic	19	9.6	10.0	9.1	95.4	−0.81	−0.55
23	45	f	1	47	No	AOS	n/a	Anomic	15	9.9	7.7	8.7	82.5	−0.21	0.38
24	41	m	1	20	No	AOS	Left ischaemic CVA, with hemorrhagic conversion Left temporal and frontal	Broca's	11	6.3	3.9	5.0	52.4	−0.81	−0.99
25	59	m	1	275	R hemiparesis	AOS, mild dysarthria	Left MCA and internal carotid haemorrhage (due to aneurism) Large left frontaltemporal lesion	Broca's	12	7.8	4.0	4.7	57.0	−0.83	−1.12
26	60	f	1	68	R hemiparesis	No	n/a	Anomic/ Conduction	12	8.7	6.4	8.5	71.2	−0.13	−0.48

(*Continued*)

TABLE A1
(Continued)

									Scores on the WAB-R subtests					Z-scores on EMWM task	
#	*A*	*G*	*Number of CVAs*	*Onset*	*Paresis/ Paralysis*	*AOS/ Dysarthria*	*Neuroimaging information*	*Aphasia type*	*SS*	*AVC*	*R*	*NaWF*	*AQ*	*ST*	*PR*
27	32	f	1	23	R hemiparesis arm and leg	AOS	Left parietal infarction and dural sinus trombosis/hematoma Left temporal, occipital, and posterior parietal	Anomic	13	8.0	7.5	7.6	72.1	−0.71	−0.75
28	60	m	2	38	R arm weaker	AOS, dysarthria	Anterior left MCA infarct Left frontal operculum region The second incident, which was a TIA, led to cerebellar lesions	Anomic	15	10.0	9.1	8.8	85.8	−0.29	−0.15

A = age; G = gender; Onset = months past onset (if multiple CVAs time from the first CVA is indicated). WAB-R subtests: SS = spontaneous speech; AVC = auditory verbal comprehension; R = repetition; NaWF = naming and word finding. EMWM tasks scores: ST = storage score; PR = processing score. Aphasia type is indicated according to the WAB-R classification. Individual Z-scores for EMWM tasks are indicated relative to the control group without aphasia.