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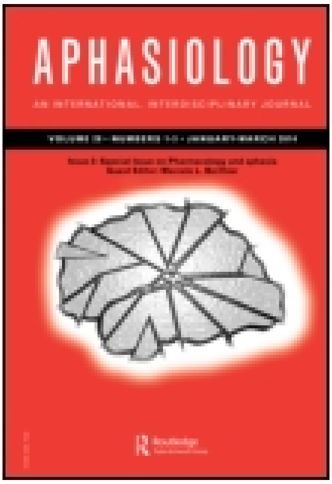

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The contribution of working memory to language comprehension: differential effect of aphasia type

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REPORT

The contribution of working memory to language comprehension: differential effect of aphasia type

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Background: Experimental studies of short-term memory and working memory (WM) in aphasia fail to discriminate cognitive impairments of different aphasia types—non-fluent, Broca-type aphasia and fluent, Wernicke-type aphasia. However, based on the varying fundamental features of these two aphasia syndromes, the potentially different underlying mechanisms of impairment and scant preliminary evidence of varying cognitive deficits, a differential relationship between cognitive function and language processing in these two groups can be predicted.
Aims: The current study investigates the hypothesis concerning the differential impact of cognitive impairments in individuals with fluent versus non-fluent aphasia types.
Methods & Procedures: Participants with fluent (n = 19) and non-fluent (n = 16) aphasia and participants without brain damage (n = 36) were presented with an eye-tracking WM task. Additionally, individuals with aphasia completed two language comprehension tasks.
Outcomes & Results: Results revealed significant decrease in WM capacity in individuals with aphasia compared with participants without brain damage. The two aphasia groups performed similarly on the WM and language tasks. Furthermore, for participants with non-fluent aphasia, it was revealed that WM makes a significant contribution to language comprehension, while for fluent individuals this relationship was not significant.
Conclusions: Overall, the present data support the claim that there are cognitive deficits in aphasia and that these cognitive deficits tend to exacerbate the language impairments of persons with non-fluent aphasia types. The results are discussed in the context of varying mechanisms of impairment in different types of aphasia. The present findings have important implications both for the assessment and the treatment of individuals with aphasia and for understanding the nature of aphasia.

Keywords: fluent aphasia; non-fluent aphasia; working memory; language comprehension

1. Background

Working memory (WM) is broadly defined as “a multi-component system responsible for active maintenance of information in the face of ongoing processing and/or distraction” (Conway et al., 2005, p. 770). Compared to short-term memory (STM) (defined as a

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*Corresponding author. Email: mvimaria@gmail.com capacity for the temporary storage of presented information), the concept of WM places a stronger emphasis on the notion of active manipulation of information instead of passive maintenance. Since the introduction of the concept of WM into cognitive psychology 40 years ago by Alan Baddeley and Graham Hitch, WM capacity has been found to be related to various cognitive tasks, including learning abilities, verbal reasoning skills, math skills, and language processing (Baddeley, 2003; Conway & Engle, 1996; Conway et al., 2005; Cowan, 1999; Engle, Tuholski, Laughlin, & Conway, 1999; Just & Carpenter, 1992). As for language processing, WM has been found to impact vocabulary acquisition, speech production, reading development, pace and accuracy of skilled reading, and language comprehension (Gathercole & Baddeley, 1993). WM's contribution to language comprehension is particularly evident as comprehension entails constant dual-tasking: storage of intermediate products of comprehension and the concomitant processing of incoming serial input. WM has been shown to qualitatively and quantitatively impact the comprehension of various syntactically complex sentences in participants without cognitive, language, or neurological impairments (Just & Carpenter, 1992). Participants with larger WM capacity were able to integrate syntactic and pragmatic information better and more quickly during sentence comprehension and to maintain several interpretations of the input during ambiguity resolution (Just & Carpenter, 1992). In addition, WM has been shown repeatedly to be related to both specific tasks of linguistic comprehension requiring the integration of successively encountered elements and general tests of language comprehension and vocabulary knowledge (Daneman & Merikle, 1996).

1.1. Working memory in aphasia

In consideration of the data demonstrating that WM is vital to normal language processing, and to language comprehension in particular, understanding the nature of WM is crucial to delineating the mechanisms of language breakdown in aphasia. The role of memory in language impairment in aphasia has been described by several authors even prior to the introduction of the notion of WM to the field of aphasia. Luria (1980) stated that a verbal memory impairment was at the core of a specific fluent aphasia type—acoustic-mnestic aphasia. Kolk and van Grunsven (1985) first proposed a (working) memory explanation of agrammatism in aphasia. They suggested that either a reduced storage capacity or an increased decay rate of information was at the core of syntactic comprehension deficits in aphasia; however, their hypothesis was not supported in a subsequent study (Martin, Wetzel, Blossom-stach, & Feher, 1989).

Tompkins, Bloise, Timko, and Baumgaertner (1994) conducted a first systematic investigation of WM in aphasia using simplified adaptations of Daneman and Carpenter (1980) complex span tasks. Since then ample empirical evidence has been accumulated demonstrating that individuals with aphasia have reduced WM capacity (for a review, see Murray, Ramage, & Hopper, 2001; Wright & Fergadiotis, 2012; Wright & Shisler, 2005). Numerous studies have shown that participants with aphasia perform worse on WM tasks than control participants who have no neurological, cognitive, or language impairments (Tompkins et al., 1994) and that reduced WM capacity negatively impacts linguistic performance (Caspari, Parkinson, LaPointe, & Katz, 1998; Wright, Newhoff, Downey, & Austermann, 2003), with language comprehension being particularly susceptible to a decreased WM capacity (Sung et al., 2009; Wright, Downey, Gravier, Love, & Shapiro, 2007). Furthermore, participants with aphasia have demonstrated more pronounced STM/WM deficits than individuals with left hemisphere brain damage but without any language impairment (Kasselimis et al., 2013; although previously Burgio & Basso, 1997, on a smaller sample have demonstrated that the presence of aphasia had no effect on memory task performance). Additionally, WM in aphasia has been shown to follow the same constraints as in healthy controls (Christensen & Wright, 2010). More recently, researchers have investigated specific aspects of memory impairments in aphasia and their differential relationships with various language abilities (Christensen & Wright, 2010; Friedmann & Gvion, 2003; Laures-Gore, Marshall, & Verner, 2011; Martin & Reilly, 2012; Mayer & Murray, 2012; Sung et al., 2009; Wright et al., 2007).

Still, despite the mounting evidence demonstrating that WM capacity is reduced in aphasia, the precise link between WM impairments and language processing remains elusive. Some of the previous studies have been able to find a significant relationship between WM capacity and scores on language tests (Caspari et al., 1998; Potagas, Kasselimis, & Evdokimidis, 2011; Sung et al., 2009; Tompkins et al., 1994), while others did not (Christensen & Wright, 2010; Ivanova & Hallowell, 2012, 2014; Mayer & Murray, 2012). The inconsistency in findings has been attributed to specific stimuli in WM tasks (Mayer & Murray, 2012), mismatch in processing load between WM and language tasks used (Christensen & Wright, 2010; Ivanova & Hallowell, 2012), and variability of the aphasia groups (Ivanova & Hallowell, 2014). The latter point has received much less attention and warrants further examination.

In studies of WM in aphasia, mixed aphasia groups are always recruited, and thus the relationship between cognitive processing impairments (WM limitations) and language ability is examined simultaneously in individuals with very distinct profiles of language impairments. At the same time, it seems reasonable that WM might play a different role in language processing depending on aphasia type. For instance, initially Kolk and van Grunsven (1985) proposed that a WM deficit is at the core of agrammatic aphasia. Some researchers continue to associate WM impairments with agrammatic aphasia types (Garraffa & Learmonth, 2013; Haverkort, 2005). Recently, Friedmann and Gvion (2003) demonstrated differential memory and language difficulties, respectively, in individuals with conduction aphasia versus Broca's aphasia. These findings necessitate further differential investigation of WM impairments in aphasia.

1.2. Types of aphasia and differential impairments

Numerous classifications of aphasia have evolved since the first scientific description of an aphasia syndrome by Paul Broca in 1861. While different names have been used and different bases for classification have been proposed, there is more uniformity than discord in the actual description of the clinical syndromes specified within different approaches to aphasia (Ardila, 2010; Caplan, 1987). The two main fundamental types of aphasia distinguished in every classification are Broca's (motor) aphasia and Wernicke's (sensory) aphasia. These two types of aphasia form the core of two general categories of aphasia sometimes described as syntagmatic and paradigmatic (Jakobson, 1956; Luria, 1973); or motor and sensory (Luria, 1980); or anterior and posterior (Benson, 1973; Tonkonogy & Puente, 2009); or non-fluent and fluent (Benson & Ardila, 1996; Goodglass, Kaplan, & Barresi, 2001). The two syndromes reflect the opposition introduced by Jakobson (1956) and further exemplified by Luria (1973): there are two basic forms of aphasic disturbances, sequencing disorder and selection disorder. This qualitative distinction between two major aphasic categories is further solidified and expanded in recent work by Ardila and colleagues (Ardila, 2010; Benson & Ardila, 1996), who in detail describe two primary types of aphasia: Broca type and Wernicke type.

Broca-type aphasia exemplifies the clinical syndrome of damage to the grammar system of language and is characterised by impairments in the sequencing process of expressive elements (Ardila, 2010). Halting non-fluent speech, verbal-articulatory difficulties, shortened sentences and morpho-syntactic agrammatism (both expressive and receptive) are typical of this type of aphasia (Menn, O'Connor, Obler, & Holland, 1995). The motor component of this syndrome is often regarded as a concomitant speech impairment (apraxia of speech). The core deficit in Broca-type aphasia is not in the selection of appropriate linguistic features or items but in binding them in the right order and generating meaningful connections between them; that is, it is a syntagmatic axis defect.

In contrast, Wernicke-type or fluent aphasia represents the clinical syndrome of damage to the lexical-semantic system of language and is characterised by impairments in the selection process at different language levels (Ardila, 2010; Edwards, 2005). Patients with Wernicke-type aphasia experience difficulties with phoneme discrimination, word selection, and associating words with specific meanings. Fluent speech with circumlocutions, phonemic and semantic paraphasias, decreased vocabulary, word finding errors, and evident language comprehension difficulties are all characteristic of this type of aphasia. Depending on the locus of the deficit, whether it is at the phoneme, lexical, or semantic level, different types of aphasia can be discriminated. For example, Luria (1980) distinguished acoustic-agnostic (sensory), acoustic-mnestic, and amnestic aphasias. All of these syndromes are included under the umbrella term Wernicke-type aphasia proposed by Ardila (2010), since the common ground for each is a deficiency in the selection process at the word level; in other words, it is a paradigmatic axis defect.

Although the debate about the utility of aphasia classification for research (Caramazza, 1984; McNeil & Kimelman, 2001) and clinical practice (Marshall, 2010) remains open, with the main concern being considerable intra-group variability of each syndrome, different types of aphasia, such as Broca's and Wernicke's aphasia, do on the whole signify distinct profiles of language impairment (Ardila, 2010). Further substantiating the universality of these categories is the fact that these distinctive syndromes occur in different languages (Menn et al., 1995), including sign language (Poizner, Klima, & Belugi, 1987). Broca- and Wernicke-type aphasias also show a consistent correspondence (albeit not unanimous) with anterior (pre-Rolandic) brain regions and posterior (post-Rolandic) regions, respectively (Kreisler et al., 2000). A recent (and the only one to date) large voxel-based lesion–symptom mapping study that included 102 patients with aphasia demonstrated that Broca's and Wernicke's aphasia types corresponded to distinct non-overlapping anterior and posterior lesion sites (Henseler, Regenbrecht, & Obrig, 2014). Taken together, this evidence speaks for the reality of these categories and for the differential involvement of neural and linguistic mechanisms in different types of aphasia.

Multiple studies have consistently demonstrated distinct linguistic effects in these two divergent aphasia categories (Benson & Ardila, 1996; Friederici, Hahne, & Yves von Cramon, 1998; Vasić, Avrutin, & Ruigendijk, 2006). However, very few studies have looked into whether different cognitive impairments would be associated with these two distinct profiles of language impairment. Only Luria (1980) proposed that a STM deficit is an essential characteristic of a certain posterior, fluent aphasia (acoustic-mnestic aphasia). Friedmann and Gvion (2003) demonstrated that a certain type of reactivation required in sentence processing (syntactic-semantic versus form/phonological) will be disrupted depending on the type of memory impaired and that this varies between agrammatic (Broca's) and conduction aphasia. Several authors associate verbal WM impairment specifically with Broca's aphasia (Garraffa & Learmonth, 2013; Haverkort, 2005). However, the available evidence is geared more towards distinguishing between different theories of agrammatism, rather than describing differential cognitive deficits in aphasia. Additionally, studies looking into the relationship between WM and syntactic comprehension often specifically recruit individuals with agrammatic aphasia, that is, non-fluent aphasia. Scant empirical evidence comparing cognitive impairments between different aphasia types reveals differences in memory capacity (Seniów, Litwin, & Lesniak, 2009a). Taken together, conceptual considerations and preliminary empirical evidence warrant further structured investigation of differential cognitive impairments in individuals with various aphasia types.

1.3. Aims of the current study

Experimental studies of STM and WM in aphasia fail to discriminate the cognitive impairments of different aphasia types. However, based on the diverging features of the two fundamental aphasia syndromes and the differing potential underlying mechanism of impairment, we can hypothesise that (a) the profile of cognitive impairments characteristic of these two syndromes will be different; and (b) a differential relationship between cognitive function and language processing will be observed in these two groups. Our study aimed to provide further insight into these issues. In the present study we follow the main distinction proposed by Ardila (2010) and recognise Broca-type/non-fluent aphasia and Wernicke-type/fluent aphasia.

The specific aims of the current investigation were to:

(1) compare verbal WM capacity in individuals without brain damage who show no language, cognitive or neurological impairments to individuals with different types of aphasia;
(2) compare cognitive processing impairments in two fundamental categories of aphasia: Wernicke type and Broca type; and
(3) investigate the contribution of verbal WM to general language comprehension in these two clinical groups.

First, we anticipated that verbal WM would be reduced in all clinical groups compared to non-brain-damaged participants without aphasia. Next, we did not have any specific predictions regarding differences in WM capacity limitations between Broca-type and Wernicke-type aphasias, given that WM deficits have been associated with varying language profiles (Friedmann & Gvion, 2003) and sites of lesion (Ivanova & Hallowell, 2012; Kasselimis et al., 2013). Finally, we anticipated that verbal WM would be related to language comprehension in Broca-type aphasia, as resources are required to perform sequencing operations with grammatical entities and preliminary findings point to WM contributing to language deficits in this type of aphasia. We expected to see a much weaker link between verbal WM capacity and language comprehension in Wernicke-type aphasia because cognitive processing deficits have never been pinpointed as the main cause of language comprehension impairments in Wernicke's aphasia.

2. Method

2.1. Participants

Individuals with and without aphasia participated in the study. Inclusion criteria for both the groups were: (a) chronological age ranging from 25 to 75 years; (b) status as a native speaker of Russian; (c) right-handedness; (d) intact visual acuity for near vision as assessed with the Lea Symbols Line Test (Precision Vision) containing symbols that vary in size (Hyvärinen, Näsänen, & Laurinen, 1980); (e) intact colour vision verified via "Colour Vision Testing Made Easy" (Waggoner, 1994); and (f) hearing acuity screened at 500, 1000, and 2000 Hz at 40 dB sound pressure level. Additionally, following the recommendations of Hallowell (2008) for vision screening in speech–language research, intactness of visual fields was evaluated with an Amsler grid and a confrontation finger counting test, and extraocular motor functions and pupil reflexes were evaluated.

2.1.1. Participants without language impairment

Additional inclusion criterion for individuals without aphasia was no reported history of speech, language, cognitive, or any neurological impairment. Thirty-six individuals without brain damage (24 females), aged 29–75 years (mean, *M* = 50; standard deviation, *SD* = 12.5), years of education (*M* = 14.6, *SD* = 1.4) participated.

2.1.2. Participants with aphasia

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

We specifically recruited participants with Broca-type (non-fluent) or Wernicke-type (fluent) aphasia (as defined by Ardila, 2010) at the in-patient unit of the Center for Speech Pathology and Neurorehabilitation in Moscow, Russia. Categorisation of a participant's aphasia type was made by an experienced neuropsychologist and a speech–language pathologist working with the patient based on extensive neuropsychological examination of language and other cognitive functions. All patients included in the current study were tested by the same neuropsychologist (third author), while the speech–language pathologist varied from patient to patient. Diagnosis of aphasia was based on clinical evaluation and performance on a series of neuropsychological tasks developed by Luria and colleagues (Christensen, 1990; Luria, 1980). Only individuals on whose aphasia type the two clinicians mutually agreed upon were included in this study (i.e., cases of mixed aphasias or when the type of aphasia could not be clearly determined were excluded from the study). Luria's (1980) classification was used to determine the original type of aphasia. Individuals with efferent motor aphasia were included in the Broca-type/non-fluent group, while individuals with sensory and/or acoustic-mnestic aphasia were included in the Wernicke-type/fluent group. Efferent motor aphasia (analogous to Broca's aphasia) is characterised by non-fluent, effortful and agrammatic language production, with relatively spared comprehension. Sensory aphasia (analogous to Wernicke's aphasia) is characterised by fluent speech with frequent phoneme and semantic paraphasias, accompanied by pervasive difficulties in phoneme perception and selection. Acoustic-mnestic aphasia represents a continuation of sensory aphasia at the word level and is primarily characterised by difficulties in word selection, naming difficulties, and reduced verbal memory span. While the match between specific aphasia types within the Luria classification and the western multidimensional approach to aphasia classification is debated (see Caplan, 1987), the general distinction between individuals with fluent or Wernicke-type aphasia and non-fluent or Broca-type aphasia is shared and accepted within both the approaches.

Here we reiterate that the assignment of umbrella terms “fluent” and “non-fluent” was not based on the scores of a single subtest targeting fluency but on the qualitative distinction between two major aphasic categories suggested by Benson and Ardila (1996) and Ardila (2010): anterior, non-fluent; and posterior, fluent. Our distinction between different aphasia types remains on the functional level, without any anatomical groundings, which is to say that our patients with non-fluent and fluent aphasia do not necessarily have lesions restricted to the prefrontal cortex and temporal cortices, respectively. The determination of the complex relations between neural substrates and language impairment profile is the goal of a completely different research agenda.

Sixteen individuals with non-fluent aphasia and 19 individuals with fluent aphasia participated in our study. In the non-fluent aphasia group, there were six females and 10 males, aged 25–75 years (M = 52.9, SD = 11.4), years of education ranged from 3 to 15 years (M = 12.8, SD = 3.1), with time post-onset ranging from 2 to 47 months (M = 17.2, SD = 12.4). In the fluent aphasia group, there were eight females and 11 males, aged 27–73 years (M = 55, SD = 12.4), years of education ranged from 10 to 15 years (M = 13.2, SD = 2.5), with time post-onset ranging from 2 to 48 months (M = 13.7, SD = 13.7). Participants in the two aphasia groups did not differ significantly in age, time post-onset, or years of education. Moreover, the two groups were not significantly different from the control group in age; the control group had slightly higher level of education compared to the aphasia group (non-fluent group: $t(17.18) = 2.09$, $p = .051$; fluent group: $t(24.24) = 2.32$, $p = .029$). Detailed participant characteristics are provided in Appendix 1.

2.2. Experimental tasks

2.2.1. WM task

To assess verbal WM the Russian version of the eye movement working memory (EMWM) task was presented to participants (for a detailed description of the task see Ivanova & Hallowell, 2012). In this task, participants were required to look at a computer screen during the 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 structure of the task was modelled after a classical complex span task designed to index WM (Conway et al., 2005) and incorporated a processing and a storage component.

The comprehension-processing component included a multiple choice visual array containing four pictures, accompanied by a verbal stimulus corresponding to one of the pictures. Verbal stimuli were short three-word present tense active declarative semantically reversible sentences (e.g., *Malchik tseluet devochku*/*The boy is kissing the girl*). The three foils in the multiple choice arrays included (a) a grammatical foil depicting the same action with reversed agent–patient roles, (b) the same referents performing a different action, and (c) a different action with reversed agent–patient roles. Foils created this way allowed any picture to be the target while maintaining the specific semantic relations between the target and foils. The location of the target in each quadrant was counterbalanced across trials. Twenty multiple choice image sets of this kind were created and presented with different verbal stimuli accompanying the visual set each time.

Following each multiple choice array (trial), an item to be remembered was presented within a separate display. Eleven distinct coloured squares were used as storage items.

Participants were explicitly instructed to remember the colours that they saw. Multiple choice arrays (trials), each one followed by a display with an item to be remembered, were presented in sequences of two to five sets. At the end of each sequence of trials, a "recognition screen" with different combinations of colours in each quadrant was presented. Participants were instructed to look at the quadrant containing the colours they just saw. In this manner three sets of each size were presented in ascending order.

The visual stimuli were presented on a 17-inch computer screen. The visual and verbal stimuli for the comprehension-processing component were presented simultaneously. The multiple choice arrays were displayed for twice the duration of the auditory stimuli plus 2 s rounded to the nearest second. Displays with storage items were presented for 2 s each without any accompanying verbal stimuli. The duration of the recognition screen was determined by the number of items to be recalled, multiplied by 2.5 s (for instance, recognition arrays for a set size of three lasted 7.5 s). Recognition arrays were also not accompanied by verbal stimuli.

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 with custom presentation software. 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 the fixation location and duration and to eliminate blink artefacts. Fixation was defined as a stable position of the eye (with six pixels horizontal and four pixels vertical tolerance) for at least 100 ms. Eye-tracking data were summarised in terms of proportion of fixation duration (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 for the recognition screens was the image containing all of the items (coloured squares) to be recalled. Thus, the WM score represented the average PFD on the target image across recognition screens. Ivanova and Hallowell (2012) have demonstrated that PFD is a valid measure to index WM capacity in the following task. Storage WM scores for the EMWM task were the mean PFD on the target images across recognition screens.

2.2.2. Language tasks

Participants with aphasia were administered two standardised language tests with a focus on auditory comprehension both designed for speakers of Russian with aphasia: the Multiple-Choice Test of Auditory Comprehension (MCTAC; Hallowell & Ivanova, 2009) and the Quantitative Assessment of Speech in Aphasia (QASA, *Kolichestvennaya otsenka rechi pri afasii*; Tsvetkova, Akhutina, & Pylaeva, 1981).

The MCTAC is a multiple choice test based on the adaptation of the Revised Token Test (RTT; McNeil & Prescott, 1978) designed by Hallowell, Wertz, and Kruse (2002) and translated and normed in Russian by Hallowell and Ivanova (2009). The MCTAC is composed of a multiple choice array of four pictures with corresponding verbal stimuli. The verbal stimuli are based on the first eight subtests of the RTT, but instead of manipulating test items, participants are required to point to an image matching the verbal stimulus. As in the RTT, squares and circles are used as shapes; black, green, red, blue, and white are used as colours; and big and little correspond to the size of the shapes. Five items comprise each of the eight subtests, with the test having 40 items overall. The verbal stimuli increase in length and complexity from subtest one ("black circle") to subtest eight ("the little green circle is to the left of the big red square"). Subtests 1–4 include varying sets of stimuli without any spatial relations between them ("green square and black square"); subtests 5–8 include complex spatial relations that must be processed accurately for the target image to be selected ("the big red square is in front of the big white circle") (see Hallowell & Ivanova, 2009, for a detailed description of each subtest). The image arrays consist of four images located at the corners of each test page. One of the images matches the verbal stimulus and serves as the target, while the other three act as foils and differ from the target in terms of visual characteristics representing semantic elements of the verbal stimulus, such as shape, colour, size, and spatial orientation. Scoring of the test is binary (correct/incorrect); the overall score is the percent of correct items out of the total number of items of the test.

The QASA (Tsvetkova et al., 1981) is a traditional Russian language battery for aphasia that includes a rating of conversational speech and production and comprehension subtests. The production subtest includes the following tasks: confrontational naming of objects and actions, sentence construction, and picture description. The comprehension subtest contains tasks on single-word auditory comprehension, sentence comprehension, and following commands. The single-word auditory comprehension requires participants to match a word(s) to a picture(s) within a 10-picture visual array. At the beginning of the task, single words are presented and then the length of the series is increased to two-word and three-word strings. Both comprehension of objects (30 items) and actions (30 items) of varying lexical frequency are tested in this manner. For each item (both single words and series of words) in these two subtests the participant can either receive a score of 1 for the correct selection of a picture or pictures; 0.5 for either showing a series of words in an incorrect order or for requiring a repetition of the verbal stimuli; or 0 for all other types of incorrect answers. In the sentence comprehension task, participants are required to match a sentence they hear to a target picture choosing amongst three to six alternatives. Presented sentences (15 items) vary in syntactic complexity ranging from simple irreversible actions ("The mother is washing the glass.") to passive sentences ("The boy is saved by the girl.") and complex spatial relations ("The barrel is in the box."). For each item in the sentence comprehension subtest, the participant can either receive a score of 2 for the correct selection of a picture; 1 for requiring a repetition of the sentence; or 0 for all other answers. In the last comprehension task, participants have to follow commands of increasing complexity (10 items) by performing certain actions (e.g., "close your eyes") and carrying out manipulations with six real objects ("take the book, put the notebook inside it and place them on the edge of the table"). For each item in the commands subtest, the participant can either receive a score of 3 for a completely correct execution of the command; 1.5 for requiring a repetition of the verbal command; or 0 for all other responses. In the current study, we included only the cumulative scores on the comprehension subtest of the QASA in the analysis.

2.3. Experimental procedures

Participants were tested individually in a quiet room at the Center for Speech Pathology and Neurorehabilitation. Experimental tasks were completed over the course of three to four 30-minute sessions. Each task would typically take up a whole session, with some participants needing two sessions to complete the QASA test. Order of tasks was counterbalanced across participants. All the participants were tested within the course of one week. The EMWM task was presented on the computer, and the eye movement data were automatically collected. The two language tasks were presented and scored by the examiner. The time period between aphasia diagnosis and experimental testing was between 1 and 3 weeks.

3. Results

3.1. *Descriptive statistics*

Descriptive statistics (*M*, *SD*, minimum, and maximum) for the WM scores (storage and processing) on the EMWM task for participants with and without aphasia, along with scores on the two language tests, are presented in Table 1. The eye movement data are summarised in terms of PFD on the target, after trials with data loss greater than 50% were eliminated. That is individual trials (presentation of each visual display within a set), where due to blink artefact, participant eye movement tracking data were recorded for less than half of the duration of the visual stimulus, were not taken into account. This ensured validity of obtained results. This preliminary filtering of eye movement data resulted in the removal of 1.9% of trials.

3.2. *Intergroup differences in performance*

Participants with aphasia had significantly lower WM storage scores than the control group (non-fluent: $t(50) = 9.37$, $p < .001$; fluent: $t(53) = 9.60$, $p < .001$). At the same time, no significant differences were found in WM scores between the two groups of participants with aphasia, $t(33) = -0.18$, $p = .86$. Also, participants with fluent and non-fluent aphasia had similar severity of language comprehension impairments, as indexed by the two language tests (MCTAC: $t(33) = 0.26$, $p = .8$; QASA: $t(33) = 1.68$, $p = .1$).

3.3. *Correlational analysis*

Pearson correlational analyses were computed to investigate the relationship between performance on the WM and language tasks for participants with aphasia. For individuals with non-fluent aphasia, WM storage scores were marginally related to performance on the MCTAC ($r(14) = .44$, $p = .08$) and significantly related to QASA comprehension subtests ($r(14) = .49$, $p = .05$). For individuals with fluent aphasia, no significant

Table 1. Descriptive statistics for working memory and language tasks.

	Participants without aphasia (*N* = 36)		Participants with non-fluent aphasia (*N* = 16)		Participants with fluent aphasia (*N* = 19)	
Tasks	*M* (*SD*)	Range	*M* (*SD*)	Range	*M* (*SD*)	Range
Eye movement working memory task	0.76 (0.12)	0.41–0.93	0.44 (0.10)	0.26–0.59	0.45 (0.10)	0.28–0.69
MCTAC	–	–	0.74 (0.10)	0.5–0.85	0.73 (0.14)	0.4–0.95
QASA comprehension	–	–	25.8 (3.0)	18–29.25	24.09 (3.07)	18.75–29.5

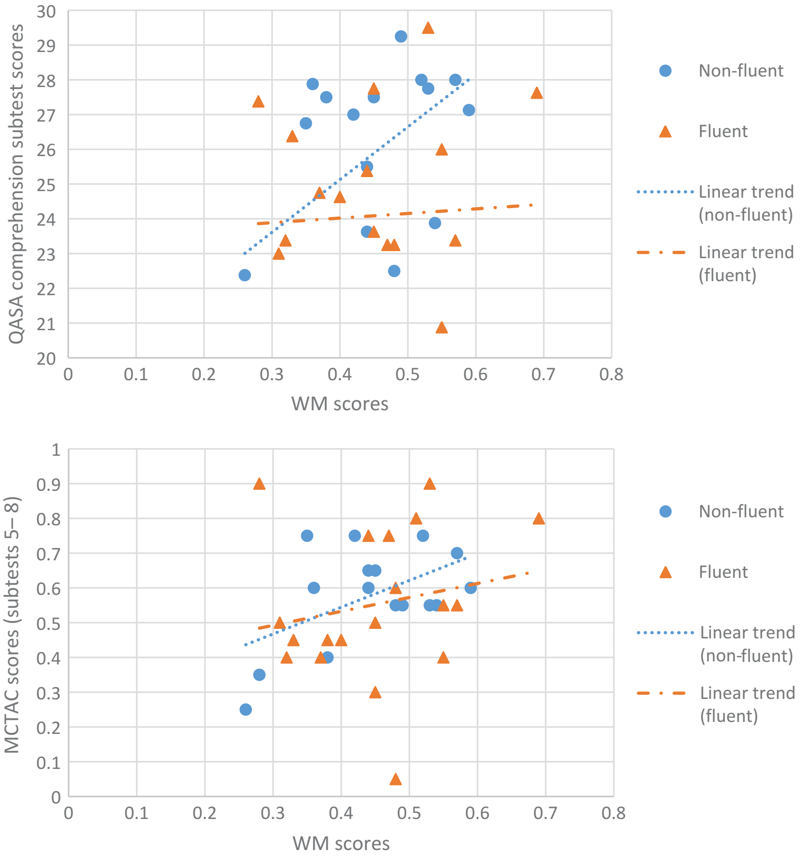

Figure 1. Scatterplots and linear trends between WM scores and language comprehension indices (QASA comprehension subtest and MCTAC scores).

relationship between performance on the WM task and language tests was observed (MCTAC: *r*(17) = .16, *p* = .51; QASA: *r*(17) = .05, *p* = .86).

When we further probed the relationship between WM scores and the MCTAC, we found that it was driven by the subtests 5–8 which contained more complex linguistic stimuli. For participants with non-fluent aphasia, the correlation between these subtests and the WM storage scores was significant (*r*(14) = .52, *p* = .04), while the correlation between subtests 1, 2, 3, and 4 which included shorter and simpler stimuli was not significant (*r*(14) = .14, *p* = .6). For participants with fluent aphasia, both of the correlations remained non-significant (for subtests 5–8: *r*(17) = .19, *p* = .42; for subtests 1–4: *r*(17) = .03, *p* = .92). The relationship between WM capacity and language comprehension is demonstrated graphically in Figure 1.

4. Discussion

4.1. WM limitations in aphasia

The current study aimed to investigate verbal WM impairments in two types of aphasia and their differential relationship to language comprehension. In accordance with our hypothesis, participants with aphasia performed significantly worse on the WM task compared to non-brain-damaged individuals without any cognitive, language, or neurological impairments. These results replicate numerous previous findings that demonstrate a reduction in WM resources as one of the prominent cognitive impairments in aphasia (Ivanova & Hallowell, 2012, 2014; Mayer & Murray, 2012; Potagas et al., 2011; Sung et al., 2009; Tompkins et al., 1994; Wright et al., 2007).

No differences in the degree of verbal WM impairment between participants with fluent and non-fluent aphasia were observed. Although there are no reported studies directly comparing individuals with fluent and non-fluent aphasia on WM, to the best of our knowledge, the present findings are compatible with multiple investigations of cognitive deficits in aphasia that failed to demonstrate a differential impairment in cognitive abilities for a specific aphasia type. Kasselimis et al. (2013) demonstrated a lack of association between lesion site and severity of verbal and visuospatial STM/WM impairment in individuals with aphasia. Ivanova and Hallowell (2014) found no significant difference in degree of WM impairment between participants with mild versus moderate aphasia. Zakariás, Keresztes, Demeter, and Lukács (2013), contrary to their initial expectations, found an impairment in executive functions, including WM abilities, in individuals with conduction aphasia as well as those with transcortical motor aphasia. Friedmann and Gvion (2003) also found impairment of WM in both Broca's and conduction aphasia, although participants showed a different pattern of comprehension deficits, depending on the type of aphasia. Only Seniów et al. (2009a) reported significant variability of cognitive impairments in individuals with different types of aphasia (with cognitive abilities being completely intact in some participants), but did not specify which individuals had better cognitive performance. In general, most previous studies of aphasia and WM, as well as related cognitive abilities such as attention and executive functions, included mixed groups (Caspari et al., 1998; Ivanova & Hallowell, 2012, 2014; Murray, 2012a; Purdy, 2002; Sung et al., 2009). All the participants in these studies showed at least some degree of impairment in the domain under investigation. In general, these findings on WM in individuals with brain damage are in accordance with neuroimaging studies of WM in healthy individuals that demonstrate a widespread neural network of frontal and posterior areas required for successful WM functioning (Chein, Ravizza, & Fiez, 2003; Collette & Van der Linden, 2002).

4.2. Relationship between WM and language

Further, and also in accordance with our initial hypothesis, our data demonstrated different relationships between verbal WM and language performance depending on aphasia type. For participants with non-fluent aphasia, it was revealed that WM makes a significant contribution to language comprehension, while for fluent individuals, this relationship was not significant. It should be emphasised that this diverging pattern cannot be attributed to differences in the severity of language impairments between the two groups, as each group performed similarly on the WM and the language tasks. Also, with respect to individuals with non-fluent aphasia, we would like to point out that only individuals with efferent motor (Broca's) aphasia were included in this group in the present study. Persons with predominant transcortical motor aphasia (or dynamic aphasia, according to Luria), whose language difficulties are regarded by many researchers (Robinson, Blair, & Cipolotti, 1998; Zakariás et al., 2013) to stem primarily from cognitive impairments (Ardila, 2010, even labels it "disexecutive aphasia"), were not included in the sample.

Our results are compatible with numerous cognitive interpretations of non-fluent, Broca-type aphasia, where overall sluggishness and a decreased rate of information processing, along with reduced processing capacity, are postulated to play a pivotal role in the observed language deficits (Kearns, 2005). Thus, memory impairment is seen as one of the sources (although not an exclusive one) of language comprehension breakdown in non-fluent aphasia. As outlined by Luria (1973, 1980), Benson and Ardila (1996) and Ardila (2010), individuals with non-fluent aphasia experience difficulties in the sequencing of information, whether it is at the syllable, word, or syntactic level. In order to perform and decode these sequencing operations, such as aligning syllables within a word or words within a sentence, processing resources are required to maintain linguistic representations in active memory while performing mental manipulations with them. Therefore, those individuals who possess a larger verbal WM capacity perform better on general comprehension tasks that require lexical-semantic reactivation.

Meanwhile in fluent, Wernicke-type aphasia, a lexical-semantic deficit is considered to be of central importance with concomitant cognitive deficits playing only a secondary role (Caspari, 2005). The deficits are more of a paradigmatic type, concerning retrieval of correct elements and inhibition of irrelevant ones (Ardila, 1993, 2010; Benson & Ardila, 1996; Luria, 1973, 1980). WM capacity plays very limited (if any) role in the processes of lexical selection and inhibition, thus no relationship between decreased WM capacity and language comprehension is observed. Therefore, while individuals with fluent aphasia do have a limited verbal WM capacity, their language comprehension abilities seem to be independent of it.

4.3. Limitations of the current study and directions for future research

The current findings of a differential relationship between WM capacity and language comprehension depending on aphasia type warrant further inquiry. Future studies in this direction should take into account the limitations of the current study while expanding the phenomena under investigation. First, the language tests used in this study assessed only auditory language comprehension at a general level and only off-line. Future studies should look differentially at various levels of language comprehension, such as lexical-semantic and syntactic processing. Additionally, it will be important to look into online and offline sentence processing, as evidence to date supports a divergence between online and offline processing impairments in aphasia (Caplan & Waters, 1999; Choy & Thompson, 2010). Likewise, Caplan and Waters (2013) indicate that the memory mechanisms involved in online parsing and interpretation differ from those used in post-interpretive processing. Second, it will be important to investigate whether the link between WM and language comprehension in aphasia is specific to verbal WM or indicates a truly domain general deficit that has an impact on language processing. This can be examined by employing non-verbal WM tasks and other minimally linguistic measures of controlled attention and executive functions.

5. Conclusion

The findings of the current study have both conceptual and clinical implications. The present data support the claim that there are cognitive deficits in aphasia and that these cognitive deficits tend to exacerbate the language impairments of persons with non-fluent aphasia. In other words, beyond the possible deficient implementation of linguistic rules and operations, adults with aphasia experience problems with manipulating those representations because of their WM deficits. These postulations have important consequences for both understanding the nature of aphasia and the assessment and treatment of individuals with aphasia. Conceptually, they warrant further specification of the complex relationship between different cognitive functions. From a practical standpoint, they necessitate different treatment approaches for different aphasia types, especially given the preliminary evidence that suggests that cognitive deficits impact language recovery in aphasia (Murray, 2012b; Seniów, Litwin, & Leśniak, 2009b). For individuals with a non-fluent, Broca-type aphasia, treatments need to be more cognitively oriented, as cognitive deficits seem to directly impact their level of performance on language comprehension tasks. In turn, for individuals with a fluent, Wernicke-type aphasia, treatment needs to be more language focused as their cognitive deficits do not seem to be intrinsic to their language impairments. Indeed, these suppositions require further thorough examination prior to practical implementation.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix 1. Characteristics of participants with aphasia.

Participant	Age	Gender	Education level	Group	Months post-onset	Primary aphasia type	Neuroimaging information
1	46	Male	University	Non-fluent	12.5	Efferent motor	Left MCA infarct
2	50	Male	University	Non-fluent	25	Efferent motor	Left ischaemic CVA, large left hemisphere lesion involving temporal and parietal lobes
3	49	Female	University	Fluent	3	Sensory	Left MCA infarct involving the frontal lobe
4	73	Male	University	Fluent	2	Acoustic-mnestic	Left CVA infarct in the terminal branches of the MCA
5	75	Female	University	Non-fluent	29	Efferent motor	Left MCA infarct involving frontal, temporal, and parietal lobes
6	59	Female	University	Fluent	10	Sensory	Left MCA infarct involving the temporal lobe
7	45	Female	High school	Fluent	2	Sensory	Left infarct in the cortical branches of the MCA
8	71	Male	High school	Fluent	3	Sensory	N/A
9	58	Male	High school	Fluent	8	Acoustic-mnestic	Left MCA infarct involving the parietal lobe
10	67	Male	Primary school	Non-fluent	11	Efferent motor	Left ischaemic CVA in cortical branches of MCA
11	57	Male	University	Fluent	48	Acoustic-mnestic	Left haemorrhagic CVA in the temporal-parietal lobes
12	55	Female	High school	Non-fluent	8.5	Efferent motor	N/A
13	45	Female	University	Fluent	30	Acoustic-mnestic	Left MCA infarct involving temporal and parietal lobes
14	48	Male	High school	Non-fluent	32	Efferent motor	N/A
15	54	Male	University	Non-fluent	47	Efferent motor	N/A
16	69	Female	University	Fluent	12	Acoustic-mnestic	Left MCA infarct involving cortical and subcortical areas of the frontal and temporal lobes, with partial cortical atrophy in the inferior frontal and insular gyri
17	57	Female	University	Non-fluent	18	Efferent motor	Left MCA and ACA infarct. Lesion in left frontal and temporal lobes involving both grey and white matter, with partial cortical atrophy of the inferior and medial portions of superior frontal gyrus and inferior portions of pre-, post-central, and insular gyri
18	46	Male	High school	Non-fluent	18	Efferent motor	Left MCA infarct involving the frontal, temporal, and parietal lobes, with partial cortical atrophy of inferior regions of pre- and post-central, supramarginal and insular gyri

(*continued*)

Appendix 1. (*Continued*).

Participant	Age	Gender	Education level	Group	Months post-onset	Primary aphasia type	Neuroimaging information
19	55	Male	High school	Non-fluent	12	Efferent motor	Left MCA and ACA infarct involving cortical and subcortical regions of the left frontal and temporal lobes. Partial cortical atrophy of the inferior medial regions of the superior frontal gyrus, inferior part of the pre- and post-central gyri, and insular gyri
20	55	Female	University	Fluent	6	Acoustic-mnestic	Left MCA infarct involving frontal and temporal lobes, with cortical atrophy of the inferior frontal and superior temporal gyri, with the lesion extending to the basal ganglia
21	70	Male	University	Fluent	18	Acoustic-mnestic	Left MCA infarct involving frontal and temporal lobes
22	38	Male	University	Non-fluent	2	Efferent motor	Left ischaemic CVA involving the left frontal lobe
23	56	Female	University	Non-fluent	30	Efferent motor	Left MCA and ACA infarcts involving the frontal and parietal lobes with partial cortical atrophy of the posterior regions of the inferior frontal, pre- and post-central gyri, and partial degeneration of the internal capsule
24	60	Male	High school	Fluent	42	Acoustic-mnestic	Lacunar infarct in the central branches of the left MCA with lesions involving the basal ganglia
25	55	Male	High school	Non-fluent	3	Efferent motor	Left MCA infarct involving both grey and white matter of temporal and parietal lobes including insular and posterior portion of superior temporal gyri
26	44	Male	High school	Fluent	8	Acoustic-mnestic	Left MCA infarct involving temporal and occipital lobes
27	35	Male	University	Gluent	23	Acoustic-mnestic	Left haemorrhagic CVA, with cyst in the left basal ganglia
28	61	Male	University	Non-fluent	3	Efferent motor	Left ischaemic CVA involving the frontal lobe with cortical atrophy of inferior and partially middle frontal gyri with extension to insular gyri
29	59	Male	High school	Non-fluent	12	Efferent motor	N/A
30	25	Female	University	Non-fluent	18	Efferent motor	N/A

(*continued*)

Appendix 1. (*Continued*).

Participant	Age	Gender	Education level	Group	Months post-onset	Primary aphasia type	Neuroimaging information
31	27	Female	University	Fluent	24	Sensory	N/A
32	59	Male	High school	Fluent	8	Sensory	Left MCA infarct involving cortical and subcortical areas of the temporal lobe
33	46	Female	High school	Fluent	4	Sensory	Left MCA infarct involving regions of the basal ganglia
34	63	Female	University	Fluent	4	Acoustic-mnestic	Left haemorrhagic CVA in the temporal and parietal lobes, involving the post-central and angular gyri
35	59	Male	University	Fluent	6	Sensory	Left MCA infarct involving cortical and subcortical areas of the parietal and occipital lobes, with partial cortical atrophy of the angular and superior temporal gyri

Notes: CVA = cerebrovascular accident; MCA = middle cerebral artery; ACA = anterior cerebral artery; N/A = no data available. Level of education: university = 15 years of education, high school = 10 years of education, primary school = 3 years of education.