Short term memory in aphasia: effects of modality and relationship with Western Aphasia

Battery-R performance

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Abstract

This study investigated three questions about short term memory (STM) performance in post-stroke aphasia. The first question was whether visual STM is impaired in persons with aphasia (PWA) given that a common neural network subserves encoding-recall of both verbal and visual STM. The second question was whether the response modality (verbal vs pointing) impacts STM span measures. The third focus was the relationship between STM and language performance, specifically on a commonly used standardized test battery, the Western Aphasia Battery-Revised (WAB-R). Data from 45 persons whose aphasia resulted from a single left hemisphere stroke were examined at the group and individual level. PWA scored lower than neurotypical controls on verbal but not visual STM tasks. Verbal STM impairments were found in about one-half of PWA. Dissociations among the three verbal STM tasks are found in one-third of PWA. There was a strong association between language performance on the WAB-R, including overall severity and individual test performance, and verbal STM (except for yes/no questions). These findings support an interplay between STM and language such that STM maintains relevant linguistic representations long enough for successful comprehension and production of language.

Keywords

Aphasia, short term memory, verbal memory, visuospatial memory

Short term memory (STM) refers the ability to temporarily retain a limited amount of verbal or visual information. While verbal and visual STM encode information from different modalities, both utilize a shared fronto-parieto-cerebellar neural network for the attentional and sequencing operations involved in encoding and recall (Majerus et al., 2010). Verbal STM deficits have been reported in aphasia, a language impairment arising from left fronto-temporo-parietal injury (Burgio & Basso, 1997; De Renzi & Nichelli, 1975; McCarthy & Warrington, 1987; Minkina, Rosenberg, Kilinyak-Fliszar & Martin, 2017; Murray, Salis, Martin, & Dralle, 2018; Shallice & Warrington, 1977). This study investigates three unresolved issues pertaining to STM in post-stroke aphasia. The first issue is whether visual STM is impaired in persons with aphasia (PWA) given that a common fronto-parieto-cerebellar neural network subserves encoding-recall of both verbal and visual STM (Majerus et al., 2010). Findings of visual STM impairment in PWA have been inconsistent (Christiansen, Wright, & Ratiu, 2018; De Renzi & Nichelli, 1975; Kasselimis, Simos, Economou, Peppas, Evdokimidis & Potagas, 2013; Potagas, Kasselimis, & Evdokimidis, 2011). The second problem addressed in this study is that of measurement, particularly the modality used to elicit a response from PWA. Most studies use a verbal response mode to measure STM (Murray et al., 2018). Given their difficulties with verbal expression, one would assume that non-verbal response modes such as pointing would yield better performance in PWA. The third focus of this study is the relationship between STM and language performance in PWA. The findings so far have been inconsistent, especially for visual STM (Caplan, Michaud, & Hufford, 2013; Martin & Ayala, 2004; Minkina, Martin, Spencer & Kendall, 2018; Paulraj, Schendel, Curran, Dronkers & Baldo, 2018; Sukurai et al., 1998).

A better understanding of STM and language performance in aphasia has theoretical relevance, as it will help elucidate whether and how STM supports language processes, and this

will inform broader questions regarding the (in)dependent of STM modalities and the neurocognitive architecture of language functions. The clinical relevance of investigating the STM-language relationship in aphasia is that it informs interpretation of clinical assessments, development of intervention goals and, possibly, prediction of treatment outcomes.

STM deficits in aphasia

STM performance in PWA has been compared with neurologically healthy controls, as well as with non-aphasic individuals with left or right hemisphere damage. For verbal STM, the results generally show that PWA have lower scores compared to controls (e.g., Albert, 1976; Burgio & Basso, 1997; Christiansen et al., 2018; De Renzi & Nechelli, 1975). When PWA are compared to non-aphasic individuals with brain damage, they generally score lower than both left- (De Renzi & Nechelli, 1975, Kasselimis, et al., 2013; Murray, 2018) and right- (Laures-Gore, Marshall, & Verner, 2011) hemisphere damaged individuals. However, there are also some findings of no difference in verbal STM performance in aphasia when compared to controls or non-aphasic individuals with brain damage (Burgio & Basso, 1997; Caplan et al., 2013; Fonseca, Raposo & Martins, 2019; Majerus, Attout, Artielle & Van der Kaa, 2015). For visuo-spatial STM in PWA, some studies have reported it to be impaired (Burgio & Basso, 1997; Kasselimis, et al., 2013; Murray, 2018; Potagas et al., 2011). However, other studies have found no visuo-spatial STM deficits in PWA (Christiansen, Wright, & Ratiu, 2018; De Renzi & Nechelli, 1975).

There could be several reasons for the disparate verbal and visuo-spatial STM findings in PWA. There could be inter-individual variability of cognitive abilities in PWA (Murray, 2012), which may be obscured by aggregate group data. Knowing how consistent verbal STM deficits are, and how consistently they are associated with visuo-spatial STM deficits, will inform us

about the domain generality of encoding-recall impairments in PWA. In this study, we examine individual data for dissociations between verbal and visuo-spatial STM. Participant characteristics, such as the severity (Lang & Quitz, 2012) and subtype of aphasia may also have influenced prior results. For instance, a gradient of STM deficits has been found based on aphasia severity (Lang & Quitz, 2012; Majerus et al., 2015), and conduction aphasia has been frequently associated with verbal STM deficits (McCarthy & Warrington, 1987; Shallice & Warrington, 1977; Sukurai et al., 1998). In this study, we examined the distribution of STM performance based on aphasia severity and subtype. Finally, differences in findings across studies might have to do with the stimuli and response mode (Knott, Patterson & Hodges, 2000; Laures-Gore et al., 2011). It is particularly important to evaluate how the response mode affects performance given the verbal deficits of PWA. This will be discussed in the next section.

Issues with STM measurement

A wide range of assessments and tasks have been used to measure STM in aphasia (Murray et al., 2018). Verbal STM is typically measured by presenting a series of digits, letters, words, pictures of objects or sentences of varying lengths and asking participants to repeat these items either in the presented sequence (serial recall) or any sequence (item recall). Visual STM has been measured by asking participants to reproduce a spatial arrangement of shapes, copy designs, or tap blocks in a specific sequence. A review of STM assessments used in published research of aphasia revealed that verbal STM is most frequently assessed using serial digit span (Murray et al. 2018). Over half of these studies (12/20) asked participants to verbally repeat the digits while the rest used a nonverbal response such as pointing. Visual STM, although less frequently assessed, was typically measured using a pointing response for visuo-spatial tasks such as block tapping. Given the well-known verbal production difficulties of PWA, the fact that

different response modalities are used for assessing verbal versus visuo-spatial STM introduces a “task-impurity” confound: the tasks differ not only in the type of information being retained (verbal versus visual) but also in terms of the response (spoken versus pointing). This is especially problematic in studies that report a dissociation between verbal and visuo-spatial STM deficits in PWA when they used spoken and pointing responses respectively to assess verbal and visuo-spatial STM (Potagas et al., 2011; Kasselimis et al., 2013, 2018).

A set of STM tasks developed by De Renzi and Nichelli (1975) addressed the response mode issue by testing digit span using both verbal and pointing responses. A three-by-three array of number blocks is used to elicit digit pointing. Word span and visuo-spatial span are similarly tested by having participants point to an array of pictures and blocks respectively. The latter is also referred to as the *Corsi Block Tapping* task (e.g., Burgio & Basso, 1997; Kasselimis et al., 2013; Minkina et al., 2018) after Corsi (1972) who originally developed this task. Verbal STM is measured using three tasks in which verbal material is presented auditorily (Digit Forward, Digit Pointing, and Picture Pointing). The similarity in response mode (i.e., pointing) across digit, picture and visuo-spatial span tasks allows for a more straightforward comparison across the type of information being retained without the confound of production deficits on verbal responses. For this reason, the present study uses de Renzi and Nichelli’s set of tasks to assess STM in PWA. De Renzi and Nichilli reported that PWA were impaired in STM tasks that probed retention of verbal information (digit and picture span) but not visuo-spatial information. They did not provide demographic and language performance details of their participants. Given that cognitive scores can shift over generations (the so-called Flynn effect, Hernstein & Murray, 2010), in the present study we collected data from a neurologically healthy matched comparison group. Another issue about the de Renzi and Nichelli study is the ambiguity in administration

instructions (Murray et al. 2018). Along these lines, most studies with the Corsi Block Tapping task do not clarify whether the blocks were arranged in a 3x3 array or in another format (Murray et al. 2018).

For PWA, it seems intuitive to predict better performance in the Digit Pointing compared to the Digit Forward task. However, the issue is more complex. Recall of verbal material is shown to be influenced by *standard modality* and *modality congruency* effects in neurotypical adults (Rummer, Schweppe & Martin, 2013). That is, recall of material is best when the stimuli are presented in their standard or typical modality – this would be the auditory-verbal modality for verbal STM. Further, recall is better when the modality of stimulus presentation and response elicitation is congruent. Based on this, it is possible that Digit Forward performance would be superior to Digit Pointing performance. Thus the Digit Forward task should show better performance in neurotypical adults, but could present either a benefit or disadvantage in PWA. The Picture Pointing task would also suffer from lack of congruency between stimulus (verbal presentation) and response (pointing).

Relationship between language and STM in aphasia

Communication places demands on short term memory: listeners need to maintain the unfolding message so that they can respond appropriately, and speakers need to maintain their own intended message and what they have already conveyed. It is thus crucial to understand the relationship between STM and language performance in neurologically healthy adults and those with aphasia. The key issue is the extent to which STM and language are distinct cognitive processes. Several decades ago, models of STM viewed language and STM as separable processes. It was assumed that auditorily presented digits or words were stored as a phonological code, but that this was distinct from the phonological processing required to produce and

comprehend language (Baddeley & Hitch, 1974; Shallice & Warrington, 1977). Later models proposed an interactive view, verbal STM was considered to rely on language processing (Burgess & Hitch, 2006), or was an inherent property of language requiring activation of semantic, phonological or syntactic representations (Acheson & MacDonald, 2009; Cowan, 2008; Majerus, 2013; Martin & Saffran, 1992). Researchers with a focus on lexical deficits in aphasia have subdivided verbal STM into semantic and phonological components based on dissociations between semantic and phonological spans and their relationship with word retrieval (Barde, Schwartz, Chrysikou & Thompson-Schill, 2010; Martin & Ayala, 2004; Martin & Saffran, 1992; Minkina, et al., 2018). Researchers who study sentence comprehension have differentiated between syntactic and semantic components (Caplan & Waters, 1999; Caplan et al., 2013). Verbal STM capacity is especially linked with complex sentence processing in aphasia (Caplan et al., 2013) and sentence comprehension under challenging conditions in neurotypical adults (Gilchrist, Cowan & Naveh-Benjamin, 2008).

While studies have examined the relationship between STM and empirical language measures, little is known about how STM interacts with standardized language assessments used in the diagnosis and profiling of aphasia. Aphasia assessments typically probe production, comprehension and repetition of words and sentences. A better understanding of the relationship between STM and specific language tasks used in standardized assessments will allow us to differentiate between different theoretical views. It will also inform interpretation of standardized test performance and clinical diagnosis by clarifying how STM deficits can confound performance. The Western Aphasia Battery-Revised (WAB-R; Kertesz, 2006) is one of the most commonly used clinical tests in countries where English is widely spoken (Kertesz, 2020). It has also been widely adapted into other languages (e.g., Kasher et al., 1999; Kim & Na, 2004; You,

1992). This study examines the relationship between performance on the language section of WAB-R and de Renzi and Nichelli's (1975) STM test battery in individuals with aphasia.

Research Questions and Hypothesis

This study investigates three aspects of STM in aphasia. The first question is the pattern of performance across verbal and visuo-spatial STM using De Renzi and Nichelli's (1975) STM tasks. We examined this both at the group and individual level. Individual participant analysis was designed to identify the extent of single dissociations (single task is impaired relative to neurotypical group) and double dissociations (spared versus impaired performance across tasks in the same participant). It was hypothesized that, at the group level, digit span and picture span would be impaired but not visuo-spatial span. Compared to words, the processing and retrieval of digits minimally relies on semantics (Rath et al., 2015). Hence we predict that digit recall will be less impaired than word recall.

The second question was whether there is a difference in digit span scores with verbal versus pointing responses. It is hypothesized that Digit Pointing span will show better performance than Digit Forward span in PWA as the latter requires verbal output. However, Digit Forward is the standard and congruent modality (Rummer et al., 2013), giving it an advantage over Digit Pointing, especially for neurotypical individuals.

The third question examined the relationship between STM performance and WAB-R (Kertesz, 2006) performance. We predicted that WAB-R subtests that demand both retention and retrieval of words (semantic knowledge) would be associated with Picture Pointing span. These include three word retrieval tasks. The Word Fluency task (generate animal names for a one minute) requires retention of already mentioned words to conduct a lexical search for new words. Similarly, Sentence Completion (produce an ending to prompts such as "Roses are red, violets

are...”) and Responsive Speech (e.g., Where do nurses work?) require retention of the prompt for successful retrieval of the response. We also expected two comprehension tasks, Yes/No questions and Sequential commands, to pattern with Picture Pointing span because both require access and maintenance of semantic representations. For the two tasks that required production of multiple words (Repetition and Word Fluency), we expected an association with Digit Forward span performance as this task requires verbal responses. It was hypothesized that Auditory Word Recognition (pointing to a presented word) and Object Naming would not show a significant relationship with verbal STM because each word is recognized or recalled individually in these tasks, so there is no need to maintain previous words in STM. The WAB-R also yields a composite score of aphasia severity, the Aphasia Quotient (AQ), and we expected AQ performance to be predicted by all three verbal STM tasks.

Methods

Participants

Participants included 45 adults with a diagnosis of aphasia following a single left hemisphere cerebrovascular accident of the middle cerebral artery territory (21 male, 24 female, age $M (SD) = 57.7 (11.0)$ years). They were all native speakers of English with a minimum of 12 years of education (education $M (SD) = 16.6 (3.3)$ years). The distribution of their highest educational degree was as follows: 22% high school diploma, 22% some college, technical, or associates degree, 27% bachelor’s degree, 27% graduate or professional degree. All except 6 participants were right-handed prior to their stroke (Edinburgh handedness inventory, Oldfield, 1971). Inclusionary criteria for PWA were: at least six months post-stroke, no prior neuropsychiatric diagnoses, and passing vision and hearing screenings. Vision screening included reading at least 20/40 on a Snellen chart and absences of visual field deficits. Hearing

screening was assessed at 40dB HL at 500Hz, 1000Hz, and 2000Hz in both ears. PWA's aphasia severity as measured by the Western Aphasia Battery-Revised (WAB-R; Kertesz, 2006) Aphasia Quotient (WAB-R AQ) ranged from 17.1 to 100.0 ($M = 75.4$, $SD = 18.8$, Maximum possible = 100). As per the WAB-R classification scheme, their aphasia sub-types included: anomia (n=14), Broca's aphasia (n = 9), conduction aphasia (n = 8), global aphasia (n = 1), transcortical motor aphasia (n = 1), Wernicke's aphasia (n = 3), and non-aphasic (with AQ > 93.8, n = 9). It is well-documented that PWA who score in the so-called *non-aphasic* range demonstrate language impairments (Fromm et al., 2017; Richardson et al., 2021) and thus were included in the present study. Participant details are provided in Table 1.

Twelve neurologically healthy (NH) adults were also recruited (7 females, 5 males, mean age (SD) = 64.4 (8.13) years, mean (SD) years of education = 17.75 (3.54) years). The PWA and NH groups did not differ significantly in age ($t(54)=1.8$, $p > .05$) or education ($t(54)=.5$, $p > .05$). Inclusionary criteria for NH were: native English speaker, at least 12 years of education, right-handed, no prior neuropsychiatric diagnoses, and no uncorrected visual or hearing impairment, as per self-report. Neurologically healthy participants had to pass a cognitive screening with score of at least 26 out of 30 on the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005; Mean (SD) scores were 28.17 (1.58)).

-----Insert Table 1 here-----

Procedures

Participants were tested individually in a quiet room after providing informed consent. Testing for neurologically healthy participants was completed in a single session and included a demographic questionnaire, cognitive screening (MoCA; Nasreddine et al., 2005), and administration of the De Renzi and Nichelli (1975) short term memory battery. Participants with

aphasia completed testing over one or two sessions. This included demographic questionnaire (with caregiver input), standardized language test using the Western Aphasia Battery-Revised (WAB-R, Kertesz, 2006) and the short term memory battery (De Renzi and Nichelli, 1975).

The WAB-R consists of tasks that fall under four broad domains: spontaneous speech, auditory-verbal comprehension, repetition and word finding. The spontaneous speech section includes response to conversational questions and description of a picture. Auditory-verbal comprehension includes responses to yes-no questions, single word comprehension (*Show me ...*) and sequential commands. Repetition consists of repeating items of varying length, ranging from single words to 8-10 word sentences. The word finding sections consists of semantic fluency (generating animal names), object naming, sentence completion and single word responses to questions (*Where do nurses work?*). A composite score, called the Aphasia Quotient (AQ), is derived from these four domain scores, in which spontaneous speech is weighted twice as the comprehension, repetition and word-finding domains.

The De Renzi and Nichelli's (1975) short term memory battery consists of four tasks. The *Digits Forward* (DF) task requires the participant to verbally repeat a sequence of digits presented verbally by the examiner. In the *Digit Pointing* (DP) task, the participant reproduces the sequence of digits spoken by the examiner by pointing to digits written on wooden blocks. The blocks of nine single digits (0-9) were placed in a 3x3 array. In *Picture Pointing* (PP), the participant points to pictures in a 3x3 array to reproduce the sequence of words presented by the examiner. The *Spatial Pointing* (SP) task requires participants to tap on a 3x3 array of blocks to mimic the spatial pattern tapped by the examiner. The digit and picture tasks have a preliminary step of repeating or pointing to the individual digits or pictures. These tasks are administered only if the participant passes this step. All four tasks proceed from series of 2 to 8 items with 2

sequences at each of the seven series lengths. The participant receives 1 point for each correct sequence and an additional .5 point for the second sequence in that series length. Thus, the maximum number of points in each task is 10.5 (1.5 points for each of the seven lengths).

Results

Short Term Memory Performance

The short term memory scores of neurologically healthy participants and those with aphasia are listed in Table 2. Levene's test of equality of error variances was significant ($F(7,214) = 3.02, p = .005$), showing that the two groups differed in homogeneity of variance. Hence non-parametric tests were used for statistical comparisons using SPSS version 24.1 with a Bonferroni adjusted significance threshold set at .0125 (.05/4 tests). Comparisons of between-group performance showed that PWA scored lower than healthy participants in Digit Forward, Digit Pointing and Picture Pointing, but not in Spatial Pointing (Mann-Whitney U test, see Table 2).

-----Insert Tables 2-3 and Figure 1 here-----

Looking at within-group performance, neurologically healthy adults' STM scores differed across the four tasks (Friedman's test, $\chi^2(3) = 19.97, p < 0.001$). Pairwise comparisons using Wilcoxon's signed ranks test are given in Table 2. Four comparisons were statistically significant (at a Bonferroni adjusted threshold of $p < .0125$): Digit Forward and Digit Pointing scores were significantly higher than Picture Pointing and Spatial Pointing scores (Figure 1). To understand the relationships among STM tasks, we ran separate linear regression analyses with each STM task as the dependent variable and the other three tasks as the predictor variables. All predictors were entered simultaneously into the regression equation. The results of the regression analyses, which are presented in Table 3, show that the regression models for all except Spatial

Pointing STM were significant. Each STM task was predicted by one other STM task: Digit Forward and Digit Pointing predicted each other, and Picture Pointing and Spatial Pointing predicted each other. In other words, DF and DP were associated with each other, while PP and SP were associated. The correlations among STM tasks are given in Table 4.

-----Insert Table 4 here-----

PWA also scored differently across the four STM tasks (Friedman's test, $\chi^2(3) = 31.49, p < 0.001$). As seen in Figure 1 and Table 2, follow-up pairwise comparisons show that PWA's performance on all tests differed significantly from one another, with the exception of Digit Forward versus Digit Pointing and Spatial Pointing. The results of the regression analyses predicting each of the four STM tasks were identical to the pattern found in neurologically healthy adults. Table 3 shows that Digit Forward and Digit Pointing predicted each other, and Picture Pointing and Spatial Pointing predicted each other. Table 4 shows that the association between Digit Forward and Digit Pointing is weaker in PWA (yet statistically significant) compared to the neurologically healthy group.

In addition to the group analyses, to examine heterogeneity of STM impairment in PWA, we compared performance of individual PWA against the neurologically healthy group (single dissociations) using Bayesian tests for a deficit using *singlims* (Crawford & Garthwaite, 2002). The numbers do not add up to 45 because not all PWA were able to complete all four tasks. Double dissociations, that is, PWA who were spared in one STM task but impaired in another (compared to the neurologically healthy group) were identified using Crawford, Garthwaite and Porter's (2010) Bayesian approach using their program *dissoc_ES*. The number of PWA with single and double dissociations is given in Table 5. Digit Forward and Spatial Pointing had the

largest and smallest number of single dissociations respectively. The most common double dissociations were between the two digit STMs and spatial STM tasks.

-----Insert Table 5 here-----

In summary, at the group level, PWA showed preserved performance in Spatial Pointing and impaired performance in Digit Forward, Digit Pointing and Picture Pointing. In terms of the effect of response mode on verbal STM, there was no difference between Digit Pointing and Digit Forward performance. At the individual performance level, there were individuals with spared performance for each of the four STM tasks. Double dissociations were seen across all STM tasks.

Relationship between STM and Language Performance

Table 6 shows the distribution of STM scores by aphasia severity and classification. The relationship between language performance and STM was examined in a series of regression analyses. The first linear regression analysis examined the relationship between aphasia severity (dependent variable) as measured by the WAB-R AQ (Kertesz, 2006) and the STM tasks. The next eight regression analyses examined the each of the subtests of the WAB-R and their relationship with the four STM tasks. WAB-R's information content and fluency scores were excluded from the regression analyses as these ratings and not on a ratio-scale of measurement. All the regression models were statistically significant, with a Bonferroni-adjusted significance threshold of .005 for the overall models (.05/9 regressions) except for yes/no questions (Table 7). Digit Forward span significantly predicted the aphasia quotient, and performance of five language subtests: sequential commands, repetition, object naming, sentence completion, and responsive speech. Picture Pointing span predicted performance on the sequential commands, word fluency and sentence completion. For the repetition subtest, in addition to digit forward,

spatial pointing span was a significant (negative) predictor. Interestingly, Digit Pointing span did not predict any language test performance. The correlations between WAB-R subtests and STM tasks show that each WAB-R subtest was significantly positively correlated with each of the three verbal STM tasks (Table 4, all r values > 0.3 , $p < 0.01$).

-----Insert Tables 6 - 7 here-----

Discussion

The present study investigated three aspects of STM impairment in aphasia: the profile of verbal and visuo-spatial STM impairment, the impact of verbal versus nonverbal response mode on verbal STM, and the relationship between STM abilities and performance on the Western Aphasia Battery-Revised (Kertesz, 2006), which is a standardized aphasia test. We found a group level impairment in verbal STM but not visuo-spatial STM in aphasia, no significant difference between verbal and pointing response mode for verbal STM in either group, and strong associations between language performance and verbal STM, particularly with the Digit Forward and Picture Pointing tasks. These findings are discussed in the following sections.

STM deficits in aphasia

The mean verbal STM scores of neurologically healthy participants in this study (Table 2) were higher than those reported by de Renzi and Nechelli (1975) in their original study (Table 1, DF: 8.36 vs 6.18, DP: 8.16 vs 5.9, PP: 5.75 vs 4.81, SP: 6.16 vs 5.92). The digit spans are over 2-points higher in the present study, but not the picture or spatial spans. This highlights the importance of using a comparable neurotypical group for determination of impaired function in PWA. There are a few potential reasons for the higher scores. The first could be the Flynn effect, which refers to increased cognitive function in a population over time (Hernstein & Murray,

2010). In fact, a meta-analysis has demonstrated the Flynn effect for verbal and visuo-spatial memory (Wongupparaj, Wongupparaj, Kumari & Morris, 2017). Secondly, unlike in English, all the digits are bisyllabic in Italian, which is the language used by de Renzi and Nechelli (1975). This is consistent with the inverse effect of stimulus length on verbal memory span, as longer words/digits have a longer phonological code (Baddeley, Thompson, & Buchanan, 1975). Third, the demographic and cognitive characteristics of the original neurotypical group are unknown. Factors such as education and age could affect scores, as well as the strict cognitive screening standards used in the present study.

Group level analyses in the present study revealed short term memory impairments in aphasia for all three verbal tasks, but not for the visuo-spatial task. This pattern is consistent with some prior studies of verbal and visuo-spatial span in PWA (Christiansen et al., 2018; de Renzi and Nechelli, 1975; Martin & Ayala, 2004), but differs from other studies that found impaired visuo-spatial span (Burgio & Basso, 1997; Kasselimis et al., 2013, 2018; Paulraj et al., 2018; Potagas et al., 2011). In these latter set of studies, the visuo-spatial STM impairments were milder and less frequent than verbal STM impairments. Some authors have attributed the visuo-spatial impairments to the use of verbal strategies (Baldo & Dronkers, 2007; Martin & Ayala, 2004) while others have implicated deficits in maintenance of serial order information (Kasselimis et al., 2018). Lesion analyses have not found a consistent region to be associated with visuo-spatial STM deficits in PWA (Kasselimis et al., 2013, 2018).

The individual single dissociation data show that verbal STM is impaired only in about half of the PWA, and is not a pervasive deficit (Minkina, et al., 2018). Preserved verbal STM in a subset of PWA is consistent with prior findings (Kasselimis et al., 2018; Majerus et al., 2015). The question is what factors differentiate between PWA who do and do not have verbal STM

impairments. Holding a sequence of digits that have no semantic relevance (unlike one's phone number) places demands on the left hemisphere dominant dorsal phonological network (Majerus, 2013). Lesion studies of PWA with verbal STM impairments have implicated both left inferior parietal regions bordering on superior temporal (Baldo et al., 2012; Kasselimis et al., 2018) and inferior frontal regions (Kasselimis et al., 2018). These regions are associated with storage and encoding of phonological representations, respectively, thus accounting for the vulnerability of digit span in some PWA.

In both the PWA and neurotypical groups, performance on the Picture Pointing task was worse than the digit tasks. The Picture Pointing task requires holding a sequence of unrelated words that are auditorily presented. Although this could be theoretically achieved by relying solely on the phonological code, evidence from better recall of nameable words suggests reliance on semantic representations (Knott, Patterson & Hodges, 2000) for this task. Thus, PWA with difficulty in encoding/retrieving words would be impaired in the Picture Pointing task. Lesions in the inferior parietal region are associated with both picture naming (Faroqi-Shah et al., 2013) and verbal STM deficits (Baldo et al., 2012; Kasselimis et al., 2018). The different demands of digit and picture span tasks are consistent with the double dissociation of digit and picture span in about 30% of PWA (Table 5). This is consistent with the idea that phonological and semantic STM can dissociate in PWA (Martin & Saffran, 1992; Martin, Minkina, Kohen, & Kalinyak-Fliszar, 2018), and rely on dorsal and ventral language networks respectively (Majerus, 2013).

Effect of response mode on STM

A critical question in the present study was the effect of response modality on performance. The null effect of pairwise comparisons between Digit Forward and Digit Pointing

(Table 2) shows no advantage of the standard/congruent modality in either the neurotypical or the PWA group. Importantly, there was no advantage of pointing responses for PWA. Thus, these two tasks can be assumed to tap into the same phonological and cognitive resources, which is also consistent with the regression analyses results (Table 3). The clinical implication of this finding is that verbal responses can be used to assess STM in PWA without a significant disadvantage in scores. However, this decision needs to be made on an individual basis based on the severity of expressive deficits and the presence of articulatory-motoric co-morbidities such as apraxia of speech. The double dissociation data show that DF and DP dissociated in one-fourth of PWA (Table 5).

Relationship between WAB-R and STM

The PWA in the present study showed a wide range of language abilities, as assessed by the Western Aphasia Battery-Revised (Kertesz, 2006) (Table 1). This allowed for a robust examination of the relationship between language and STM. All three verbal STM tasks were significantly correlated with each of the WAB-R subtests, and visuo-spatial span was correlated with some WAB-R subtests (Table 4). Overall, the regression models with the four STM tasks as predictors were significant for each WAB-R measure (except for Yes/No Questions) (Table 7). Our hypotheses about the relationships between specific STM and WAB-R measures were mostly confirmed. Among the three comprehension subtests of the WAB-R, only the Sequential Commands subtest was predicted by two STM tasks, DF and PP. Good performance on this subtest requires successful completion of three-step commands (e.g., Put the book on top of the pen and give it to me) which needs both retention and comprehension of the stimulus. This explains its association with both phonological (DF) and semantic (PP) types of STM. Each of

the three word retrieval subtests showed a different, but intuitive pattern. Word Fluency, requiring generation of animal names, was predicted by PP, suggesting reliance on semantic representations. Responsive Speech was predicted by DF. We had also predicted PP for this task, which failed to reach significance. Sentence completion was predicted by both DF and PP. Finally, Repetition, a task that has been most frequently associated with STM in the literature, was predicted by DF. Repetition was also negatively predicted by visuo-spatial span (SP). The reason why Digit Pointing did not emerge as a significant predictor is most likely because of its strong collinearity with DF: DP failed to account for any variance when DF was already in the regression model. Overall, the results highlight the intertwined relationship between verbal STM and language performance, and its impact on clinical language assessment in PWA.

Theoretical Implications

At a broad level, the findings of the present study highlight the strong interaction between language and cognitive performance in persons with aphasia. These findings are consistent with prior studies of interaction between language and other cognitive domains, including attention (Murray, 2012), cognitive control and processing speed (Faroqi-Shah & Gehman, 2021), executive functions (Mohapatra & Marshall, 2020) and working memory (Caplan et al., 2013).

The following cognitive processes are engaged in short term memory tasks: attending to the stimuli, encoding and recall of the items and their sequence. Of these processes, attention and sequencing are domain general and performed through a common fronto-parieto-cerebellar network (Majerus et al., 2010; 2015). The individual double dissociation data (Table 5) of the present study do not indicate any impairments in these attentional and sequencing operations: if these operations had been impaired, there would have been a strong co-occurrence of visual and

verbal span impairments in the same participants. We can conclude that, generally, these domain general operations engaged in STM span tasks are not impaired in PWA (Attout, van der Kaa, George, & Majerus, 2012; Majerus et al., 2015). We can also conclude that, generally, visual STM span is not impaired because 93% of the PWA failed to show an impairment (Table 5) (Christiansen et al., 2018; De Renzi & Nechelli, 1975).

Next, we discuss what we learn about the nature of verbal STM and its relationship with language performance. The three verbal span tasks are significantly positively correlated in neurotypical adults and PWA (Table 4), although there are dissociations between these tasks in about one-third of PWA (Table 5). Thus, there is a strong, but not invariable, relationship between tasks that require retention of verbal materials. Within the three tasks, however, we also see evidence of a distinction between digit span and picture span from the regression analyses (Table 3). This supports a distinction based on the type of linguistic material being encoded, as has been suggested by others (Barde et al., 2010; Martin & Ayala, 2004; Martin & Saffran, 1992; Minkina et al., 2018).

This study found strong associations between the three verbal STM spans and language performance on the WAB-R, supporting theoretical views that integrate verbal STM and language processing (Burgess & Hitch, 2006; Acheson & MacDonald, 2009; Cowan, 2008; Majerus, 2013; Martin & Gupta, 2004; Martin & Saffran, 1992). To comprehend and produce language, semantic and phonological representations of words, as well as syntactic representations of multi-word utterances need to be activated and maintained while the sentence is unfolding. Verbal STM enables activation and maintenance of these representations during language comprehension and production. Thus, when verbal STM is impaired, linguistic representations cannot be maintained long enough (i.e., decay), thus impacting language

performance. For example, while producing a word, the semantic features of the target word may decay before the corresponding phonological representation is selected. This would result in the typical anomia word retrieval behavior observed in PWA. Similarly, during sentence production, the verb's argument structure framework may not be maintained long enough for successful retrieval of the lexical representations of the verb's arguments. This would result in abandoned utterances or omission of verb arguments (e.g., The boy is throwing...[the ball]).

Conclusions

Verbal STM, as measured in the present study, is impaired in about one-half of PWA. Dissociations among the three verbal STM tasks are found in one-third of PWA. Visuo-spatial STM is impaired in less than one-tenth of PWA. Language performance on the WAB-R, including overall severity and individual test performance, is strongly predicted by verbal STM (except for yes/no questions). The findings support an interplay between STM and language such that STM maintains relevant linguistic representations long enough for successful comprehension and production of language.

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Tables

Table 1. Demographic details of participants.

Participant	Age	Gender	Education	Handedness	Subtype	Aphasia Quotient
1	74	M	13	R	Global	17.1
2	62	F	13	R	Broca's	33.6
3	44	F	17	R	Conduction	45.4
4	54	F	17	R	Wernicke's	47.7
5	54	F	16	R	Broca's	49.5
6	63	M	19	R	Broca's	52.4
7	54	M	17	R	Broca's	57.2
8	69	F	17	R	Anomic	58.2
9	61	F	NA	R	Broca's	61.1
10	56	M	19	R	Conduction	61.8
11	42	F	19	R	Conduction	62.9
12	75	M	30	R	Conduction	63.4
13	46	F	14	R	Broca's	64.6
14	64	F	13	R	Broca's	65.7
15	47	M	15	R	Anomic	67.2
16	47	M	13	L	Transcortical motor	68.8
17	44	M	19	R	Broca's	71.2
18	39	M	19	R	Wernicke's	74.1
19	50	F	17	R	Conduction	74.1
20	68	M	12	R	Anomic	74.1
21	57	F	19	L	Conduction	75.3
22	55	M	17	R	Conduction	76.9
23	49	M	13	R	Anomic	78.7
24	55	F	17	R	Wernicke's	79.1
25	55	M	13	R	Anomic	80.5
26	66	M	19	R	Anomic	81.6
27	49	F	15	L	Conduction	82
28	65	M	19	L	Anomic	87.2
29	69	M	16	R	Anomic	87.6
30	81	M	13	R	Anomic	88.1
31	57	F	13	R	Anomic	88.2
32	54	F	15	R	Anomic	88.8
33	54	F	15	R	Anomic	89.6
34	55	F	17	R	Anomic	90.8
35	46	F	17	R	Anomic	91.1
36	58	M	17	R	Broca's	92.8
37	56	F	11	R	NA-WAB	94
38	84	F	17	NA	NA-WAB	94
39	55	F	17	R	NA-WAB	94.6

40	79	F	19	R	NA-WAB	95
41	60	M	15	R	NA-WAB	95.2
42	57	M	19	L	NA-WAB	96.6
43	58	F	18	L	NA-WAB	97
44	56	F	15	R	NA-WAB	99.6
45	48	M	24	R	NA-WAB	100

NA= not available, NA-WAB = non-aphasic as per the Western Aphasia Battery, Aphasia Quotient = severity score obtained from the Western Aphasia Battery-Revised (Kertesz, 2006), Maximum = 100.

Table 2. Results of the statistical analyses comparing neurotypical and aphasic groups on each memory measure (top) and within group pairwise comparisons (bottom).

Task	Neurotypical		Aphasia		Statistics, Mann Whitney U, <i>p</i>
	Mean (SD)	Range	Mean (SD)	Range	
Digit Forward	8.36 (1.47)	6 to 10.5	4.40 (2.36)	0 to 8.5	$U = 452, p < .001$
Digit Pointing	8.16 (1.64)	6 to 10.5	3.91 (2.20)	0 to 8	$U = 484, p < .001$
Picture Pointing	5.75 (1.30)	4 to 9	3.06 (1.68)	0 to 6.5	$U = 463, p < .001$
Spatial Pointing	6.16 (1.40)	4 to 10.5	5.31 (1.75)	0 to 8.5	$U = 328, p = .15$
Pairwise Comparisons, Wilcoxon Z, <i>p</i>					
	Z	<i>p</i>	Z	<i>p</i>	
Digit Forward vs Digit Pointing	-0.73	0.46	-2.21	0.027	
Digit Forward vs Picture Pointing	-2.94	0.003	-3.26	0.001	
Digit Forward vs. Spatial Pointing	-2.7	0.007	-1.94	0.052	
Digit Pointing vs Picture Pointing	-2.98	0.003	-2.69	0.007	
Digit Pointing vs Spatial Pointing	-2.51	0.012	-3.62	.000	
Picture Pointing vs Spatial Pointing	-1.56	0.12	5.06	.000	

Table 3. Results of the regression analyses examining relationships between the four short term memory tasks for the neurotypical and aphasic groups. * $p < .0125$

	Model (F, p , adjusted R^2)	Standardized Coefficient (β), t, p			
		Digit Forward	Digit Pointing	Picture Pointing	Spatial Pointing
<u>Neurotypical</u>					
Digit Forward	$F(3,11) = 8.59, p = .007, R^2 = .76$		0.78, 3.48, .008*	0.13, .45, .66	.01, .06, .95
Digit Pointing	$F(3,11) = 8.94, p = .006, R^2 = .77$	0.78, 3.48, .008*		.24, .82, .43	-.21, -.84, .42
Picture Pointing	$F(3,11) = 6.09, p = .018, R^2 = .70$	.18, .45, .66	.32, .82, .43		.61, 3.06, .015
Spatial Pointing	$F(3,11) = 3.45, p = .072, R^2 = .56$	.03, .06, .95	-.39, -.84, .42	.61, 3.06, .015	
<u>Aphasia</u>					
Digit Forward	$F(3,31) = 12.03, p < 0.001, R^2 = .54$		.64, 4.5, .000)	.21, 1.34, .19	-.11, -.79, .43
Digit Pointing	$F(3,31) = 13.11, p < 0.001, R^2 = .56$	.61, 4.5, .000*		.15, .98, .33	.13, .94, .35
Picture Pointing	$F(3,31) = 7.34, p = .001, R^2 = .41$	.26, 1.34, .19	.2, .98, .33		.37, 2.6, .015
Spatial Pointing	$F(3,31) = 3.79, p = .02, R^2 = .27$	-.18, -.79, .43	.21, .94, .35	.37, 2.6, .015	

Table 4. correlations between short term memory tasks for each group, and between short term memory and Western Aphasia Battery-Revised scores. * $p < .05$, **, $p < .01$.

	Digit Forward	Digit Pointing	Picture Pointing	Spatial Pointing
<u>Neurologically Healthy</u>				
Digit Forward				0.174
Digit Pointing	.857**			0.142
Picture Pointing	.630*	.691*		0.438
<u>Aphasia</u>				
Digit Forward				0.155
Digit Pointing	.572**			.345*
Picture Pointing	.512**	.532**		.572**
<u>WAB-R</u>				
Yes/No Questions	0.49**	.53**	.52**	.32*
Auditory Word Recognition	0.64**	0.68**	0.63**	0.34*
Sequential Commands	0.57**	0.61**	0.74**	0.44**
Repetition	0.81**	0.59**	0.48**	0.14
Object Naming	0.54**	0.47**	0.49**	0.26
Word Fluency	0.41**	0.58**	0.67**	0.50**
Sentence Completion	0.64**	0.42**	0.66**	0.32*
Responsive Speech	0.54**	0.58**	0.61**	0.36*
Aphasia Quotient	0.75**	0.72**	0.62**	0.35*

Table 5. Individual participant analysis showing single dissociations (impaired compared to neurotypical group) and double dissociations (impaired across tasks in a single participant).

Single Dissociations	Spared		Impaired	
	N	%	N	%
Digit Forward	17	42.5	23	57.5
Digit Pointing	20	46.5	23	53.5
Picture Pointing	23	56.1	18	43.9
Spatial Pointing	39	92.8	3	7.2

Double Dissociations	N	%
Digit Forward vs Digit Pointing	10	25.6
Digit Forward vs Picture Pointing	11	30.5
Digit Forward vs. Spatial Pointing	21	56.7
Digit Pointing vs Picture Pointing	12	30
Digit Pointing vs Spatial Pointing	24	60
Picture Pointing vs Spatial Pointing	16	40

Table 6. Short term memory scores based on aphasia severity (Aphasia Quotient) and aphasia classification (from the Western Aphasia Battery-Revised, Kertesz, 2006). The fluency cut-off score for Fluent and Nonfluent was 5.

	N	<u>Digit Forward</u>		<u>Digit Pointing</u>		<u>Picture Pointing</u>		<u>Spatial Pointing</u>	
Category		Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
<u>Aphasia Quotient</u>									
<39	2	0 (0)	0	1.0 (0)	1	2.5 (0)	2.5	5.0 (1.4)	4.0 - 6.0
40-60	6	1.8 (1.0)	0.0-2.5	1.4 (1.1)	0.0-3.0	0.9 (1.2)	0.0-3.0	4.5 (2.3)	0.0-6.0
60-80	16	3.8 (1.7)	1.5-7.5	3.2 (1.6)	1.6-6.5	2.9 (1.3)	1.5-6.5	5.2 (1.7)	2.5-8.0
81-100	21	6.2 (1.7)	2.5-8.5	5.3 (1.9)	1.5-8.0	3.9 (1.5)	1.5-6.5	5.7 (1.7)	2.5-8.5
<u>Aphasia Classification</u>									
Anomic	14	5.2 (2.2)	0-8.5	4.0 (2.2)	0-8.0	3.3 (1.7)	0-6.5	4.6 (2.1)	0-8.0
Broca's	9	3.3 (2.1)	0-7.5	2.6 (2.0)	1-7.5	2.4 (1.9)	0-6	5.4 (1.6)	3.0-8.0
Conduction	8	2.9 (1.5)	1.5-5.5	3.2 (1.8)	1.0-6.5	2.3 (0.8)	1.5-3.5	5.5 (0.7)	4.0-6.0
Global	1	-	-	-	-	-	-	4.0 (0)	4
NA-WAB	9	6.8 (1.4)	5.0 - 8.5	5.8 (1.4)	3.0 - 8.0	4.8 (1.4)	2.5 - 6.5	6.6 (1.0)	5.5 - 8.5
Transcortical Motor	1	5	-	2.5	-	1.5	-	3	-
Wernicke's	3	3.2 (1.2)	2.5-4.5	3.7 (2.4)	1.0-5.5	2.0 (1.0)	1.0-3.0	5.0 (2.2)	2.5-6.5
<u>Aphasia Fluency</u>									
Fluent	14	4.7 (1.8)	3 to 9	4.7 (1.8)	3 to 8	3.1 (1.3)	2 to 6	5.2 (1.7)	2.5 - 8
NonFluent	19	3.3 (2.3)	0-8	2.2 (1.6)	0-7	2.3 (1.6)	0-7	4.9 (1.8)	0 - 8

Table 7. Results of the regression analyses predicting performance of Western Aphasia Battery-Revised subtests.

	Model (F , adjusted R^2 , p)	Standardized Coefficient (β), t , p			
		<u>Digit Forward</u>	<u>Digit Pointing</u>	<u>Picture Pointing</u>	<u>Spatial Pointing</u>
Yes/No Questions	$F(4,30)=3.42$, $R^2 = .22$, $p=.02$	0.26, 1.16, .25	0.22, .95, .35	0.24, 1.21, .24	-0.15, -.86, .39
Auditory Word Recognition	$F(4,30)=6.44$, $R^2 = .39$, $p=.001^{\#}$	0.29, 1.46, .16	0.27, 1.35, .18	0.31, 1.78, .08	-0.18, -1.17, .25
Sequential Commands	$F(4,30)=10.70$, $R^2 = .53$, $p< .001^{\#}$	0.46, 2.6, .012*	-.07, -.38, .7	.47, 3.05, .005**	.04, .27, .78
Repetition	$F(4,30)=16.60$, $R^2 = .65$, $p< .001^{\#}$	0.64, 4.2, .000***	.16, 1.04, .30	.19, 1.42, .16	-.33, -2.8, .009**
Object Naming	$F(4,30)=4.94$, $R^2 = .32$, $p=.004^{\#}$	0.55, 2.6, .01*	-0.05, -.22, .83	0.16, .86, .39	0.05, .33, .74
Word Fluency	$F(4,30)=5.44$, $R^2 = .34$, $p=.002^{\#}$	0.05, .23, .81	0.23, 1.1, .28	0.44, 2.44, .02*	0.04, .26, .79
Sentence Completion	$F(4,30)=13.29$, $R^2 = .59$, $p< .001^{\#}$	0.70, 4.3, .000***	-0.22, -1.34, .18	0.34, 2.4, .02*	0.09, .70, .48
Responsive Speech	$F(4,30)=8.35$, $R^2 = .46$, $p< .001^{\#}$	0.46, 2.48, .02*	-0.01, -.04, .96	0.29, 1.78, .08	0.17, 1.16, .25
Aphasia Quotient	$F(4,30)=18.07$, $R^2 = .67$, $p< .001^{\#}$	0.49, 3.34, .002**	0.31, 2.07, .047	0.21, 1.66, .11	-0.11, -.93, .35

Figure Legend

Figure 1. Performance on short term memory tasks of neurotypical and aphasic participant groups. Error bars indicate standard error of the mean (SE), *** $p < .001$.

Figure 1. Performance on short term memory tasks of neurotypical and aphasic participant groups. Error bars indicate standard error of the mean (SE), *** $p < .001$. F=forward, P=pointing, Pict = Picture, Spa = Spatial.