Is phonological working memory involved in sentence comprehension? The difference between phonological and semantic reactivation

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ABSTRACT

This study explored the nature of the relation between phonological working memory (pWM) and sentence comprehension, via the assessment of comprehension in 12 Hebrew-speaking individuals with conduction aphasia who had severe pWM limitation. A series of 10 recall and recognition span tasks indicated that all the participants had limited pWM, which was significantly poorer than that of 146 control participants. Experiments 1 and 2 tested the comprehension of relative clauses, which require semantic-syntactic reactivation, using sentence-picture matching and plausibility judgment tasks. Experiments 3 and 4 tested phonological reactivation, using a paraphrasing task for sentences with lexical ambiguity for which the disambiguation requires re-access to the word form, and a task of rhyme judgment within sentences. The distance between a word and its reactivation site was manipulated in three ways: by the number of words/syllables, by intervening arguments, and by intervening embeddings. Although their pWM was very impaired, the individuals with conduction aphasia comprehended relative-clauses well even with long phonological and syntactic distances, and were unaffected by the distance. However, they failed to understand and judge sentences that required phonological reactivation when the phonological distance was long. The results suggest that pWM is not involved in sentences that require semantic-syntactic reactivation. pWM does, however, support comprehension in very specific conditions: when phonological reactivation is required after a long phonological distance.

INTRODUCTION

Linguists who study the way people parse sentences often refer to “working memory” when they describe certain stages in sentence parsing (Ackema & Neeleman, 2002; Grodzinsky & Reinhart, 1993; Kimball, 1973; Pritchett, 1992; Reinhart, 2004). What exactly is this memory that supports sentence processing? Is it a single entity that is responsible for all types of sentence processing? Is it what psychologists measure when they give participants lists of unrelated words or nonwords to recall? This study asks these questions via the assessment of sentence comprehension in individuals who have, following brain damage, a severe limitation in working memory. They cannot repeat more than two or three words – can they understand sentences? The current study compares relative clause sentences, which require the reactivation of the antecedent (the moved constituent) at the trace position, and sentences that require phonological reactivation of words that appeared earlier in the sentence.

The question of whether working memory is a single capacity that supports all types of verbal

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processing interested many researchers. The conclusions of different studies are, though, quite confusing. Some researchers find evidence for working memory being a single capacity (as has been claimed by Caspari, Parkinson, LaPointe, & Katz, 1998; King & Just, 1991; Just & Carpenter, 1992; MacDonald, Just, & Carpenter, 1992; Miyake, Carpenter, & Just, 1994; Pearlmutter & MacDonald, 1995), whereas other researchers find evidence for separate capacities supporting different types of language processing (Caplan & Waters, 1990, 1999; Hanten & Martin, 2000, 2001; Martin, 1995; Martin & Feher, 1990; Martin & He, 2004; Martin & Lesch, 1995; Martin & Romani, 1994; Martin, Shelton, & Yafee, 1994; Waters, Caplan, & Hildebrandt, 1991; Withaar & Stowe, 1999).

Looking at the types of tasks and sentences used to assess comprehension, the picture starts to elucidate. Most of the studies that report associations between limited phonological working memory (pWM) and comprehension tested sentences that are overloaded with lexical items, such as the Token Test (Baddeley, Vallar, & Wilson, 1987; Bartha & Benke, 2003; Martin & Feher, 1990; Martin, Shelton, & Yafee, 1994; Vallar & Baddeley, 1984; Waters et al., 1991; Wilson & Baddeley, 1993), and tasks that require verbatim repetition (Hanten & Martin, 2000; Martin et al., 1994; Willis & Gathercole, 2001). Importantly, the other findings, which show that the comprehension of sentences is not necessarily impaired when WM is limited, typically come from studies that tested syntactically complex sentences like relative clauses, passives, and garden path structures but without lexical-phonological overload (Baddeley et al., 1987; Butterworth, Shallice, & Watson, 1990; Martin & Feher, 1990; McCarthy & Warrington, 1987; Miera & Cuetos, 1998; Vallar & Baddeley, 1984; Waters et al., 1991; see Caplan & Waters, 1999 for a review). Martin and her colleagues (Martin, 2003; Martin et al., 1994; Martin & Feher, 1990; Martin & He, 2004; Martin & Romani, 1994) conducted a series of experiments that found double dissociations between verbatim repetition and comprehension of sentences that require maintenance of semantic information. These experiments describe individuals who are taken to be impaired in pWM who show deficits in verbatim repetition and in sentences overloaded with lexical items, but with preserved comprehension and plausibility judgment of sentences that require maintenance of semantic information, and other individuals who have semantic WM impairment who show the reversed pattern. Similar dissociations are also reported in developmental case studies (Butterworth, Campbell, & Howard, 1986; Hanten & Martin, 2001; Zandman & Friedmann, 2004), in children with acquired traumatic brain injuries (Hanten & Martin, 2000) and young healthy children with low and high spans (Willis & Gathercole, 2001). Some other studies report impaired comprehension of complex syntactic structures in the presence of limited pWM (Bartha & Benke, 2003; Just & Carpenter, 1992; King & Just, 1991; Papagno & Ceccheto, 2006; Papagno, Cecchetto, Reati, & Bello, 2007; see Carpenter, Miyake, & Just, 1994 for a review). However, whereas dissociations are a reliable tool for identifying the lack of relation between two abilities, associations, for example associations between limited pWM and impaired comprehension of complex syntactic structures, do not necessarily imply that the abilities are related, they might co-exist by chance or because of neurological proximity etc.

What we want to suggest is that the key is in the type of reactivation that is required in a sentence. In a previous study (Friedman & Gvion, 2003) we tested sentence comprehension of individuals with conduction aphasia who had limited spans. We began by testing their ability to understand subject and object relative clauses. Whereas individuals with agrammatic aphasia consistently show very impaired comprehension of object relatives, the individuals with conduction aphasia in our study had very good performance in these sentences. We even manipulated the distance between the antecedent and the gap by adding words (and syllables) between them, creating distances of 2,5,7, and 9 words. The individuals with conduction aphasia did not show any effect of phonological distance, and understood well even the sentences with the longest antecedent-gap distance. We suggested that it was the type of reactivation required in the sentence that enabled the participants to understand them. Relative clauses such as "*I know the woman that the girl drew* _" include a constituent (*the woman*) that is pronounced early in the sentence, but has to be reactivated at its original position (at the gap, after the verb "drew") in order to be interpreted (Nicol & Swinney, 1989; Swinney, Ford, Frauenfelder, & Bresnan, 1988; Swinney, Shapiro, & Love, 2000). Love and Swinney (1996) showed that this reactivation of the antecedent at the gap is semantic rather than phonological in nature. Namely, it is the meaning of the word rather than its word form that is reactivated. If semantic reactivation does not require pWM, it should not be impaired when pWM is impaired. Consequently, we surmised that if we give the same individuals with conduction aphasia sentences that require them to re-access the phonological, rather than semantic form of the word, they will fail to do it when the word is no longer available in their phonological memory.

In order to test phonological reactivation we used a novel paradigm. We constructed sentences with ambiguous words (like *dates* and *toast*), and put them a context strongly biasing toward one of the meanings. At a later point in the sentence, it became evident that the meaning that was initially chosen was the incorrect one, and in order to reanalyze the sentence, the participants had to re-access the other meaning. In this case, naturally, keeping only the meaning of the ambiguous word cannot assist comprehension, so the participants had to re-access the phonological word form in order to reactivate all meaning again, and to choose the congruent one. In this experiment too, the distance between the polysemous word and its reactivation was manipulated. The results were very clear: the same patients who previously understood even very long object relatives very well could not understand the sentences that included a long distance between the polysemous word and its phonological reactivation (and performed better in the short distances).

Friedmann and Gvion's (2003) study included only three participants with conduction aphasia, and only one task per each type of reactivation. In the present study we examine these questions on a larger group of 12 individuals with input conduction aphasia, and test with the same participants, the comprehension of other types of sentences. We used the same two experiments, and added two experiments – one that manipulated the syntactic distance between the antecedent and the gap in object relative clauses, the other tested phonological re-access using a different task – rhyme judgment in a sentence.

The new study of semantic reactivation asked the following question: in the first study we tested semantic reactivation that took place a long distance after the antecedent, a distance that was measured in phonological units: words and syllables. We also manipulated a syntactic aspect of the distance by using object relatives in which an argument of the verb intervenes between the antecedent and the gap hampers their comprehension. But it did not. The participants did not have any problem reactivating the antecedent even after a long phonological distance, and they were able to understand object relatives. The new experiment will test semantic reactivation after a different type of syntactic distance: the number of embeddings (see Gibson, 1998; Gibson & Thomas, 1999). Object relatives already contain one embedding, and we added another embedding (sentential complement) between the antecedent and the gap. We compared object relatives with one embedding to object relatives with double embedding, and tested whether the introduction of an additional embedded clause affects comprehension. If syntactic load is processed in the pWM, we would expect impaired comprehension of such sentences. If, however, as we assume, syntactic and semantic processes are supported by a different type(s) of WM and not by pWM, individuals with limited pWM will be able to understand object relatives even with double embedding between the antecedent and the gap.

EXPERIMENTAL INVESTIVGATION

In order to examine the relation between limited phonological working memory and sentence comprehension, we administered a series of 10 phonological working memory tests to establish pWM limitation, and then we conducted four sentence processing experiments.

Participants

The participants were 12 Hebrew-speaking individuals with conduction aphasia. They were 3 women and 9 men, aged 30-73 years (with mean age of 52;3 years, SD = 13;7). All of them had at least 12 years of education and had pre-morbidly full control of Hebrew. Eight of them were right handed, and four were left handed. All of them sustained a left hemisphere damage, nine participants had a stroke, 2 had TBI, and one had aphasia following tumor removal. They were tested at least 2 months after the stroke, four years at most[1]. The criteria for inclusion in the study were input conduction aphasia (conduction aphasia with a deficit in the phonemic input buffer, also known as repetition conduction aphasia, Shallice & Warrington, 1977), and limited phonological working memory in recall and recognition spans. They were identified with conduction aphasia using the Hebrew version of the Western Aphasia Battery (WAB, Kertesz, 1982; Hebrew version by Soroker, 1997), and as having a phonemic input buffer deficit according to the FriGvi (2002) working memory battery, described in the next section. In addition to input conduction aphasia, six of the participants had phonological errors (substitutions, transpositions, or deletions of segments) in spontaneous speech, repetition, and naming, indicating deficits in the phonological output lexicon or in the phonological output buffer in addition to their input deficit. Detailed information on each participant is given in Table 1.

[1] For the three individuals who were tested 2-3 months post onset, all tests were administered within a short time, and each session included retesting of span test, and no change in spans was detected for either of them within the testing period.

Table 1. Background description of the participants with conduction aphasia

Participant	Age	Gender	Education	Hand	Hebrew	Etiology	Lesion localization	Time post onset	Aphasia type
AF	30	M	12	right	native	TBI	Left Parietal following craniotomy	4 y	Input conduction
TG	32	M	16	left	native	stroke	Left fronto-temporal hemorrhage	2 m	Mixed conduction
MK	39	M	12	left	native	stroke	Left parietal hemorrhage and subarachnoid hemorrhage	3 m	Mixed conduction
GE	47	F	16	left	native	tumor	After left parietal craniotomy a large left parietal low density area	8 m	Mixed conduction
GM	50	M	12	right	45 years	TBI	Left temporal craniotomy	4 y	Input conduction
YM	52	F	12	right	native	stroke	Left temporo-parietal infarct	5 m	Mixed conduction
MH	55	M	12	right	native	stroke	Left hemisphere stroke	3 m	Input conduction
ND	58	M	16	left	native	stroke	Acute infarct in the middle portion of the left MCA.	4 m	Mixed conduction
BZ	59	M	17	right	native	stroke	Left temporal low density area	8 m	Input conduction
AB	59	M	12	right	native	stroke	Left parietal infarct	8 m	Input conduction
ES	72	F	12	right	55 years	stroke	Left temporo-parietal	4 m	Mixed conduction
DS	73	M	12	right	native	stroke	Sub acute infarct in the left MCA area	5 m	Mixed conduction

TBI: traumatic brain injury; MCA: middle cerebral artery.

The participants in the *control group* had no history of neurological disease or developmental language disorders, had full control of Hebrew, and had at least 12 years of education. Because decline in working memory capacity is reported in elderly people (see Carpenter et al., 1994 for a review), and as our aphasic participants varied in age, the control group for each of the tests consisted of at least 60 healthy normal controls in age groups of 10 years, at least 10 participants per age group (from 20 to 77 years). The specific number of control participants is given in the description of each test.

Auditory discrimination and rhyme judgment

Auditory discrimination. Four of the participants (YM, MH, ND, DS) were tested on *auditory discrimination* using PALPA 1, which includes same-different judgment of minimal pairs of nonword syllables (Kay, Lesser, & Coltheart, 1992; Hebrew version by Gil & Edelstein, 1999). They all showed performance of 97.5% and above, indicating they had no deficits in the early stage of auditory processing.

Auditory rhyme judgment was tested for six of the participants (MK, GE, YM, ND, ES, DS). The 36 rhyming pairs consisted of 18 penultimate rhymes (פרח-קרח, /**pe**rax/-/**ke**rax/; משלחת-מקלחת, /mish**la**xat/-/mik**la**xat/) and 18 ultimate rhymes (סינור-כינור, /si**nor**/-/ki**nor**/; עצמאות-חקלאות, /acma'**ut**/-/xakla**'ut**/). All rhymes were classical rhymes which were identical in stress pattern (the stressed syllables in the examples are boldfaced). The penultimate rhymes were identical in the stressed vowel and the phonological segments that followed it, the ultimate rhymes were identical in the final stressed syllable and the vowel that immediately preceded it (if there was one). The 18 non-rhyming pairs differed in all the segments of the final syllable (כלב-חולצה, /**ke**lev/-/xul**ca**/; מפלצת-חסידה, /mif**le**cet/-/xasi**da**/). Half of the rhyming and half of the non-rhyming pairs were two-syllable words and half were three-syllable words. All the participants but ND judged the non-rhyming pairs flawlessly, and performed pretty well on the rhyming pairs (MK 83%, GE 83%, YM 83%, ES 75%, DS 100%). ND rejected correctly 83.3% of the non-rhyming pairs, but was only 33% correct on the rhyming pairs. Because he had perfect performance (100%) on the auditory same-different task (PALPA 1), his difficulties in the rhyming judgment task cannot be ascribed to a deficit in the early auditory perceptual stage but rather to a phonological deficit, possibly in rhyme segmentation. Therefore, ND was included in the current study, but did not participate in the rhyming experiment.

Statistical analysis

The performance of each individual aphasic participant was compared to his or her age-matched control group using Crawford and Howell's (1998) *t*-test. The performance of the experimental group was compared to the performance of the control group using Mann-Whitney test (for more than 10 participants the *z* score was calculated in the Mann-Whitney test, otherwise it was reported with *U*). Within-participant comparisons between performance in two conditions were conducted using a chi-square test, and if the participants showed the same tendencies, a comparison between conditions at the group level was conducted using Wilcoxon Signed-Rank test (results reported with *T,* the minimum sum of ranks). We chose to use non-parametric tests because of the relatively small size of the group, and because we could not assume normal distribution within the aphasic group. For the control groups, ANOVA, linear contrasts, and t-tests were used to compare between age groups and to compare conditions within the groups. When ANOVA found a significant difference, a post-hoc Tukey test was conducted to find the source of the difference. An alpha level of 0.05 was used in all comparisons.

WORKING MEMORY EVALUATION

To assess working memory limitation we developed and administered an extensive battery of 10 working memory tests in Hebrew (FriGvi, Friedmann & Gvion, 2002). The battery included recall and recognition tasks.

Recall tasks

Word and nonword spans. Three tests of word span and one test of nonword span were administered. Word- and nonword lists were presented orally at a one-item-per-second rate and the participants were asked to recall the items serially. Each span test included 6 levels, of 2-7 word/nonword sequences, with 5 sequences per level. Span for each test was defined as the maximum level at which at least 3 sequences were fully recalled; half a point was given for success in 2 out of 5 sequences (e.g., a participant who recalled three 3-word sequences and two 4-word sequences had a score of 3.5).

The word span tests included sequences of semantically unrelated words. To assess length and phonological similarity effects (Baddeley, 1966, 1997), three word span tests were administered and compared. The *basic word span* test included phonologically different 2-syllable words. To test word length effect (Baddeley, Lewis, & Vallar, 1984; Baddeley, Thomson, & Buchanan, 1975), a *long word span* test was used, with 4-syllable word sequences. Word length effect was calculated by the comparison of the 2-syllable word span to the 4-syllable word span. To evaluate the effect of phonological similarity (Conrad, 1964; Conrad & Hull, 1964), a *phonologically similar words span* test was administered. In this task, the sequences included 2-syllable words that were similar in all but a single phoneme. The position of the different phoneme in the words was balanced across initial, medial, and final positions. Phonological similarity effect was calculated by the difference between the similar and basic (dissimilar) word spans.

The *nonword span* included 2-syllable nonwords, constructed by changing a single consonant in real words. Lexicality effect was calculated by the difference between the basic word span (the 2-syllable non-similar word list), and the nonword spans.

Digit span. Sequences of digits were presented orally at a one-digit-per-second rate. Because individuals with output phonological buffer impairment typically have lexical paraphasias when they produce numbers (Cohen, Verstichel, & Dehaene, 1997; Dotan & Friedmann, 2007; Semenza, et al., 2007), we used pointing instead of oral recall. The participants were asked to point to digits on a written 1-9 digit list in the order they appeared in the sequence. The test comprised 8 levels, 2-9 digit sequences, 5 sequences in each level.

Recognition tasks

Listening span. A version of the listening span task (Caspari et al., 1998; Daneman & Carpenter, 1980; Tompkins, Bloise, Timko, & Baumgaertner, 1994) was created for Hebrew-speaking individuals with aphasia. The test was composed of five levels (2-6 sentences per set), each containing five sets. The participants were requested to make true/false judgments to each sentence in increasingly larger sets of unrelated sentences, and to recognize the final word in each sentence after the whole set was read. The sentences were simple sentences without embedding and without passives, controlled for length in words (3-4 word length) and for number of correct and incorrect sentences in each level. All final words were 1-2 syllable nouns. Span was defined as the highest level at which at least three out of five sets of sentences resulted in full recognition of the final words; success in two out of five sets was scored as an additional half a point. Recognition of the final words was assessed by pointing to the words in a set of 2n+1 presented words (e.g., for a set of 4 sentences, 9 words were given); the foils had no semantic or phonological relation to the target words. Prior to the listening span task, each participant was trained separately on true/false decision and on final word retention, and then on the combination of the two tasks.

Recognition span. The same sets of words that were used in the listening span test were also used without a preceding sentence (and without delays between words), in a simple word recognition task, with the same foils as in the listening span test. The recognition span and the listening span tests were administered in two different sessions. We included this test in order to study the type of encoding our participants used, by comparing this test to the listening span test. We conjectured that if individuals with conduction aphasia rely on semantic, rather than phonological encoding, the preceding sentence may assist them, and yield larger spans compared to the spans without preceding sentences.

Probe test. In this test, the participant heard a list of eight words, at a one-per-second rate, and then the experimenter presented eight additional words, and the participant was requested to judge for each word whether it had appeared in the original list. The two lists contained 2-syllable words varied in frequency, imageability, and lexical category. Four of the words in the second list contained matching words; 2 were semantic distractors that were synonyms or closely related to the words from the first list (such as coat/jacket, false/wrong), and 2 were phonological distractors (cap/gap). The position of the words and the distractors was balanced across serial positions in the second list. Twenty lists were presented for judgment.

Matching digit order span (*PALPA* 13) (Kay et al., 1992). In this task the participants heard two lists containing the same digits and were asked to judge whether the order of the items in the two lists was the same. On the non-identical pairs, the two lists differed in the order of two adjacent digits. Position of the reversal was balanced across serial positions.

Matching word order span. This task was similar to the matching digit task, but included two-syllable unrelated words instead of digits. The word sequences differed in the relative order of two adjacent words and the position of the reversal was balanced across serial positions.
In both the matching digit order span and the matching word order span the sequences were presented at a one word per second rate. In both tests there were 6 levels, 2-7 digits/words per set, each composed of 5 matching and 5 non-identical pairs. The span level was defined as the maximal level at which the participant performed correctly on at least seven items.

Results

Control group

Table 2 presents the mean span and the standard deviation for each task for each control age groups and the number of control participants in each test. We compared the performance of the age groups in each working memory test using one-way ANOVA. No difference was found between the different age groups in the nonword recall span. Significant differences between the age groups were found in all other working memory tests ($p < .04$), as well as significant linear contrasts on age groups ($p < .05$). Most of the differences were found between the two youngest age groups, the 20-30 and the 31-40 year old groups (henceforth: the 20s and 30s) and the oldest groups, with participants aged 61-70 and 71-77 (the 60s and 70s).
Given the differences between the age groups, we compared each aphasic individual to his/her age group in each task. Because no differences were found between the two youngest age groups in any of the tests, we combined their data to a single 20-40 age group and these data were compared to the performance of the aphasics within this age range. As to the nonword span, the only memory test that did not yield any differences between age groups and no linear contrast, the span data of all age groups were collapsed.

Another analysis related to factors that affect spans: phonological similarity, length, lexicality, recency, sentential context effect, and primacy effects (see details on Table 2). The *phonological similarity effect* was assessed by the comparison, for each participant, of the span obtained in the basic phonological non-similar words and the basic word span. Recall was significantly better for the basic word span in which the words were not phonologically similar compared to the span for phonologically similar words. This was significant for all the control subjects as a group, t(66) = 14.30, $p < .01$, as well as for each age group separately ($p < .01$), with no significant difference between age groups in the size of the similarity effect, and no linear contrast. To test for the existence of *length effect*, we compared the span obtained in basic two-syllable word span and the long four-syllable word span. This comparison also revealed significantly better recall of short words compared to long words for the control group, t(66) = 15.28, $p < .01$, as well as for each age group, $p < .01$, with no difference in effect size between age groups and with no linear contrast. *Lexicality effect* was calculated by comparing the performance of each participant in the basic span test and the nonword span test. Words were recalled significantly better than nonwords for all age groups ($p < .01$). ANOVA revealed no significant difference in effect size between age groups ($p = .1$), but a linear contrast was found as a function of age, F(1,114) = 7.73, $p = .006$. The decrease of the lexicality effect with age is probably due to the fact that the recall of nonwords remained stable over time whereas the word spans decreased linearly after age 50, as seen in Figure 1.

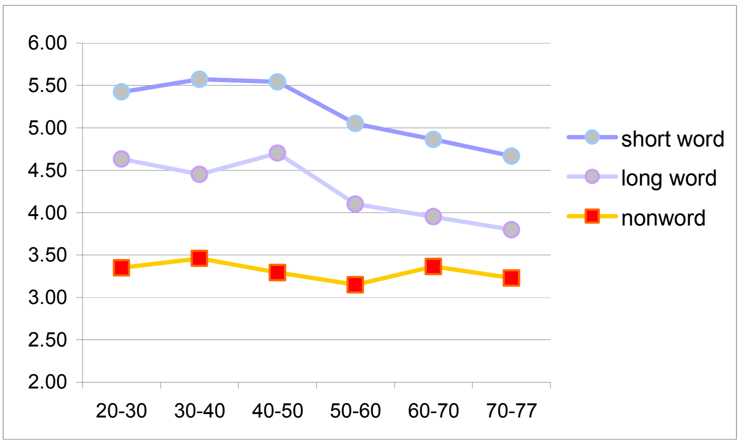

Figure 1. Spans of the control group as a function of age: decrease in word spans and stable nonword span

No *recency effect* was found for the control group, probably because the participants were required to recall the items in serial order (see similar findings in Dalezman, 1976). Therefore the absence of a recency effect was not taken as a defining criterion for limited phonological memory.

Table 2. Recall and recognition spans of the control group according to age groups

Age group / **Test**	**20-30**	**31-40**	**41-50**	**51-60**	**61-70**	**71-77**	**Average**	**F**	**Linear contrast**
Basic									
Mean (SD)	5.42[7] (.71)	5.57[67] (.75)	5.54[7] (.45)	5.05 (.64)	4.86 (.78)	4.67 (.68)	5.33 (.75)	(5,126)=4.67**	(1,126)=21.78**
n	52	35	12	10	11	12	132		
Similar									
Mean (SD)	4.50[6] (.60)	4.58[6] (.52)	4.60[6] (.52)	4.10 (.39)	3.80 (.67)	3.95 (.64)	4.29 (.63)	(5,65)=4.17**	(1,65)=17.01**
n	19	12	10	10	10	10	71		
Long (4 syl.)									
Mean (SD)	4.60[67] (.68)	4.45 (.50)	4.70[67] (.75)	4.10 (.21)	3.95 (.44)	3.80 (.42)	4.32 (.63)	(5,63)=5.19**	(1,63)=21.79**
n	19	10	10	10	10	10	69		
Nonword									
Mean (SD)	3.35 (.51)	3.46 (.54)	3.29 (.45)	3.15 (.34)	3.36 (.45)	3.23 (.41)	3.35 (.49)		
n	66	37	12	10	11	11	146		
Digit									
Mean (SD)	7.2[6] (1.01)	7.05 (1.28)	7.50[6] (1.00)	6.50 (1.22)	5.95 (.72)	6.45 (1.13)	6.96 (1.14)	(5,116)=3.60**	(1,116)=13.13**
n	52	29	10	10	10	11	123		
Listening span									
Mean (SD)	5.96[7] (.13)	6.00[7] (.00)	5.90 (.32)	5.70 (.42)	5.70 (.42)	5.46 (.69)	5.79 (.43)	(5,60)=3.10*	(1,60)=14.09**
n	14	10	10	10	10	12	66		
Recognition word									
Mean (SD)	5.89 (.22)	5.73 (.47)	6.00[6] (.00)	5.90 (.21)	5.55 (.44)	5.65 (.41)	5.78 (.36)	(5,54)=2.54*	(1,54)=4.02*
n	9	11	10	10	10	10	60		
Probe (total)									
Mean (SD)	88.96(3.59)	88.29 (5.28)	87.70(3.98)	85.43 (3.09)	84.33(4.30)	83.15(3.35)	86.67 (4.14)		
n	11	10	10	10	9	10	60		
Probe (match)									
Mean (SD)	88.64[7] (5.71)	87.63[7] (7.36)	84.75 (8.74)	87.16[7] (4.97)	83.29 (7.55)	76.74 (8.80)	84.83 (8.12)	(5,54)=3.54**	(1,54)=12.89**
Probe(no-match)									
Mean (SD)	89.65 (7.67)	89.88 (6.02)	90.67 (8.10)	83.66 (6.27)	85.38 (8.80)	89.95 (5.80)	89.97 (7.43)		
Matching Word									
Mean (SD)	6.40 (1.07)	6.33 (.98)	6.80[6] (.42)	6.10 (.87)	5.70 (1.16)	5.45 (.93)	6.13 (1.01)	(5,57)=2.86*	(1,57)=9.17**
n	10	12	10	10	10	11	63		
Matching Digit									
Mean (SD)	6.70 (.48)	7.00[6] (.00)	7.00[6] (.00)	6.50 (.85)	6.27 (.79)	6.50 (.71)	6.65 (.63)	(5,54)=2.86*	(1,54)=6.27**
n	10	10	10	10	11	10	61		
Effects on WM									
Similarity									
Mean (SD)	1.28 (.71)	1.05 (.64)	1.4 (1.35)	1.35 (1.58)	1.15 (.34)	0.85 (.62)	1.19 (.93)		
n	18	10	10	10	10	10	68		
Length									
Mean (SD)	1.08 (.55)	1.6 (1.12)	0.9 (.57)	0.83 (.66)	1.00 (.53)	1.00 (.47)	1.02 (.54)		
n	18	9	10	9	10	10	66		
Lexicality									
Mean (SD)	2.01 (.52)	2.1 (.60)	2.18 (.34)	1.90 (.57)	1.64 (1.21)	1.50 (.64)	1.99 (.88)		(1,114)=8.45**
n	50	35	11	10	7	7	120		
Sentential									
Mean (SD)	0.06 (0.30)	0.20 (0.42)	-0.10 (0.32)	-0.2 (0.35)	0.15 (0.45)	0.30 (0.48)	0.07 (0.42)		
n	9	10	10	10	10	10	59		

* $p < .05$, ** $p < .01$; [6] indicates significantly better performance in the task than age group 61-70, $p < .05$; [7] indicates significantly better performance in the task than age group 71-77, $p < .05$; No other significant differences were found between the age groups.

Table 3. Recall and recognition spans of individuals with conduction aphasia compared to age-matched norms

	AF	TG	MK	GE	GM	YM	MH	ND	BZ	AB	ES	DS	Average
Basic	*3	*2.5	*4	*2	*2	*3	*3.5	*2	*3.5	*3	*2	4	**2.88**
Norm	5.48	5.48	5.48	5.54	5.54	5.05	5.05	5.05	5.05	5.05	4.67	4.67	
(SD)	(.72)	(.72)	(.72)	(.45)	(.45)	(.64)	(.64)	(.64)	(.64)	(.64)	(.68)	(.68)	
Similar	*2	*2	*3	*1.5	*2	*2	*3	*2	*3	*3	*1.5	*2.5	**2.29**
Norm	4.53	4.53	4.53	4.60	4.60	4.10	4.10	4.10	4.10	4.10	3.95	3.95	
(SD)	(.56)	(.56)	(.56)	(.52)	(.52)	(.39)	(.39)	(.39)	(.39)	(.39)	(.64)	(.64)	
Long	*1	*1	*3	*1	*2	*1.5	*2.5	*1.5	*2	*3	*2	3.5	**2.0**
Norm	4.57	4.57	4.57	4.70	4.70	4.10	4.10	4.10	4.10	4.10	3.80	3.80	
(SD)	(.62)	(.62)	(.62)	(.75)	(.75)	(.21)	(.21)	(.21)	(.21)	(.21)	(.42)	(.42)	
Nonword	*1	*1	*1	*1	*1	*2	*2	*1	*1.5	*2.5	*1	*2	**1.42**
Norm	3.35	3.35	3.35	3.35	3.35	3.35	3.35	3.35	3.35	3.35	3.35	3.35	
(SD)	(.49)	(.49)	(.49)	(.49)	(.49)	(.49)	(.49)	(.49)	(.49)	(.49)	(.49)	(.49)	
Digit	*2.5	*4	*3	*2.5		*2	*4	*3	*3	5		5.5	**3.45**
Norm	7.14	7.14	7.14	7.50		6.50	6.50	6.50	6.50	6.50		6.45	
(SD)	(1.10)	(1.10)	(1.10)	(1.0)		(1.22)	(1.22)	(1.22)	(1.22)	(1.22)		(1.13)	
Listening	6	6	*5.5	6	*3	5	5.5	*4	6	*3.5	*4	*2.5	**4.75**
Norm	5.98	5.98	5.98	5.90	5.90	5.70	5.70	5.70	5.70	5.70	5.46	5.46	
(SD)	(.10)	(.10)	(.10)	(.32)	(.32)	(.42)	(.42)	(.42)	(.42)	(.42)	(.69)	(.69)	
Recognition	*3	*4	*5	*4.5	*2.5	*4	*5	*3	*4.5	*5	*4.5	*4	**4.08**
Norm	5.8	5.8	5.8	6.00	6.00	5.90	5.90	5.90	5.90	5.90	5.65	5.65	
(SD)	(.04)	(.04)	(.04)	(.00)	(.00)	(.21)	(.21)	(.21)	(.21)	(.21)	(.41)	(.41)	
Probe (Match)			*74	*64		*51		*56		*68	72	69	**65**
Norm			88.15	84.75		87.16		87.16		87.16	76.74	76.74	
(SD)			(6.40)	(8.74)		(4.97)		(4.97)		(4.97)	(8.80)	(8.80)	
Probe (no-match)			83	97		97		96		91	87	66	**88.14**
Norm			89.88	90.67		83.66		83.66		83.66	89.59	89.59	
(SD)			(6.02)	(8.1)		(6.27)		(6.27)		(6.27)	(5.80)	(5.80)	
Matching Words			*3			*3		*3		*3	*3	4	**3.17**
Norm			6.36			6.10		6.10		6.10	5.45	5.45	
(SD)			(1.0)			(.87)		(.87)		(.87)	(.93)	(.93)	
Matching Digits			*3			7		*3		5	*3	*4	**4.17**
Norm			6.85			6.50		6.50		6.50	6.50	6.50	
(SD)			(.37)			(.85)		(.85)		(.85)	(.71)	(.71)	

*Significantly poorer than the age-matched control group, $p < .05$

Conduction aphasia group

The results for the recall and recognition spans for each individual participant as well as the mean and standard deviation of the group for each subtest are presented in Table 3.[2]

All the individuals with conduction aphasia were tested with the 3 recall word span tests, the nonword span test, the listening span test, and the recognition word span test. Ten of them were tested with the digit span test. Because we started using the matching and probe tasks at a later stage of the research, only 6 patients took the two matching tests, and 7 took the probe test.

A comparison of the aphasic group to the control group in each memory test yields significant differences in all memory tests ($p \leq .02$) except for the listening span task, as can be seen in Table 4. When taking the whole array of memory tasks of each individual with conduction aphasia, and comparing it to the age-matched control group using Wilcoxon test, a significant difference is evinced for each patient, $p \leq .02$, as can be seen in Table 5.

Table 4. Comparison between the conduction aphasic group and control group in each memory test

Memory task	Mann-Whitney analysis
Basic	z = 4.16 $p < .0001$
Phonologically similar	z = 2.71, $p < .003$
Long words	z = 4.16, $p < .0001$
Nonwords	z = 4.16, $p < .0001$
Digits	z = 3.96, $p < .0001$
Listening span	No significant difference
Word recognition	z = 4.16, $p < .0001$
Probe	z = 3.55, $p < .0001$
Matching word	z = 3.37, $p = .0001$
Matching digit	z = 2.34, $p = .02$

[2] Because some of the aphasic participants had phonological output deficits as well, it was impossible in certain cases to decide whether an erroneous response indicated a recall failure or a phonological output deficit. We wanted to avoid false lexical effect as a result of mistakenly accepting a response with mild phonological errors as a correct recall response in the various word spans tasks, while rejecting inaccurate responses in the nonword span. We therefore analyzed the spans in three ways: in the first only accurate responses were accepted as correct recall responses, counting all types of errors as incorrect recalls. In the second analysis we were more permissive and accepted also phonological errors ("dable" or "cable" for "table") as correct recalls, and finally we also accepted responses that indicated correct semantic encoding in the absence of phonological word form (such as pointing to the ear for the word 'ear, or giving a definition). The first two counts yielded exactly the same spans for each of the participants. On the more permissive count, only the spans of a single participant, TG, changed: his phonologically similar word span increased from 2 to 2.5; his basic word span changed from 2.5 to 3, and his long word span changed from 1 to 3.5 words. The results presented in the results section are the results of the two first counts.

Table 5. Comparison of each aphasic individual performance to the matched control group in all memory tasks

Participant	Wilcoxon analysis
AF	T = 1, $p = .02$
TG	T = 1, $p = .02$
MK	T = 0, $p < .01$
GE	T = 1, $p < .01$
GM	T =0, $p = .02$
YM	T = 1, $p < .01$
MH	T = 0, $p < .01$
BZ	T = 1, $p = .02$
AB	T = 0, $p < .01$
ND	T = 0, $p < .01$
ES	T = 0, $p < .01$
DS	T = 0, $p < .01$

All the individuals with conduction aphasia showed very limited *digit-, word-, and nonword-spans* in all the recall and recognition tasks. Looking at the individual data, presented in Table 3, each of the individuals with conduction aphasia had significantly poorer performance than the control group in most of the recall span tasks (one participant, DS, had smaller recall spans than the matched control group in approximately 1 SD, but only his nonword and phonologically similar spans were significantly smaller using Crawford & Howell's t-test).

The analysis of phonological similarity and length effects (see Table 6 for the effects on spans for each individual) reveals that ten of the individuals with conduction aphasia had smaller *phonological similarity effect* compared to the matched controls, for 6 of them this effect was smaller than 1 standard deviation below the control average. Six aphasics had smaller *length effect* than the norms, for four of them this effect was more than 1 standard deviation below the matched control average.

To examine the existence of a *lexicality effect*, which is critical for the distinction between impairment in phonological memory and semantic memory, we calculated the basic word span minus the nonword span. All the individuals with conduction aphasia showed lexicality effect of 0.5-3 (M = 1.46, SD = .69). The size of the effect for each participant with aphasia did not differ significantly from that found in the matched controls, except for MK who had a significantly larger effect than the norm ($p = .045$), and GE, GM, and AB who had lexicality effects, but their sizes were smaller than their respective matched controls ($p < .03$).

The analysis of serial position effects focused on primacy and recency effects. *Primacy effect* was calculated by the comparison of the rate of recalling the first item (mean=65%, SD=25%) compared to the rate of recalling the medial item (mean=50%, SD=23%). This analysis revealed primacy effect for all participants as a group and for 9 participants individually. Similarly to normal controls, no *recency effect* was evinced, as average rate of correct recall of the final item was 50% (SD = 15%), just like the rate for the medial items.

A severe working memory impairment was also evinced in the span tasks that did not involve overt output (see Table 3). In the *matching digit order* and *matching word order* span tasks the participants with conduction aphasia showed limited spans, which were smaller than the control groups' spans for all participants (except YM in the digit task), significantly so for 5 of them in the word task, and 4 of them in the digit task.

The analysis of the *probe task* once again indicated a severe limitation in input phonological working memory: the total score (match and no-match items) of all seven participants was lower than their control groups, for 4 of them significantly so. Similarly, in the analysis of the match items all 7 participants performed poorer than controls, a difference which was significant ($p < .025$) for all but the two older participants. In the analysis of the no-match items, only one of the participants differed significantly from the controls. A reason for the difference in performance between the match and no-match items in the probe test might be that phonological WM impairment causes the items in the list to decay, and hence biases the patients to respond that the item did not appear in the list. This would create errors in the match items, but correct responses for the items that did not occur.

The participants performed better in the *listening span* task. Their mean span was 4.75 (range: 2.5-6; SD = 1.29). For 6 patients this span was significantly poorer than the matched control groups ($p < .01$), but 6 other patients reached ceiling values. Each of them performed at least 90% correct in the true/false judgments. The relatively good performance of the individuals with conduction aphasia in this task was probably due to semantic encoding and reliance on the sentence that preceded the word (and possibly also a facilitatory effect of the syntactic context), because when the same words were used in a *recognition task* without the preceding sentences, all 12 patients had very limited spans, which were significantly smaller than the spans of the control participants ($p < .01$) (see Butterworth et al., 1990 for a discussion of the difference between memory for word lists and memory for words within sentences). The difference in performance in the recognition of the same words with and without a sentential context (*sentential effect*) is presented in Table 6 for each individual patient. Whereas the addition of a sentential context had a very small effect on the spans of the control participants (only 0.07), it helped most of the individuals with conduction aphasia to remember an additional item and even more, indicating they relied on the sentence to improve their recognition of the words.

Table 6. Phonological similarity, length, lexicality, and sentential effects

	AF	TG	MK	GE	GM	YM	MH	ND	BZ	AB	ES	DS	Average
Similarity effect	1	.50^{s}	1	0.5^{s}	0^{s}	1	0.5	0^{s}	0.5	0^{s}	0.5	1.5	**0.58**
Norm (SD)	1.20 (.69)	1.20 (.69)	1.20 (.69)	1 (.50)	1 (.50)	0.89 (.65)	0.89 (.65)	0.89 (.65)	0.89 (.65)	0.89 (.65)	0.85 (.63)	0.85 (.63)	
Length effect	2	1.5	1	1	0^{s}	1.5	1	0.5	1.5	0^{s}	0*	0.5^{s}	**0.87**
Norm (SD)	1.15 (.53)	1.15 (.53)	1.15 (.53)	0.90 (.57)	0.90 (.57)	0.83 (.66)	0.83 (.66)	0.83 (.66)	0.83 (.66)	0.83 (.66)	1 (.47)	1 (.47)	
Lexicality effect	2	1.5^{s}	3^{+}	1*	1*	1^{s}	1.5	1^{s}	2	0.5*	1	2	**1.46**
Norm (SD)	2.05 (.55)	2.05 (.55)	2.05 (.55)	2.18 (.34)	2.18 (.34)	1.90 (.57)	1.90 (.57)	1.90 (.57)	1.90 (.57)	1.90 (.57)	1.50 (.65)	1.50 (.65)	
Sentential effect	3^{+}	2^{+}	0.5	1.5^{+}	0.5^{+}	1^{+}	0.5	1^{+}	1.5^{+}	-1.5^{+}	-0.5	1.5^{+}	**0.92**
Norm (SD)	0.13 (.37)	0.13 (.37)	0.13 (.37)	-0.1 (.32)	-0.1 (.32)	-0.2 (.35)	-0.2 (.35)	-0.2 (.35)	-0.2 (.35)	-0.2 (.35)	0.3 (.48)	0.3 (.48)	

*significantly smaller than the norm, $p < .01$,**significantly smaller than the norm, $p < .05$, ^{s}1 SD below the norm, $^{+}$significantly larger than the norm, $p < .05$.

How do the participants with limited pWM encode words in span lists?

One of the intriguing questions is how individuals with limited phonological working memory encode verbal material in short term memory. Do they keep using their impaired phonological memory and encode the items phonologically, or do they use a different route, encoding the items semantically when possible?

In order to determine which encoding method is used by each patient, two sources of data can be used: types of errors in recall span tasks, and type of distractors chosen in the probe test (semantic or phonological). Semantic substitutions in recall tasks may indicate spared semantic encoding without the ability to maintain the phonological form of the items. Similarly, semantic encoding of items in the probe task should result in choosing the semantic foils rather than the phonological ones when making an error.

The analysis of the erroneous recall responses reveal that the story is not so simple. The group of individuals with conduction aphasia produced 54 non-lexical phonological paraphasias, 17 formal paraphasias, and 42 responses that indicated correct semantic encoding (close semantic substitutions, paraphrases, or conveying the meaning using appropriate gestures or pointing). However, given that many of the participants also had an output deficit, we cannot determine if these errors resulted from failure to encode the items phonologically or rather from failure to produce the words. When we consider only the errors made by the participants who had no output disorders (GM and AB), we see that they made only 2 formal paraphasias and 2 semantic encoding errors. Most of their errors were omissions of words from the list. Thus, such an analysis does not seem to solve the riddle, and it only indicates that the items decayed from their memory.

The analysis of the type of errors in the probe task turned out to be more informative. We assumed that if aphasics tend to encode items semantically, they will choose more semantic than phonological foils in the probe task. The control participants tended to make more phonological errors: 74% of the distractors they incorrectly accepted as an item previously presented were phonological (and 26% were semantic). This pattern of more phonological than semantic errors was significant in each of the age groups (the 20s and 30s: $t(19) = 5.35$, $p < .01$; the 40s: $t(9) = 2.51$, $p = .03$; the 50s: $t(7) = 6.56$, $p < .01$; the 60s: $t(6) = 6.12$, $p < .01$; the 70s: $t(8) = 2.36$, $p = .04$).

The individuals with conduction aphasia made significantly more errors than the controls ($p < .01$). Importantly, their error pattern was similar to the controls: they chose more phonological distractors (62% of the non-matched errors) than semantic distractors (38%). This difference was significant ($p \leq .03$) for 4 individuals, but was not significant at the group level. Interestingly, one patient, ND, showed the opposite pattern, with significantly more ($p < .01$) semantic distractors (81%) compared to phonological distractors (19%).

These findings demonstrate that most of the individuals with conduction aphasia still tend to encode verbal material in span tasks phonologically, similarly to healthy adults, despite their limited phonological capacity. One of the participants, ND, showed a preference for semantic encoding.

Summary – working memory tests

The working memory tasks indicated that all the participants with conduction aphasia have limited input working memory, evinced in very short recall and recognition spans.

Because all of the participants had a deficit in at least some of the recognition tasks, and in fact all of them showed impairments in both recall and recognition tasks, we can conclude that all of them had a deficit in the input buffer. Five of them (AF, GM, MH, BZ, AB) had no or only few phonological errors in their output (in naming and spontaneous speech), and we therefore conclude that they had a selective deficit to the input phonological buffer (sometimes termed repetition conduction aphasia). The other seven participants had deficits in both input and output: they had limited phonological working memory capacity in recognition (and recall) tasks, and they had a phonological output deficit, which caused their phonological errors in spontaneous speech and naming.

All of the participants had better performance on words compared to nonwords, indicating that their deficit is in phonological, rather than semantic, memory. The findings that nine of them also had primacy effect, and ten had a sentential effect further exclude the possibility of a semantic memory deficit.

The following sections describe the four experiments that explored the nature of the relation between phonological working memory deficit and sentence comprehension.

SENTENCE COMPREHENSION EXPERIMENTS

After establishing that the participants with conduction aphasia had limited input pWM, four experiments were conducted in order to test how they understand sentences, and assess which type of sentence processing, if any, is affected by limited phonological working memory. Experiments 1 and 2 tested sentences that require re-access to the meaning of a word. *Experiment 1* tested the comprehension of subject and object relatives in 4 gap-antecedent distances, counted in number of words and syllables interpolated between the antecedent and the gap. In *Experiment* 2, the same type of reactivation is tested in object relatives, with a different type of distance manipulation. We used syntactic load, counted by the number of CPs between the antecedent and the gap, instead of a phonological load. If indeed the comprehension of relative clauses requires only semantic reactivation, then the participants with limited phonological working memory should understand the relative clauses even when the distance between the antecedent and the gap is long, both when the distance is manipulated in phonological items, and when it is manipulated in syntactic items. In Experiments 3 and 4 we turn to examine the comprehension of sentences that require phonological reactivation. *Experiment* 3 tested the comprehension of sentences that require re-access to the word form of a polysemous word, in order to reactivate all its meanings and choose a different meaning from the one that was initially chosen. These sentences were constructed so that right after the temporary lexical ambiguity, a certain meaning is chosen, but at a later point, the sentence gets disambiguated and another meaning of the ambiguous word becomes relevant, and thus a reactivation of the original phonological word is required in order to re-access all meanings and allow for reanalysis. The number of words between the polysemous word and its disambiguation point was manipulated. *Experiment 4* further tested phonological processing using a rhyme judgment task of words in sentential contexts. The phonological distance between the rhyming words was manipulated, under the assumption that, given unimpaired rhyming judgment, the participants will fail to judge rhymes only when the distance between the rhyming words is too long for the phonological form of the first word to be maintained and re-accessed. Thus if indeed pWM supports phonological reactivation, the prediction for Experiments 3 and 4 is that the participants with limited pWM will perform well in the short distance condition, but will fail in the long distance condition, in both the comprehension of sentences with ambiguous words and the rhyme judgment tasks.

Experiment 1: Does pWM limitation impair the comprehension of relative clauses?

We tested **semantic-syntactic reactivation** through the assessment of comprehension of relative clauses. The aim was twofold: to test whether the comprehension of relative clauses, which require semantic reactivation of the moved constituent at the gap, is impaired when pWM is limited, and to test whether increasing the distance between the antecedent and the gap has any effect on comprehension of individuals with limited pWM.

If pWM supports semantic reactivation, we would expect individuals with limited pWM to fail in the comprehension of relative clauses, because they require semantic reactivation of the antecedent at the gap. If, however, semantic reactivation relies on a different type of WM, then individuals who are only impaired in phonological WM should be able to understand both subject and object relatives.

Increasing the number of words between the antecedent and the gap served to answer a further question. The phonological loop is limited (to the number of words that can be rehearsed in about 2 seconds, Baddeley, 1997), so that recalling a word that is encoded phonologically would be problematic when too many additional words are heard. How does the addition of words affect the recall of the meaning of a word? If a word is encoded semantically, does the addition of words to the phonological loop cause its meaning to decay? We manipulated the number of words (and syllables) between the word and its reactivation site in order to test whether additional verbal material damages the re-access to the meaning of the word. If pWM supports semantic reactivation, and if additional phonological units are stored with semantic units, we would expect individuals with limited pWM to fail in the comprehension of subject and object relatives as the phonological distance gets longer. If, however, semantic encoding and reactivation are not done by pWM, the distance should not have an effect on comprehension.

(1) Subject relative: This is the woman$_i$ **that** t_i hugs the girl

(2) Object relative: This is the woman$_i$ **that the girl hugs** t_i

The distance between the antecedent and the gap was also manipulated syntactically. Syntactic distance was manipulated by the addition of another argument of the verb between the moved argument and the site of its reactivation. Whereas subject relatives (example 1) do not include any argument between the antecedent and the gap, in object relatives the embedded subject intervenes between the moved argument and its reactivation (in sentence 2, *the girl* intervenes between the moved argument *the woman* and the gap). If pWM supports the holding in memory of arguments until they receive their thematic role, and limitation in pWM does not allow the addition of a second argument without a role, individuals with limited pWM would be expected to fail in the comprehension of object relatives. If, however, this is a task of a different type of WM (a syntactic WM for example), individuals who are impaired only in phonological WM are expected to understand object relatives.

Procedure

The experimental design and the sentences were taken from Friedmann and Gvion (2003). Comprehension was assessed using a binary sentence-picture matching task. The participants heard a sentence while two pictures were presented on the same page in front of them – the matching picture and a foil picture in which the roles were reversed. The participant was asked to select the picture that matched the sentence. Each picture included two figures, one of them performing the action; the other was the theme/recipient of the action. In half of the trials the top picture was the matching one, and in the other half the bottom picture matched the sentence. The position of the matching and non-matching pictures was randomized. Before task administration, identification of the figures in the pictures was assessed and trained. Each sentence was read only once. In order to make sure that the participants attended to the padding material, they were instructed to pay attention to the sentence and were asked to answer questions regarding the post-subject or the post-object adjuncts[3]. The test was administered in a quiet room, with only the experimenter(s) and the participant present.

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[3] In fact, it should not matter even if the participants decide not to attend to the padding material. Baddeley (1997) and Salamé and Baddeley (1987, 1989) described the *unattended speech effect*, according to which immediate recall is impaired even when the verbal material that is heard when trying to remember a sequence is irrelevant and unattended.

Material

The test 168 semantically reversible Hebrew relative clauses. The number of words between the antecedent and the gap (2,5,7, or 9 words), and the relative clause type (subject vs. object) were manipulated. Of the 168 sentences, 80 were subject relatives (example 3 in Table 7), and 80 were object relative sentences (example 4). Within each type of relative clause, there were 20 sentences each of the 2, 5, 7, and 9 word distances. The gap-antecedent distance (GAD) was manipulated by adding adjunct prepositional phrases and adjectives to the noun. The GAD in each object relative included the complementizer, the embedded subject, and the verb (4a), and when padding material was added to the GAD (sentences 4b-4d), prepositional phrases and adjectives followed the agent in half of the sentences (4b, 4c), and followed the theme in another half (4d). In the subject relative sentences, prepositional phrases and adjectives had to follow the subject and precede the object in order to be located between the antecedent and the gap (see sentences 3a-d). In order to discourage the participants from adopting a strategy according to which the padded NP is the agent, 8 subject relatives in which prepositional phrases and adjectives followed the object (GAD 0, see example 3e) were added, two within the first 10 sentences of each of the four sessions. The subject and the object relatives were matched in terms of the number of noun phrases between the antecedent and the gap, and did not differ significantly in this respect. The mean number of syllables between the antecedent and the gap in the 2, 5, 7, and 9-word GADs were 6, 16, 22, and 28 syllables, respectively. These GADs also differed significantly ($p < .01$) in terms of the GAD duration measured in seconds, calculated on a post-hoc analysis of the recorded experimental sessions. The mean duration of the 2,5,7,9 GADs in the subject relatives was 1.47 sec (SD = 0.3), 3.86 sec (SD = 0.33), 4.90 sec (SD = 0.69), and 6.35 sec (SD = 0.69), respectively. The mean durations measured for the 2,5,7,9 GADs in the object relatives were 1.91 sec (SD = 0.30), 3.43 sec (SD = 0.35), 5.08 sec (SD = 0.46), and 6.17 sec (SD = 0.40), respectively. Each GAD had a significantly shorter duration than the next GAD, both for the subject relatives ($t(24) > 6.83$, $p < .01$), and for object relatives ($t(24) > 8.85$, $p < .01$).

The sentences were presented in a random order, with no more than two consecutive sentences of the same condition. The 168 sentences were divided into four sets with the same number of sentences of each condition; each set was administered in a different session.

Table 7.

Examples for subject and object relatives in the different GADs used in Experiment 1

(3) Subject relatives

(a) GAD 2 (SR2):
Ze **baxur**$_i$ im zakan she-**t**$_i$ -malbish et ha-xayal.
This guy with beard that-dresses acc the-soldier
This is a guy with a beard that dresses the soldier.

(b) GAD 5 (SR5):
Zo ha-**baxura**$_i$ im ha-mixnasaim ha-xumim ve-ha-xulca ha-levana she-**t**$_i$-mexabeket et ha-yalda.
This the-woman with the-pants the-brown and-the-shirt the-white that-hugs acc the-girl
This is the woman with the brown pants and the white shirt that hugs the girl.

(c) GAD 7 (SR7):
Zo ha-**yalda**$_i$ ha-blondinit ha-nemuxa im ha-mixnasaim ha-kehim ve-ha-xulca ha-levana she-**t**$_i$-mexabeket et ha-isha.
This the-girl the-blond the-short with the-pants the-dark and-the-shirt the-white that-hugs acc the-woman
'This is the short blond girl with the dark pants and the white shirt that hugs the woman.'

(d) GAD 9 (SR9):
Ze ha-**xayal**$_i$ ha-nexmad im ha-se'ar ha-kacar im madei ha-cava ha-yeshanim ha-yerukim she-**t**$_i$-ma'axil et ha-'ish.
This the-soldier the-nice with the-hair the-short with uniform the-army the-old the-green that-feeds acc the-man
This is the nice soldier with the short haircut with the green worn-out army uniform that feeds the man.

(e) GAD 0, object padding (filler, SR0):
Zo ha-**yalda**$_i$ she-**t**$_i$-menagevet et ha-isha im ha-se'ar ha-arox ve-ha-mishkafaim ha-kehim.
This the-girl that-dries acc the-woman with the-hair the-long and-the-glasses the-dark
This is the girl that dries the woman with the long hair and the dark glasses.

(4) Object relatives

(a) GAD 2 (OR2):
Ze ha-**baxur**$_i$ she-ha-yeled tofes **t**$_i$
This the-guy that-the-boy catches
This is the man that the boy catches.

(b) GAD 5 (OR5):
Ze ha-**xayal**$_i$ she-ha-rofe im ha-xaluk ha-lavan mecayer **t**$_i$
This the-soldier that-the-doctor with the-robe the-white draws
This is the soldier that the doctor with the white robe draws.

(c) GAD 7 (OR7):
Ze ha-**rofe**$_i$ she-ha-xayal im ha-madim ha-yeshanim be-ceva yarok mecayer **t**$_i$
This the-doctor that-the-soldier with the-uniform the-old in-color green draws
This is the doctor that the soldier with the worn-out green-colored army uniform draws.

(d) GAD 9 (OR9):
Ze ha-**saba**$_i$ ha-nexmad im ha-eynaim ha-xumot ha-ne'imot ve-ha-zakan ha-lavan she-ha-yeled mexabek **t**$_i$
This the-grandfather the-nice with the-eyes the-brown the-pleasant and-the-beard the-white that-the-boy hugs
This is the nice grandpa with the pleasant brown eyes and the white beard that the boy hugs.

Results

Control group

The 65 participants in the control group scored 92.5% correct and above in all sub-tests and in both types of relative clauses. The results of the control participants by age group are presented in Table 8.

Table 8. Control groups: average percentage correct (SD)

Relative type	Age group GAD	20-30 n=13	31-40 n=10	41-50 n=10	51-60 n=10	61-70 n=10	71-77 n=12	Average
Subject relative	2	100 (0)	100 (0)	100 (0)	99 (3.2)	100 (0)	100 (0)	99.83 (0.41)
	5	100 (0)	100 (0)	100 (0)	100 (0)	99 (3.2)	99.2 (1.9)	99.7 (0.47)
	7	100[7] (0)	100[7] (0)	100[7] (0)	100[7] (0)	100[7] (0)	98.7 (2.3)	99.78 (0.53)
	9	99.6 (1.4)	100 (0)	99 (3.2)	99 (3.2)	100 (0)	98.3 (3.2)	99.32 (0.67)
Object relative	2	99.2 (1.9)	100 (0)	98 (6.3)	97 (4.8)	100 (0)	95 (7.1)	98.2 (1.96)
	5	99.6[7] (1.4)	100[7] (0)	99[7] (3.2)	100[7] (0)	99 (3.2)	95.8 (6)	98.9 (1.58)
	7	99.2 (1.9)	94 (7)	95 (7.1)	97 (4.8)	98 (4.2)	95 (6)	96.37 (2.02)
	9	99.2[7] (1.9)	97[7] (4.8)	99 (3.2)	96[7] (7)	100 (0)	92.5 (7.8)	97.28 (2.78)

[7] Significantly better performance in the task than age group 71-77

No significant differences were found between the age groups on the different conditions except for the group aged 71-77, whose performance was poorer than that of the younger groups in three conditions: SR7, OR5 and OR9 (Tukey test, $p < .05$). ANOVA and linear contrast were also administered to compare between the performance of the control participants within each relative type between the different distances. No differences and no linear contrast were found in the performance on subject relatives. A single difference was found in the object relatives ($F(5,59) = 2.9$, $p = .03$), which according to the Tukey test was due to a better performance in OR5 compared to OR7. Importantly, no other differences were found between the different distances in object relatives, and no linear contrast was found between the different GADs of the object relatives.

Conduction aphasia group

All the participants with conduction aphasia showed good comprehension of relative clauses, as seen in Figure 2. Although they had very limited phonological WM, their average performance was 90.3% correct, and they understood relative clauses in most of the conditions above 80% correct. Their performance on subject relatives and their performance on object relatives were significantly above chance (using Binomial test), for each individual participant, as well as for the group.

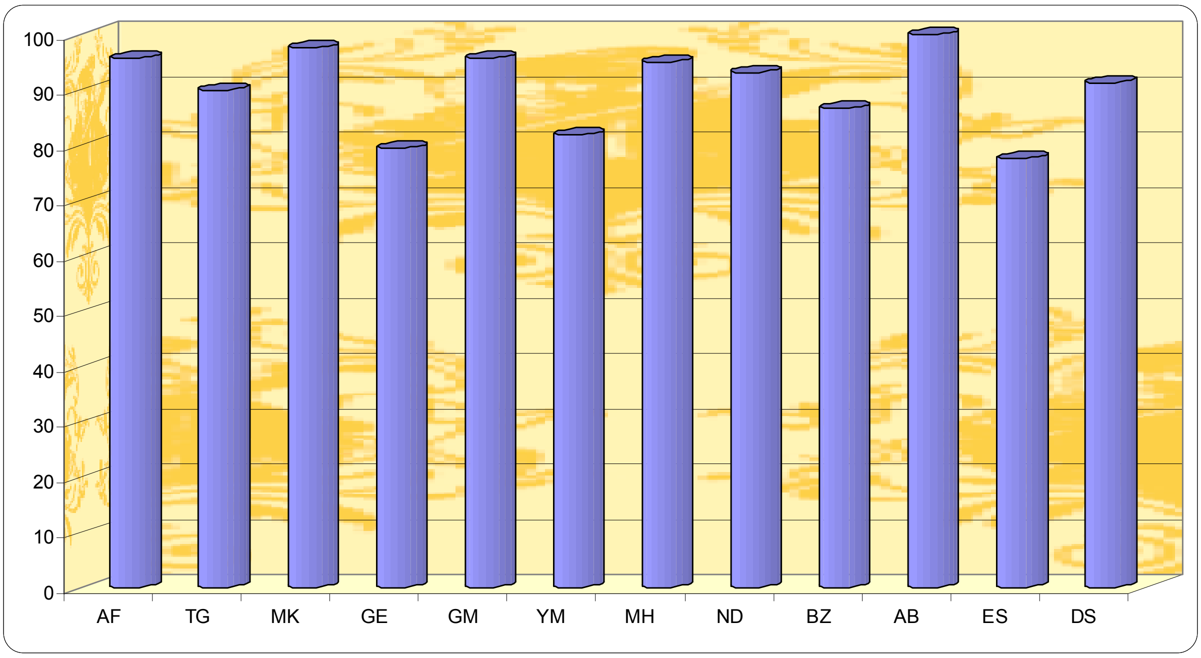

Figure 2. Individuals with conduction aphasia: comprehension of subject and object relative

The performance of each of the participants in subject relatives and object relative with each of the distances is presented in Figures 3 and 4. An analysis of the performance of each of the dozen participants on each of the eight conditions using the binomial test shows that in most of the conditions the participants performed significantly above chance. (The few exceptions in which the participants performed above 50% but not significantly better than chance were not necessarily in the longer distances: GE and YM in SR2 and OR7, and ES in SR2, OR2, OR9)[4].

[4] For TG we have data only from one set of sentences, 5 sentences for each condition, and he made errors in two sentences from two conditions - 2 and 9 GAD, so his performance in these conditions was also not significantly better than chance.

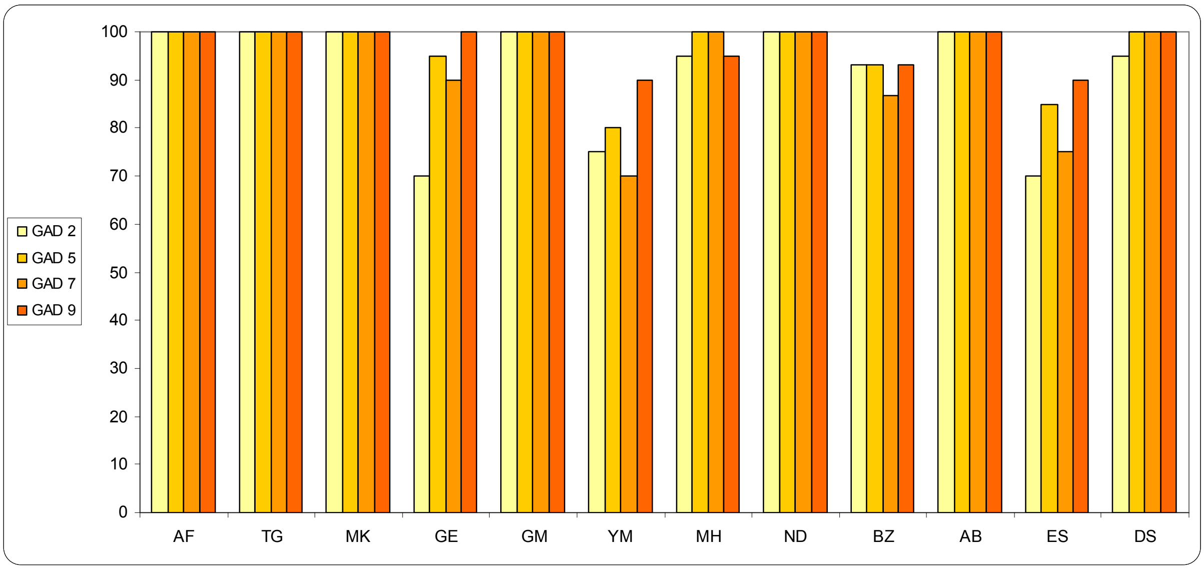

Figure 3. Subject relatives: % correct of the individuals with conduction aphasia.

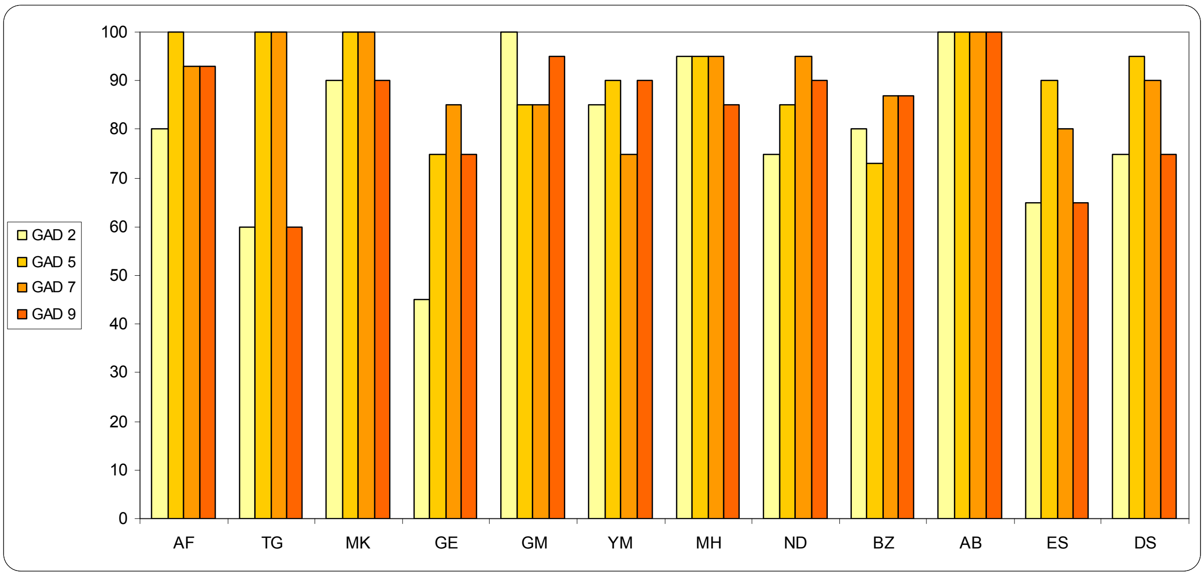

Figure 4. Object relatives: % correct of the individuals with conduction aphasia.

Importantly, none of the patients was affected by the distance between the antecedent and the gap. This can be seen in two analyses. The comparison of performance in the shortest GAD (2 words) and the longest GAD (9 words), presented in Table 9, showed no significant difference in performance between the two conditions, and even slightly poorer performance on the shortest condition, for both subject- and object relatives. This finding was further confirmed by the absence of linear contrast between the different GADs in both subject- and object relatives.

The comparison of performance of the individuals with conduction aphasia to the control participants indicated no difference in any of the subject relative conditions (except for SR2 in which the performance of the controls was significantly better). The individuals with conduction aphasia performed significantly poorer than the control group on all four conditions of the object relatives ($p < .01$), regardless of the gap-antecedent distance, but still their performance in object relatives was 86% correct on the average, and significantly above chance.

Table 9. Aphasic group: difference between the percentage correct on GADs 2 and 9

	SR2-SR9	**OR2-OR9**
AF	0	-13
TG	0	0
MK	0	0
GE	-30	-30
GM	0	5
YM	-15	-5
MH	0	10
ND	0	-15
BZ	0	-7
AB	0	0
ES	-20	0
DS	-5	0
Average	**-5**	**-6**

The current experiment thus replicates our previous findings concerning the comprehension of relatives with various GADs in patients with conduction aphasia with limited input phonological WM. The findings show that limited phonological WM does not interact with relative clause comprehension. Participants with limited pWM of 2-3 lexical units easily reactivated the antecedent at the gap position even when the gap-antecedent distances reached 9 words (28 syllables), a distance that is far larger than their spans. As we suggested in Friedmann and Gvion (2003), we believe that the type of processing required in the sentence is the crucial factor. Because the reactivation required for the comprehension of relative clauses is syntactic-semantic, a phonological WM limitation should not prevent individuals from reactivating the meaning of a moved NP even when this reactivation takes place after a long phonological distance. In Experiment 2 we further examined this assumption but this time with the manipulation of the distance between the antecedent and the gap in other syntactic units.

Experiment 2*:* Does distance in syntactic units affect object relative comprehension?

Experiment 2 was also designed to test semantic-syntactic reactivation through the comprehension of object relative clauses, but in this experiment the distance between the word and its reactivation site was manipulated in syntactic units. In Experiment 1 we already saw that when the reactivation required is semantic-syntactic, increasing the phonological distance to the reactivation site does not impair comprehension for individuals with impaired phonological WM. Will the same results be obtained when the distance to the semantic-syntactic reactivation site is increased in syntactic units? Previous research (see Gibson & Thomas, 1999) found that the addition of a CP, namely, of a clause embedded with "that" or "who", has a syntactic memory cost. On the basis of this finding, we used the addition of embedding between the antecedent and the gap to manipulate syntactic memory load. If semantic reactivation is not problematic when pWM is impaired, then the introduction of double embedding between the antecedent and the gap should not impair the comprehension of individuals with limited pWM more than it impairs the performance of healthy controls.

Stimuli and procedure

Eighty Hebrew object relative clauses were included in a plausibility judgment task. The syntactic distance was manipulated by adding a single or double embedding. Of the 80 sentences, 30 were object relatives with double embedding (5), 30 were object relatives with a single embedding (6) and 20 sentences were simple control sentences without embedding (7). The duration of the gap-antecedent distance was 2.5 seconds (SD = 0.17) for the double embeddings, and 1.2 seconds (SD = 0.12) for the single embedding. This duration difference was significant ($t(8) = 31.22$, $p < .01$).

Half of the sentences of each type were plausible (5a, 6a, 7a) and half were implausible (5b, 6b, 7b, for ease of reading examples are given in English because the word order in Hebrew was the same). The implausible sentences with single and double embeddings were constructed so that the semantic relations between the most embedded verb and the reactivated antecedent were incongruent, thus creating a semantic violation. The implausible sentences without embedding (7b) included reversed thematic roles. The sentences were orally presented to each participant only once. The participants were asked to determine whether the sentence was plausible or not.

5a) This is the parcel <u>that</u> the woman saw <u>that</u> the child picked.

b) This is the bread that the man wanted that the child will drink.

6a) This is the milk that the man drank.

b) This is the juice that the man ate.

7a) The policeman read the newspaper.

b) The hat wore Danny.

Results

Control participants

The 61 control participants performed well in all types of sentences. As can be seen in Table 10, their performance was at ceiling level. Because no differences were found between the plausible and implausible sentences in each of the three sentence types, we lumped together the scores for further statistical analysis. No differences were found between the age groups in any of the sentence types. Significant differences were found between the conditions, $F(2,180) = 4.78$, $p = .009$, and the linear contrast between the three sentence types was significant, $F(1,180) = 8.98$, $p = .003$. According to Tukey test the difference stemmed from a difference between the double embedding condition and the no-embedding condition, $p = .009$.

Table 10. Control participants: %correct in double, single, and no-embedding sentences

Age group	20-30 n=10	31-40 n=10	41-50 n=10	51-60 n=10	61-70 n=10	71-77 n=11	Average
No embedding	100.00	100.00	99.50	100.00	100.00	100.00	99.91 (0.20)
Single embedding	99.33	100.00	99.33	100.00	99.67	99.70	99.67 (0.30)
Double embedding	98.67	100.00	99.67	99.33	97.67	98.79	99.02 (0.84)

Results are presented for plausible and implausible sentences together

Individuals with conduction aphasia

Ten individuals with conduction aphasia participated in this experiment. The patients as a group and each participant individually performed above chance in all the sentence types (using binomial distribution, $p < .05$) reaching in most of the subtests 90% and above (see Figure 5). No significant difference was found between the performance in the plausible and implausible sentences for the group, and for each of the aphasic participants (using χ^2, except DS, who performed better in the implausible sentences than the plausible ones in the double embedding sentences, and plausible better than implausible in the single embedding sentences).

Importantly, in the sentences that require reactivation, i.e. the relative clauses, there was no significant difference at the group level between double embedding and single embedding, neither for the plausible nor for the implausible condition. Similarly to the control participants, significant differences were found only in the comparison of the embedded sentences to the simple sentences: plausible simple sentences without embedding were judged better than the sentences with double embedding (T = 1, $p < .01$) and single embedding (T = 2, $p = .02$). The comparison of the plausible and implausible sentences together yielded similar results, with Tukey test indicating a significant difference only between the no-embedding and the single embedding conditions ($p = .05$).

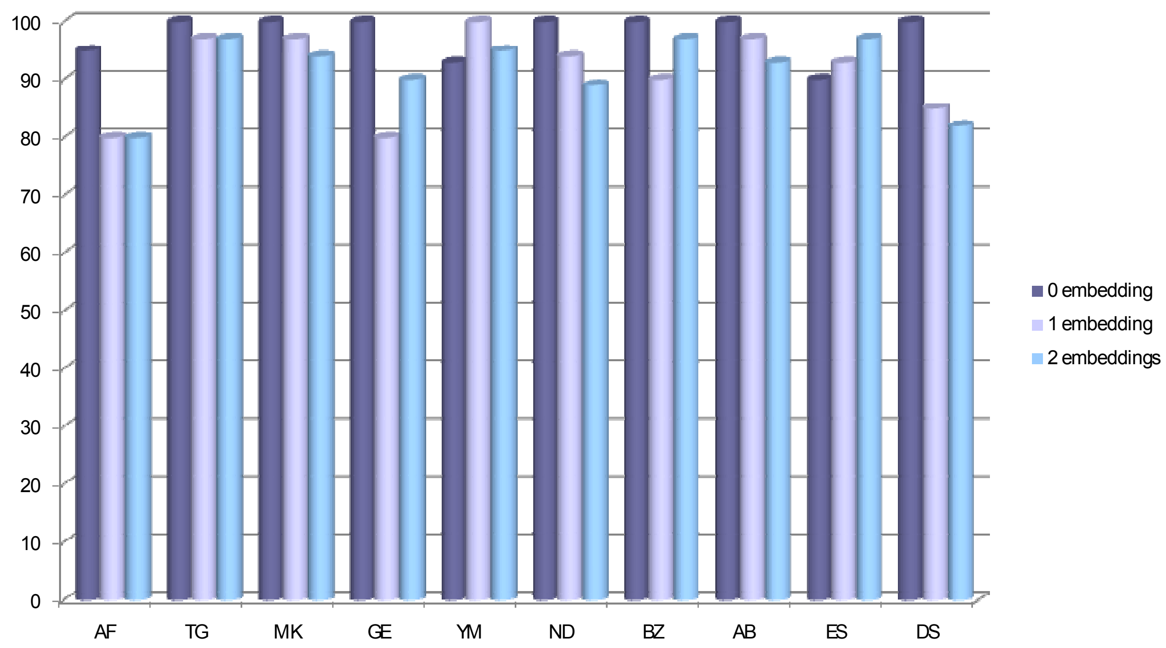

Figure 5. Conduction aphasics: Plausibility judgment of object relatives with double, single, or no embedding

The same analysis for each individual participant revealed the same pattern for all of the aphasic participants: no significant differences between double and single embedding. Four of the participants showed significant differences ($p < .05$) between the embedding and the non-embedding conditions: GE showed significant differences between single and no embedding, YM in double vs. single embedding, ND in double vs. no embedding, and DS in double and single vs. no embedding.

A comparison between the individuals with conduction aphasia and the control group reveals significant differences in performance on sentences with double embedding ($z = 4.64$, $p <$

.01), and sentences with single embedding (z = 4.42, p < .01), but not in the simple, non-embedded sentences. But crucially, they performed well on all conditions.

Thus, in the group with conduction aphasia, like the control group, no difference was found between object relatives that require reactivation with single and double embedding; like the controls they also showed better performance on the simple sentences compared to the embedded sentences.

Summary and interim conclusions: Experiments 1 and 2

Experiments 1 and 2 examined the comprehension of relative clauses in individuals with very limited pWM. The distance between the antecedent and the gap was manipulated in Experiment 1 in terms of phonological units – syllables and words, and in Experiment 2 by syntactic units - number of intervening CPs. All the participants, even those who had very limited phonological spans of no more than 2-3 units, performed well above chance in all types of sentences, and were unaffected by any type of distance. The addition of another argument of the verb between the antecedent and the gap was also tested, using object relatives, in which the agent intervenes between the moved theme and the verb. The individuals with conduction aphasia showed good comprehension of object relative and performed 86% correct in Experiment 1 and 91.4% in Experiment 2, indicating that a limited pWM is not the source of deficits in understanding sentences that include movement of one argument across the other, as is the case in agrammatic aphasia (Grodzinsky, 2005, 2006).[5]

Friedmann and Gvion (2003) suggested that antecedent-gap distance had no effect on comprehension because the processing at the gap position, involves semantic, rather than phonological, reactivation of the antecedent (Love & Swinney, 1996, and McElree, 2000). We suggest that this is why phonological memory limitation does not affect relative clause comprehension, even in cases of considerable distance between the antecedent and the gap, be it phonological or syntactic. If this is correct, there are other types of sentences that are predicted to be impaired in case of pWM limitation: sentences that require phonological reactivation, in which semantic reactivation does not suffice. This led us to examine comprehension in structures that require phonological reactivation in Experiments 3 and 4.

[5] For comparison, the individuals with conduction aphasia who participated in Experiment 1 performed significantly better than the 5 individuals with agrammatism reported in Gvion (2007) on the 80 subject relatives and 80 object relatives (U = 67.5, p = .02, U = 82, p = .0004, respectively), and also significantly better than 14 individuals with agrammatism (7 agrammatic aphasics reported in Friedmann and Shapiro, 2003, and 7 reported in Gvion, 2007) in the sentences with 2 GAD (U = 186.5, p =.05, for subject relatives, U = 240.5, p < .0001, for object relatives). Similarly, in Experiment 2, their comprehension of object relatives with double embedding was between 80 and 97 percent correct, whereas the 3 individuals with agrammatism in Gvion (2007) performed only 57-63 percent correct and not significantly above chance.

Experiment 3: Does pWM limitation affect accessing a decayed meaning of an ambiguous word?

(8) The toast that the elderly couple had every morning was always for happy life and for love.

In order to test phonological reactivation within a sentence we used sentences like (8) with an ambiguous word, in a context strongly biasing toward one of the meanings, which gets disambiguated toward a different meaning at a later point in the sentence. The rationale was the following: when we hear a sentence with an ambiguous word, immediately after the ambiguous word, all of the meanings of the word are activated (Swinney, 1979; see also Love & Swinney, 1996; Onifer & Swinney, 1981). When the sentence continues to unfold, only the meaning that seems relevant for the biasing context remains activated, and the other meanings decay. When we get to the point of disambiguation, the meaning that was initially (incorrectly) chosen and remained active cannot be used to understand the sentence, and we need to access the other meaning. Crucially, re-access to the semantic representation that remains active will not suffice, and therefore we need to reactivate the *phonological word form* of the original ambiguous word, in order to re-access all its possible meanings. Because semantic reactivation does not suffice, and these sentences require phonological reactivation, the comprehension of individuals with limited pWM is expected to be hampered in cases of phonological overload.

We used the experimental design and sentences from our previous study (Friedmann & Gvion, 2003), in which we tested three individuals with conduction aphasia. In the current experiment we tested this design on a larger group of patients.

Stimuli and procedure

The test included 148 Hebrew sentences: 88 plausible sentences with an ambiguous word and 60 filler sentences. The task required plausibility judgment and paraphrasing. The distance between the ambiguous word and the reanalysis position was manipulated in order to test the effect of phonological load. Forty-four ambiguous words were selected; each appeared in one long-distance and one short-distance sentence. Disambiguation occurred either shortly after the ambiguous word (2-3 words distance, mean duration of 1.44 sec., see example 9a) or after a longer interval (7-9 words distance, mean duration of 5.06 sec, example 9b).

9 a) For her dinner party, Hanna found several good **dates**, carefully filled them with marzipan, and put them on the table next to the dried apricots and the figs.

b) After the discussion with her future husband, Hanna chose the perfect **date** which she thought will make him very happy, and put it in his mouth, without the pit.

10) During dinner, the very important businessmen ate filled jackets.

We determined the various possible meanings of each of the ambiguous words as well as the relative frequency of these meanings on the basis of judgments of 18 Hebrew-speaking individuals without language impairment. Additional 42 healthy adults were asked to listen to the first part of each sentence (that included the ambiguous word, the biasing context but without the disambiguation part) and to complete the sentences using their own words. This was done in order to examine whether the biasing context leads indeed to the more frequent meaning of the ambiguous word. Only sentences that biased at least 70% of the pilot participants toward the most frequent meaning were included in the test. The rest of the sentences (5 sentences) were re-constructed.

The fillers were 60 semantically implausible or plausible sentences matched to the tested sentences in number of words. Twenty of the fillers were implausible long sentences matched in number of words to the long distance sentences with ambiguous words; 20 implausible short sentences matched in number of words to the short distance sentences with ambiguous words. The implausible sentences were constructed by replacing a word in a plausible sentence with a semantically or pragmatically incongruent word (see example 10 for an implausible short sentence). Twenty additional fillers were long plausible sentences. The sentences were randomized and divided into two sets with the same number of sentences of each condition, administered with an interval of at least two weeks. Each ambiguous word appeared only once in each session, namely, the short and the long distance sentences for each ambiguous word were administered in different sessions. The order of the sessions was randomized among participants.

Each sentence was presented auditorily only once and the participants were requested to judge whether it was “good or bad”. If they judged the sentence as good, they were asked to paraphrase it as accurately as possible; if they judged it as a “bad sentence” they were asked to explain why it was bad. When the patients had difficulties in oral paraphrasing, hand gestures were accepted as well. The sessions were audio-tape recorded and transcribed.

Results

Control group

Ninety five control participants were tested. Their performance in the sentences with ambiguous words was above 80% correct even in the most taxing condition, as shown in Table 11. All of them performed flawlessly on the plausible and semantically implausible sentences without the ambiguous words. No linear contrast was found for the different age groups. A main effect was found for disambiguation distance, $F(1,89) = 22.39$, $p < .0001$; The performance on the ambiguous short distance sentences was significantly better than on the long ambiguous sentences for three of the age groups: the 20s, the 30s, and the 70s ($p < .01$).

Table 11. Control participants' judgment of sentences with ambiguous words: Average %correct (sd)

Age group	**20-30 n=32**	**31-40 n=20**	**41-50 n=10**	**51-60 n=9**	**61-70 n=10**	**71-77 n=14**
short distance	95.0 (4.6)	93.0 (6.6)	97.3 (3.7)	93.9 (7.3)	92.0 (5.5)	92.9 (4.3)
long distance	89.3 (9.2)	83.5 (13.1)	95.0 (8.4)	94.1 (8.2)	88.4 (14.3)	81.7 (10.6)

Conduction aphasia participants[6]

The group with conduction aphasia showed a severe deficit in the comprehension of sentences containing ambiguous words with long disambiguation distances.

The participants' difficulty in the comprehension of long sentences with an ambiguous word was manifested in their performance in the plausibility judgment, as well as their explanations for the judgments, and their paraphrases, which usually indicated that they kept the initial meaning of the word and could not incorporate it in to the end of the sentence (see examples 11-12).

(11) The following target sentence includes the ambiguous word "**cir**". In the beginning, the meaning that seems relevant is "consul", but the meaning that is actually suitable for the sentence is "a door hinge".

Target: "**ha-cir** she-higia me-arcot ha-brit be-hazmanat misrad ha-xuc ha-israeli **mutkan** be-delet ha-lishka shel rosh ha-memshala"

The-*consul/hinge* that-arrived from-states the-union in-invitation/order-of ministry-of the-outside the-Israeli is-installed in-door-of the-office of head-of the-government

[6] Some of the patients found the test very frustrating, so we had to stop the test at a certain point without completing it. For several patients we had to discard some of the sentences from the data analysis because it was impossible to judge from their responses whether they understood the sentence or not. This is why the analysis of the results is based on a slightly smaller number than the number of participants times the number of sentences.

The-consul/hinge that arrived from the USA by an order of the Israeli ministry of foreign affairs is installed in the door of the prime minister's office.

BZ: kol-kax harbe mebulbalim she-ze mamash bdixa. Yesh shagrirut arcot habrit ze kol-kach mebulbal ve-lo kashur she-ze lo hegyoni.

So many confused that-this really joke. There's embassy-of states the-union... it's so confused and-not connected that-this not logical.

"*So many confused that this is really a joke. There's an embassy of the US... its so confused and not connected that this is illogical.*"

MK: Lo. ha-cir... hevi cir lo cir ani yode'a. Hevi'u cir le-rosh ha-memshala ze cir, ze nasi - hu lo yaxol lasim oto ba-delet!

No. The consul/hinge brought consul/hinge not consul/hinge I know. Bring-plural consul/hinge to-head-of the-government it's consul/hinge, it's president - he no can to-put him in-the-door.

"*No. The consul… brought consul no consul I know. A consul was brought to the prime minister it is consul, it's a president - he can't put him in the door!*

(12) A sentence with the ambiguous word ***"lenakot"*** which initially is taken to mean "to clean" and later disambiguates to mean "to deduct".

Target: "Ha-misrad be-macav nora ve-laxen yatxilu **lenakot** be-horaat menahalei ha-misrad u-le-lo kol dixuy nosaf **asara** axuzim mi-maskorot ha-bxirim".

The-office in-condition terrible and-therefore will-start to-clean/deduct in-order-of managers-of the-office and-to-no any delay additional ten percent from-salaries-of the executives.

"The office is in a terrible condition and they will therefore start to-clean/deduct immediately and without further ado following the order of the office managers 10 percent of the executives' salaries."

DS: "Lo. Ein shum kesher bein maskorot ve-bxirim le-vein ha-nikayon shel ha-misrad".

No. There's no relation between salaries and-executives to-between the-cleanliness of the-office.

"No. There's no relation between salaries and executives and the cleanliness of the office*."*

The average score for the long distance sentences with ambiguous words was 57.5% (SD = 19.7%). As can be seen in Figure 6, most of the aphasic participants (AF, GM, MH, ND, BZ, AB, ES, DS) showed a severe deficit in the long distance sentences, with average performance on only 47.3% (SD = 11.7%) but performed significantly better when the same ambiguity was resolved at a short distance from the ambiguous word (M = 84.6%, SD = 12.0%). The performance of these 8 participants in the short-distance sentences was significantly better than the long ones for the group, T = 0, $p < .01$, as well as for each individual, using χ^2, $p < .03$. In this group, AF, MH, ND, AB, and DS performed significantly poorer than the normal controls in the long ambiguous sentences ($p \leq .01$) but did not differ from the controls in the short ambiguous sentences; GM, BZ, and ES showed significantly poorer performance than the controls ($p \leq .01$) on both the long and the short ambiguous sentences, indicating that the short-distance disambiguation was already overloading for them.

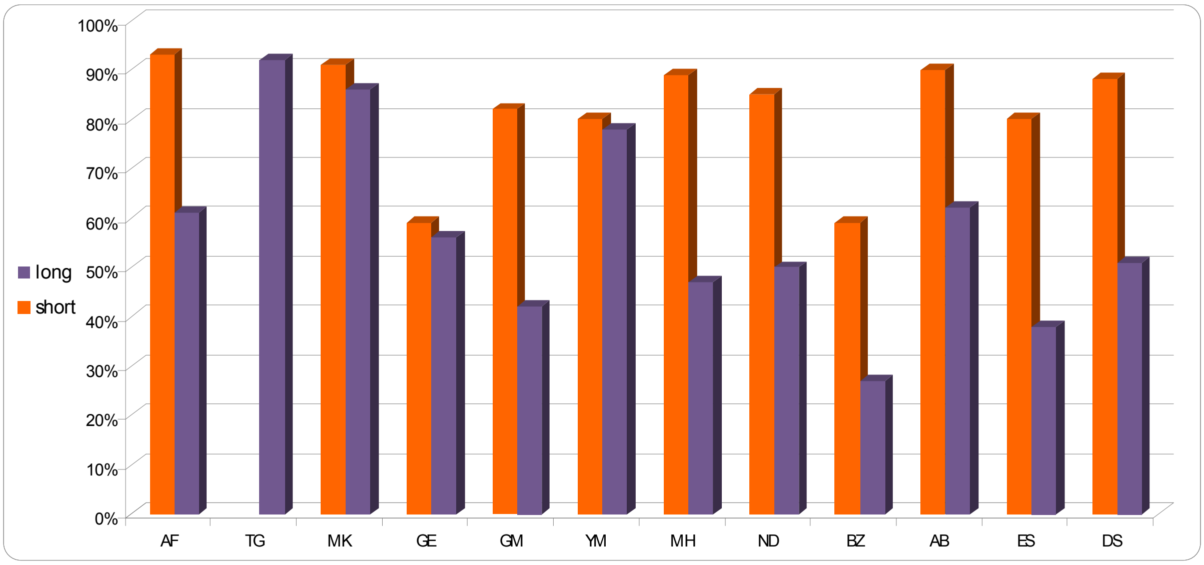

Figure 6. Conduction aphasics: % correct on sentences with an ambiguous word.

The four other patients' performance was not significantly affected by the disambiguation distance. GE performed poorly on both the short and the long ambiguous sentences (59% and 56% respectively), and her performance in both conditions was significantly poorer than that of the controls ($p \leq .01$). It may indicate that the short distances were already overloading her pWM. YM also showed similar performance on both distances: 80% on the short sentences and 78% on the long sentences. Her performance was almost 2 standard deviations below the average of her control group, but it differed significantly from the controls only on the short condition ($p < .01$). Two patients performed relatively well in this task and not significantly poorer than the controls: TG was tested only on the long ambiguous sentences and performed 92% correct, and MK performed 90% on the short ambiguous sentences and 86% on the long condition.

Mann-Whitney test showed that the difference in performance between the long and the short ambiguous sentences was significantly larger for the aphasic group compared to the control group ($z = 3.95$, $p < .0001$). An analysis at the individual level revealed a similar result for nine of the twelve aphasic participants: a larger distance effect on performance for each participant compared to the matched control group.

The performance in the plausible sentences without ambiguity and in the semantically implausible sentences was high: an average of 96.8% (range: 88%-100%) accuracy on the semantically plausible sentences, and an average of 97.4% (range: 89%-100%) on the long implausible sentences and 96.2% (range: 90%-100%) on the short implausible sentences.

Thus, the current experiment showed that for most of the participants, comprehension of sentences can be impaired, when the sentence are constructed in a way that taxes their phonological WM. When the reactivation required is phonological, and the distance from the first occurrence of the word to its reactivation site is too long, individuals with limited pWM have severe difficulties understanding the sentence. Their comprehension was much better when the distance between the ambiguous word and the point of reactivation was short. In the next experiment we examined phonological reactivation using another task: a rhyming judgment task of words within sentences, manipulating the phonological load by interpolating words between the rhyming words.

Experiment 4: Does pWM limitation affect rhyme judgment?

This experiment was aimed at further testing the ability of individuals with conduction aphasia to perform tasks that require re-access to the phonological form of a word, this time through judgment of rhyming. In order to judge whether two words in a sentence rhyme, the phonological forms of the words should be compared. Semantic encoding and access to the meaning of the words cannot be of help in such a task, because the judgment relates to phonological aspects of the words, hence access to the phonological word form is required. Therefore, we expected that that if too many words occur between the rhyming words, individuals with limited phonological WM will not be able to retain the phonological form of the word, it will decay and they will no longer be able to detect rhyming. As a result, the participants are expected to judge sentences with rhyming words as non-rhyming. When the sentence does not include rhyming, it is possible that the deficit would not be manifested, because a decay of the words would lead to a correct judgment, of no-rhyme.

Like in our previous experiments, we manipulated the distance between the rhyming words within the sentence. We examined whether the detection of rhyming is more impaired when there is a longer distance between the rhyming words.

Stimuli and procedure

The test included 184 Hebrew sentences presented auditorily: 100 sentences with two rhyming words (see examples in 13) and 84 sentences without rhyming words (examples in 14). All the rhymes were penultimate and ultimate classical rhymes, which are the prototypical rhymes in Hebrew (Ravid & Hanauer, 1998). In the penultimate classical rhymes the two words had penultimate stress position, and were identical in the stressed vowel and all the phonological segments that followed it. The ultimate rhymes were precise classical rhymes, identical in the stressed (final) syllable, and most of them (91%) also in the vowel before the final syllable. The non-rhyming sentences did not include any rhyming words or phonologically similar words. The sentences that contained rhyming pairs were constructed so that a word in the middle of the sentence, at the end of the first phrase (hence: word A) would rhyme with the last word of the sentence (hence: word B). Each pair of rhyming words was presented twice, in two different sentential contexts, once with short distance between the rhyming words, and once with a long distance between them. The distance between the rhyming words was manipulated. In half of the rhyming sentences the distance between the rhyming words was short (examples 13a, an average of 4.19 words, 9.5 syllables, and duration of 2.81 seconds, with a range of 2-5 words, 4-13 syllables). The other half of the sentences included longer distance between the same rhyming words (examples 13b, an average of 9.88 words, 26.72 syllables, duration of 6.54 seconds; range of 8-14 words and 18-38 syllables). The non-rhyming sentences included the same first word (word A) from the rhyming sentences, but in these sentences, the final word did not rhyme with it. The non-rhyming sentences also included half short and half long distance between words A and B (example 14).

13) a. Short rhyming:

Ha-xayelet hifgina **gvura**, ki lo hayta **brera**

The-soldier-fem demonstrated courage because no was other-option

b. Long rhyming:

Hu kara harbe al **gvura**, ve-hevin she-ze lo metuxnan tamid me-rosh pashut ze kore kshe-en **brera**

He read a-lot about courage and-understood that-this not planned always in-advance simply it happens when-there-is-no other-option

14) a. Short no-rhyme

Ha-ish pacax be-**shira**, le-kol tru'ot ha-tayarim ba-**otobus**

The-man started singing, to-the-sound-of shouts-of the-tourists in-the-bus

b. Long no-rhyme

ha-baxur ha-ragish she-asak be-**shira**, lakax shana xofesh me-avodato ke-mankal mif'al le-mashkaot kalim kedei letayel be-**hodu**

The-guy the-sensitive that-was-involved in-singing, took a year off from-his-work as-a-manager-of factory for-drinks light in-order-to tour in-India

The sentences were divided into four sets, which included the same number of sentences of each condition (rhyming/non-rhyming, short/long). Each set contained each word A only in one condition. Each set was presented in a different session (or two sessions), with at least one week interval between sessions.

Each sentence was presented only once to each participant, and the participant was asked to judge whether the sentence included rhyming words. The responses were tape-recorded and transcribed, and then coded by two judges.

Coding of responses

Misdetections of rhyming in rhyming sentences and false detection of rhyming in non-rhyming sentences were scored as incorrect, and so were “Don’t know” responses. Because most of the patients had a phonological output impairment, we accepted responses as correct even when they judged rhyming pairs as rhyming but failed to produce the rhyming words. When they judged the stimuli with rhyming pairs as non-rhyming but retrieved the correct words, these responses were also scored as correct, because they indicated their ability to access the words. Responses in which the patient correctly judged the sentence as containing rhyming but retrieved non-rhyming words were discarded from the analysis (both from the total number of sentences and from the number of responses). Seven out of 280 sentences with short distance rhyming pairs, and 5 of 311 long distance rhyming sentences were discarded from the analysis on this basis.

Results

Control group

The 62 control participants performed well on all four conditions, with performance of above 88% in all conditions, as seen in Table 12. A main effect was found for distance, $F(1,56) = 80.22$, $p < .0001$; Their performance in the short rhyming sentences was significantly better than in the long rhyming sentences in all age groups ($p < .01$), but still the long rhyming condition yielded a performance around 89% correct. The non-rhyming sentences yielded ceiling performance, with no significant differences between the short and the long-distance sentences. No significant differences were found between the different age groups in all conditions, and no linear contrast was evinced. No interaction was found between age group and distance.

Each control age group performed significantly better than chance level (Only 3 participants from three different age groups (30, 40, and 70) performed at chance in the long condition; the one in the oldest age group also had very limited spans, which were 1.5-2 standard deviations below her age group in all span tasks.)

Table 12. Rhyming judgment in the control groups: average % correct (and SD)

Condition	Age group	20-30 n=11	31-40 n=10	41-50 n=10	51-60 n=10	61-70 n=10	71-77 n=11	Average
Rhyming	Short	98.69 (1.67)	99.17 (1.76)	97.39 (6.61)	96.77 (3.21)	98.18 (3.06)	96.52 (6.64)	97.78 (1.06)
	Long	89.59 (5.24)	88.75 (12.15)	89.79 (12.96)	89.56 (9.00)	89.49 (8.31)	84.70 (12.37)	88.65 (1.97)
	Distance effect	9.10	10.42	7.60	7.21	8.69	11.81	9.14
Non-rhyming	Short	99.35 (1.54)	100.00 (0.00)	100.00 (0.00)	100.00 (0.00)	100.00 (0.00)	99.78 (0.72)	99.85 (0.26)
	Long	98.92 (1.95)	97.50 (5.62)	100.00 (0.00)	100.00 (0.00)	98.92 (2.67)	99.24 (2.51)	99.10 (0.92)
	Distance effect	0.43	2.50	0	0	1.08	0.54	0.76

Conduction aphasia group

Seven individuals with conduction aphasia participated in Experiment 4, their performance is presented in Table 13. Their average percentage correct in the short rhyming sentences was 90.5%, but they were only 61.4% correct on the long rhyming condition. This difference between their ability to detect rhyming in long and short sentences was significant at the group level, T = 0, $p < .01$, as well as for each individual, $p < .05$.

Table 13. Rhyming judgment in the conduction aphasia group: % correct

	Participant Condition	TG	MK	GE	YM	AB	ES	DS	Aphasics average (SD)	Norm average (SD)
Rhyming	Short	98.4	97.4	70.8	95.5	92.3	79.2	100	90.50 (11.12)	97.78 (4.30)
	Long	73.6	52.8	51.0	79.6	66.7	43.5	62.5	61.37 (12.98)	88.60 (10.09)
	Distance effect	24.8	44.6	19.8	15.9	25.6	35.7	37.5	29.1	9.2
Non-rhyming	Short	100	97	95.1	100	100	100	97.6	98.49 (2.02)	99.85 (0.72)
	Long	95	100	90.2	97.4	100	89.5	100	96.02 (4.60)	99.10 (2.82)
	Distance effect	5.0	-3.0	4.9	3.6	0.0	10.5	-2.4	2.5	0.8

The group with conduction aphasia performed significantly poorer than the control group in the long rhyming sentences, z = 3.93, $p < .0001$, and in the short rhyming sentences, z = 2.64, $p = .01$.

In the long condition, the comparison of each participant to the control group showed that all of them performed poorer than the control group (for TG, MK, GE, AB, and ES, $p \leq .03$, for DS, $p = .058$; YM's score was more than 1 SD below her matched control group, but it did not reach significance using Crawford & Howell's t-test). In contrast, in the short rhyming sentences only two participants, GE and ES, performed significantly poorer than the control group ($p = .002$; $p = .03$ respectively), indicating that the short distances were already too long for them. GE showed consistent performance in Experiments 3 and 4: she performed poorly on both the short and the long distance conditions. In Experiment 3 she performed 56%-59% correct on the short and long ambiguous sentences, in the current experiment she performed significantly poorer than the controls ($p < .01$) on both conditions. Still, she detected rhyming significantly better ($\chi^2 = 3.99$, $p = .04$) on the shorter distances (70.8%) compared to the longer ones (51%), which were at chance level. It seems that both distances were beyond her capacity (notice that in the preliminary task in which she only had to judge rhyming of word pairs she did significantly better, 83% correct). The aphasic group performed near ceiling in the short and long non-rhyming sentences (98.5% and 96.0%, respectively), with no significant difference between the short and long non-rhyming conditions.

Four out of the 7 individuals with conduction aphasia (MK, GE, ES, and DS) performed at chance level in the long rhyming sentences. In contrast, all individuals with conduction aphasia performed above chance in the short rhyming sentences and in the non-rhyming sentences.

Finally, a Mann-Whitney comparison revealed a significantly larger distance effect, measured by the difference in performance between short and long rhyming sentences, in the aphasic group compared to the control group ($U = 24$, $p < .01$). A larger distance effect compared to the control group was also found for each individual with conduction aphasia, significantly so for 5 of them ($p < .01$). The aphasic and the control groups did not differ in distance effect for the non-rhyming sentences, on the group as well as on the individual level, except for ES.

A comparison of Experiments 3 and 4

In both Experiments 3 and 4, most of the individuals with conduction aphasia showed serious deficits in the comprehension of sentences that require re-access to the word form after a long phonological distance, whereas they were still able to understand such sentences when the distance was short.

In Experiment 3, two participants showed a different pattern: TG and MK. Although their pWM was impaired, they demonstrated good comprehension even on the long ambiguous sentences and their performance did not differ from controls. Experiment 4, however, was able to expose TG and MK's impairment. In Experiment 4 they did show impaired performance on the long condition. Their performance on the long rhyming sentences was significantly poorer than on the short condition (MK: $\chi^2 = 19.96$, $p < .01$; TG: $\chi^2 = 15.23$, $p < .01$) and significantly poorer than controls ($p \leq .01$), whereas their comprehension of the short rhyming sentences did not differ from the controls. In addition, the difference between their performance on the short and the long conditions was significantly larger than in the control group ($p < .02$). It thus appears that rhyme detection was more sensitive to phonological reactivation deficits than the lexical ambiguity resolution task.

Interim summary: Experiments 3 and 4

The two experiments tested whether individuals who have a considerable pWM limitation can process sentences that require lexical-phonological reactivation. Experiment 3 tested the comprehension of sentences that include ambiguous words, and Experiment 4 tested the detection of rhyming words in sentential contexts. In Experiment 3, access to the phonological form of the word was required in order to reactivate the various meanings of the ambiguous word and select a different meaning than the one that was initially adopted. In the rhyming detection task in Experiment 4, the listener needs to access the phonological form of the word in order to decide whether there are rhyming words. In both tasks reliance on semantic encoding does not suffice for the correct comprehension or judgment. Semantic reactivation of the meaning of the ambiguous word that was initially (incorrectly) chosen would leave the listener with the wrong interpretation at the reanalysis position, and thus the sentence would be incorrectly judged as implausible. Similarly, semantic encoding of words does not allow for the detection of rhyming. In both experiments the distances between the reanalysis position and the word to be reactivated were manipulated in terms of number of words and syllables. Both experiments demonstrated at the group and at the individual level that individuals with conduction aphasia who have limited pWM fail to re-access the phonological form of the word after a long phonological distance. In the short distances, however, which are within their phonological capacity, their performance was significantly better and similar to that of the normal controls.

Importantly, the difficulty in sentence comprehension and judgment in these experiments is in marked contrast with the findings of Experiments 1 and 2, which tested semantic reactivation, and in which comprehension was intact, and no distance effect was evinced.

Thus, the two experiments that tested phonological reactivation showed that sentence processing of individuals with conduction aphasia on a sentence level *can* be impaired. But, crucially, it is only when the sentence requires word-form, rather than semantic, reactivation and when the distance from the first occurrence of the word to its reactivation is too long.

DISCUSSION

The aim of this study was to explore the relationship between phonological working memory and sentence comprehension. More specifically, we wanted to examine whether sentence comprehension is affected by limitation of phonological working memory, and if so, which types of sentences are affected. This was explored by the comparison of the way individuals with conduction aphasia whose pWM was very limited understand sentences that require two different types of reactivation: syntactic-semantic and phonological.

Syntactic-semantic reactivation was tested using relative clauses. We assume that the reactivation required at the gap of relative clauses is syntactic-semantic, because it is guided by syntax and, crucially, because it only requires re-access to the meaning of the antecedent, rather than to its word-form (as illustrated in Love & Swinney, 1996). This type of reactivation was tested in Experiments 1 and 2. The main result of these experiments was that syntactic-semantic processing was *not* impaired by phonological WM limitation. All twelve participants with conduction aphasia, who had very limited input phonological spans, performed well and similarly to healthy controls on the comprehension of subject and object relative sentences. The performance of the participants was not affected by the distance between the antecedent and the gap, neither by phonological distance, manipulated by the number of words and syllables, nor by syntactic distance, manipulated by adding another argument of the verb, or by interpolated embeddings. The results thus clearly show that even when phonological WM is very limited, comprehension that requires syntactic-semantic reactivation and does not demand the maintenance or reactivation of the phonological word form can be unimpaired.

Sentences and tasks that require phonological reactivation showed a dramatically different picture – they were clearly hampered by phonological working memory limitation. Phonological reactivation was tested in two experiments, using two different tasks: lexical ambiguity resolution and rhyming judgment. In Experiment 3 we tested the comprehension of sentences that included ambiguous words incorporated in a context strongly biasing toward one of the meanings. At a certain point in the sentence, it turned out that the meaning that had been chosen (according to the beginning of the sentence) was in fact not the one suitable to the sentence. At this point, because the meaning that turned out to be relevant has already decayed and only the irrelevant meaning remained active, a phonological, word-form reactivation of the ambiguous word is required in order to access all its meanings again and select the one relevant for the sentence. The processing of such sentences requires, then, reactivation of the word form.

And indeed, when the individuals with conduction aphasia were presented with these sentences they failed to understand them when the distance between the initial presentation of the ambiguous word and its reactivation was long. They understood well and similarly to the controls the sentences with the short reactivation distance, indicating that they do not have a problem accessing all meanings of the ambiguous word. However, when the distance was long, exceeding their phonological spans, they could no longer reactivate the ambiguous word. They were left, puzzled, with the initially chosen meaning, and judged the sentence implausible, without being able to paraphrase it correctly. Their performance in this task, then, was in marked contrast to their very good comprehension of sentences in which the meaning of the words was enough to understand the sentence, as in Experiments 1 and 2.

Another task we used to assess the participants' ability to maintain the phonological form of a word in sentential context was a task of rhyme judgment. In Experiment 4 the participants were asked to judge whether words within a sentence rhymed, and the number of words between the rhyming words was manipulated. In this task too, the individuals with conduction aphasia were able to detect rhyming when the distance between the rhyming words was short, but when the distance was longer their performance declined dramatically, to a level significantly poorer than on the short distance rhymes and significantly poorer than the controls. Their good performance on the short distance rhyme judgment indicates that their failure did not relate to a basic inability to judge rhyming, but rather to the fact that they had to maintain the phonological form of the first rhyming word for a longer distance than they could. Thus, the need to re-access or retain a word that appeared earlier in the sentence is not generally problematic for individuals with WM limitation. It is only re-access to the word-form that requires phonological WM resources, and hence only this type of reactivation is impaired when pWM is impaired.

The results of the two first experiments, which showed that limited phonological working memory does not impair comprehension of sentences that require syntactic-semantic reactivation, are in line with previous findings (Hanten & Martin, 2000; Martin, 1987, 1993; Martin & Feher, 1990; Vallar & Baddeley, 1984; Waters et al., 1991; Willis & Gathercole, 2001). Our results are also consistent with McElree (2000), who suggested, on the basis of his findings in a speed-accuracy tradeoff paradigm in healthy participants, that the reactivation or binding of fillers and gaps is content-addressable and therefore unaffected by the amount of interpolated material. The innovation of the testing of semantic reactivation in the current study (in addition to the larger number of participants) was that both the type of distance (in phonemes or in syntactic nodes or arguments) and the load (requiring short or long-distance reactivation) were manipulated.

The comprehension of sentences that require phonological reactivation or maintenance have received less attention in previous research. Two tasks were typically used to assess phonological processing: verbatim repetition (Hanten & Martin, 2000; Martin, 1993; Martin et al., 1994; Willis & Gathercole, 2001) and comprehension of sentences with many lexical items (see Caplan & Waters, 1999 for a review; Martin et al., 1994; Martin & Feher, 1990; Smith & Geva, 2000; Vallar & Baddeley, 1984; Waters et al., 1991). When individuals with limited pWM repeat sentences verbatim, they typically fail to maintain the phonological form of the sentences, but understand them well. This can be seen in their keeping the gist of the sentences in their repetition, and in their good comprehension of these sentences in direct comprehension tasks (Hanten & Martin, 2000; Willis & Gathercole, 2001). Patients with limited pWM typically fail to comprehend sentences with many relatively arbitrary lexical items, a failure that is attributed to the absence of phonological back-up (see Caplan & Waters, 1999 for review; Martin et al., 1994; Martin & Feher, 1990; Smith & Geva, 2000; Vallar & Baddeley, 1984; Waters et al., 1991). In the present study two novel experimental designs were used to examine phonological processing: testing the comprehension of sentences with ambiguous words that require phonological reactivation, and rhyme judgment, a task that requires maintenance of the phonological form of words. Our results from the comprehension of sentences with lexical ambiguity and from the rhyme judgment task are in line with the earlier results from repetition studies, indicating that limited phonological working memory impairs the ability to access the phonological form of the words. The current results add an important aspect to our knowledge of the intricate relations between phonological working memory and sentence comprehension. They show that sentence comprehension can be affected when comprehension depends on the access to the phonological form.

This distinction, between sentences that require phonological reactivation and sentences that require semantic reactivation, opens an interesting window to look at the relation between WM and the comprehension of garden path sentences (MacDonald et al., 1992; Waters & Caplan, 1996). Using the same way of thinking, garden path sentences can be classified into two types: those that require only structural reanalysis, and those that require, in addition to structural reanalysis also phonological reactivation, in order to re-access a word and choose a different meaning. The latter, but not the former, are expected to be impaired in cases of pWM impairment. Indeed, in a study we recently conducted (Friedmann & Gvion, 2007), individuals with conduction aphasia who had limited pWM comprehended structural-reanalysis garden paths very well, but failed to understand garden paths that also required the re-access to the word form of one of the words in order to choose a different meaning of the word or a different thematic grid for a verb. This indicates again the importance of the type of reactivation required in a sentence as a predictor of its dependency upon pWM.

These findings thus support domain specificity within working memory. They suggest that there is a phonological working memory that is responsible for the retention and reactivation of phonological information but not of semantic and syntactic information. In recent years researchers have shown evidence for the existence of another type of working memory: *semantic* working memory. Unlike individuals with phonological WM limitation, who usually show lexicality effect, incorrect acceptance of phonological (rhyming) foils in probe tasks, and lack of recency effect, individuals with impaired semantic WM do not show lexicality effect, have limitation in various semantic span tasks such as category probe and no primacy effect, and their performance on span tasks is generally better (Martin et al., 1994; Martin & Romani, 1994). The case studies of semantic WM impairment report impaired retention of semantic information throughout the sentence, with preserved comprehension of various syntactic structures such as center embedded relative clauses, and reversible active and passive sentences (Martin & Romani, 1994; see also Martin, 2003; Romani & Martin, 1999). Their verbatim repetition was preserved or at least much better (Hanten & Martin, 2000; Willis & Gathercole, 2001). Experiments on healthy adults also demonstrated the relation between semantic-conceptual span and the ability to detect anomaly of adjective-noun combinations when the distance between the critical words increases (Haarmann, Davelaar, & Usher, 2003; see Martin & Romani, 1994 regarding the same effect in a patient with limited semantic capacity).

Taken together, the data strongly point to a domain-specific WM system, in which each WM type supports a different language domain: phonology, semantics, and syntax (Haarmann et al., 2003; Hanten & Martin, 2000; Martin & He, 2004; Martin & Romani, 1994; Martin et al., 1994; Romani & Martin, 1999). Each type of working memory is responsible for the retention and reactivation of verbal information in a different domain, and each type of processing addresses sentences differently, with content-addressable processing for syntactic-semantic information (McElree, 2000) and search-based mechanism for phonological processing. So far there is strong evidence for phonological and semantic capacities. The question that naturally arises is whether a syntactic working memory exists, what are its units, and what it does.

Syntactic WM

One case study that shows an indication for what might be a syntactic WM impairment was reported by Martin and Romani (1994). Their participant, MW, had basically normal phonological spans. He performed well (95% correct) in a grammaticality judgment task that included a wide range of grammatical violations, but when the distance between the words that cause the syntactic violation was manipulated (*The man was not, according to the American detective agency, watched the woman*), he showed difficulty in "maintaining incomplete syntactic structures". When words were added at other points in the sentence, he could detect the ungrammaticality better, in passive and subject auxiliary inversion sentences. He also performed better on sentences that require semantic retention of information.

What can the responsibilities of a syntactic WM be, and what are its units? One domain that might require such a memory is the building of the syntactic tree. The syntactic tree consists of three hierarchically ordered layers: the C(omplementizer) P(hrase), the I(nflection) P(hrase), and the V(erb) P(hrase). One can assume that each layer adds load to the syntactic WM, and that limited syntactic WM might allow for the projection of only few layers. And indeed, individuals with agrammatic aphasia construct "pruned trees" – some of them cannot project CP, and as a result are unable to produce embedded sentences, V-C movement, and Wh questions (Friedmann, 2001, 2002, 2006; Friedmann & Grodzinsky, 1997, 2000). Other individuals with agrammatism cannot even project TP, and fail to inflect verbs for tense (Friedmann, 2005). Studies of brain activation during sentence comprehension draw a similar picture: several areas of the brain show significantly more activation when hearing a sentence that includes embedding and hence, includes three additional layers (CP, IP, VP), in comparison to a sentence that is exactly the same except that it includes a PP rather than an embedded CP (Shetreet, Friedmann, & Hadar, 2007). Another task that might be performed by a syntactic WM is maintaining two competing syntactic representations in order to compare and choose between them. Such a mechanism is suggested for the processing of various syntactic structures. For example, Grodzinsky and Reinhart (1993) suggest that in order to evaluate pronominal binding relations, two derivations need to be compared. The temporary storage that holds these derivations until a decision is made might be the syntactic WM. Indeed, Grodzinsky and Reinhart suggested that agrammatic aphasics and young children fail to comprehend these sentences because of the processing demands on the WM that require the maintenance of two representations in the same time. See also Reinhart (2004) for similar claims regarding focus acquisition and stress shift, and Fox (1995 and 2000) for additional contexts in which holding of two representations is required, and see Vosse and Kempen (2000) for stages in processing that require holding tentative attachments between nodes of lexical frames until a single syntactic tree is built. Researchers of the brain tissue reach similar conclusions. For example, Thompson-Schill and her colleagues (1997, 2005) suggested, on the basis of fMRI data, that Broca's area has a role in selection among competing alternatives from semantic memory. Finally, another task that might be assigned to a syntactic WM is the maintenance of arguments of a verb until they receive their thematic role. The introduction of an additional argument of the same verb to this memory before the first argument has received its role might be problematic for individuals who have limited syntactic WM. One context in which an argument intervenes between another argument and the verb is sentences that are derived by movement of a noun phrase (object relative clauses, object Wh questions, topicalized sentences). For example, in the object relative clause *I love the <u>water department clerk</u> that <u>the comic artist</u> drew,* the word *comic artist* intervenes between the *clerk* and the verb that assigns it its role, *drew.* The comprehension of these structures is severely impaired in S-SLI (Ebbels & van der Lely, 2001; Friedmann, Gvion, & Novogrodsky, 2006; Friedmann & Novogrodsky, 2004, 2007; Levy & Friedmann, in press; Stavrakaki, 2001; van der Lely & Harris, 1990) and agrammatic aphasia (Friedmann, 2008; Friedmann & Shapiro, 2003; Grodzinsky, 1989, 1990, 2000; Grodzinsky et al., 1999; Zurif & Caramazza, 1976). Indeed, such a deficit in assignment of thematic roles crossing another argument of the same verb has been suggested as the source of the comprehension deficit in agrammatism (Grillo, 2005; Grodzinsky, 2005, 2006) and syntactic SLI (Friedmann & Novogrodsky, 2007). Thus, one way of thinking about the agrammatic deficit is as a deficit in syntactic WM (see Grodzinsky, 2005). An interesting question remains open as to how to distinguish between a deficit in syntax itself and a deficit in syntactic WM.

Implications for agrammatism and syntactic SLI

The results of the current study also bear on whether pWM limitation can be taken as the source of the deficit in the comprehension of relative clauses in agrammatic aphasia and syntactic SLI. Individuals with agrammatic aphasia understand subject relatives at a level above chance, but fail to understand reversible object relatives (Grodzinsky, 1989, 1990, 2000; Zurif & Caramazza, 1976; see Grodzinsky et al., 1999 for a review), and so do children with S-SLI (Friedmann, Gvion, & Novogrodsky, 2006; Friedmann & Novogrodsky, 2004, 2007; Levy & Friedmann, in press; Stavrakaki, 2001). The finding that the individuals who had very limited pWM understood relative clauses well rules out pWM as the source for the deficit in agrammatism and S-SLI. Furthermore, these results rule out a possible explanation for the asymmetry between subject and object relatives. It could have been claimed that the asymmetry results from the difference in number of words between the antecedent and the gap in subject and object relatives. In subject relatives the minimal GAD is only one-word long (the embedding marker *that*); in object relatives, however, the minimal GAD is longer, including at least the complementizer, the subject, and the verb of the embedded clause. Because distance did not affect the comprehension of individuals with limited pWM, the source for this asymmetry cannot be limited pWM that is affected by the number of words between the antecedent and the gap.

Clinical implications

What are the implications of the current study for everyday comprehension of individuals who have limited pWM? In a way, the findings are encouraging. Without overlooking the difficulties individuals with conduction aphasia are constantly faced with when they wish to convey a verbal message (when their phonological output lexicon or buffer are impaired as well), it seems that only very specific sentences would be difficult for them to understand. They will find it difficult to understand only sentences that require reactivation of the phonological form of a word after a long verbal distance. One point that might be difficult for them that does occur in everyday conversations is the access to a proper name. If a new proper name is introduced into the discourse and later referred to using anaphors and pronominals, they will probably know what the pronouns refer to, but will not be able to come up with the name (This has in fact been found for children with impaired pWM, Zandman & Friedmann. Other than proper names, assuming that most of the sentences in daily language input can be understood without phonological reactivation, these individuals are expected to understand most of the sentences well, as long as they understand the meaning of the sentence and do not attempt to encode it phonologically.

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