What does a patient with semantic dementia remember in verbal short-term memory? Order and sound but not words

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Abstract

In this study, we explored capacities for three different aspects of short-term verbal memory in patients with semantic dementia. As expected, the two patients had poor recall for lexico-semantic item information, as assessed by immediate serial recall of word lists. In contrast, their short-term memory for phonological information was preserved, as evidenced by normal performance for immediate serial recall of nonword lists, with normal or increased nonword phonotactic frequency effects, and increased sensitivity to phonological lures in a delayed probe recognition task. Furthermore, the patients appeared to have excellent memory for the serial order of the words in a list. These data provide further support for the proposal that language knowledge is a major determining factor of verbal STM capacity, but they also highlight the necessary distinction of processes involved in item and order recall, as proposed by recent models of STM.

142 words

INTRODUCTION

The present study examines verbal short-term memory (STM) for item and order information in two patients with semantic dementia (SD). SD is a neurodegenerative condition marked by a progressive degradation of semantic knowledge, arising from structural and functional abnormalities in bilateral anterior and inferior temporal lobes (Hodges, Patterson, Oxbury, & Funnell, 1992; Snowden, Goulding & Neary, 1989). Apart from the intrinsic interest of developing a better understanding of verbal STM in SD, the nature of the deficit in SD provides a valuable opportunity to shed light on the relation between long- and short-term memory processes in tasks such as serial recall.

SD patients present with fluent and well articulated speech, but with a progressive impairment in comprehension and production of content words. In verbal STM tasks, patients with SD produce a distinctive type of “blend” error in immediate serial recall (ISR) for words, especially when the stimulus sequences are composed of words whose meanings are degraded for that patient (Hodges, Patterson & Tyler, 1994; Jefferies, Jones, Bateman & Lambon Ralph, 2004a; Knott, Patterson, & Hodges, 1997; McCarthy & Warrington, 2001; Patterson, Graham & Hodges, 1994; see also Caza, Belleville & Gilbert, 2002 and Forde & Humphreys, 2002, for reports of the same phenomenon in semantically-impaired patients with other aetiologies). These blend errors, which may themselves be words but are more often nonwords, are recombinations of parts of items presented in the stimulus list (for example, “mint, rug” becomes “rint, mug”: Hodges et al., 1994). Normal participants produce frequent blend errors in ISR for nonwords (Treiman & Danis, 1988), but rarely if ever do so for lists composed only of real words. Patterson et al. (1994) proposed that blend errors on words by SD patients reflect the deterioration of semantic knowledge which, in the normal system, may be one source of coherence that binds phonological elements into word units. By this hypothesis, when semantic knowledge is reduced, word forms for speech production become unstable and thus provide poor support for recall. This interpretation, which is supported by the fact that patients show a STM advantage for words they can still comprehend (the so-called “known” vs. “degraded” effect demonstrated in a number of studies), implies that the verbal STM impairment observed in SD is indeed related to impaired lexico-semantic knowledge in long-term memory (LTM) (Jefferies, Patterson, Jones, Bateman & Lambon Ralph, 2004b). The implication of this research is that STM systems themselves should be largely intact in SD, and any deficits should be restricted to conditions where normal individuals would benefit from information in LTM.

The dominant view of how LTM helps recall from STM focuses on the concept of redintegration. That is, degraded traces in STM are thought to be reconstructed using information in LTM (e.g. Schweickert, 1993). This would place the role of long-term knowledge entirely at the retrieval stage. It is also possible that, as suggested by Patterson et al. (1994) and Martin, Lesch and Bartha (1999), LTM can support the maintenance of information in STM. In either case, long-term knowledge should only benefit recall of item information, as tasks requiring recall of serial order generally use word sequences lacking any natural or familiar order to minimize any role for long-term sequence representations. Semantic dementia therefore provides an interesting test case with respect to this issue. That is, does the impairment of lexico-semantic knowledge in SD only affect recall of item information, or is there any consequent impairment of recall of serial order?

Most current models of verbal STM treat the coding for serial order and the coding for item information in STM as, in some regard, distinct (e.g., Brown, Preece & Hulme, 2000; Burgess & Hitch, 1992, 1999; Gupta & MacWhinney, 1997; Gupta, 2003; Henson, 1998). There is already some evidence consistent with this proposal. For example, Saint-Aubin and Poirier (1999) showed that in immediate serial recall, only item recall was influenced by semantic similarity and lexical frequency of the component words. No effect of these linguistic variables was observed for order recall (see also Poirier & Saint-Aubin, 1996; Saint-Aubin & Poirier, 2000). Nevertheless, further strong empirical evidence for this proposal would be valuable. One of the important aspects of this distinction lies in the idea that the mechanism for order is specific to STM processing whereas item information is fundamentally linked to word knowledge that serves other aspects of language processing (e.g., Gupta, 2003). In this regard, studies of verbal STM in patients with SD seem to offer a productive way in which to investigate one side of this distinction. It is well established that such patients have dramatically impaired lexico-semantic knowledge. If, in verbal STM, they nonetheless retain the correct order of any items that they can remember, this outcome would support the separation of these two components.

A first aim of this study was to conduct a comprehensive assessment of verbal STM in SD, by distinguishing item and order recall. With respect to item recall, we were interested in the influence of semantic, lexical and sublexical knowledge on STM performance. If verbal STM performance per se is preserved in SD, then we should expect not only preserved serial order STM capacity, but also a preserved contribution to item recall that relies on knowledge that is preserved in SD. Hence, we should observe a normal influence of sublexical phonological information on item recall, but lexical and semantic influences should be reduced. Furthermore, if poor verbal STM performance in patients with SD is related to diminished support from semantic knowledge, they should treat word lists somewhat more like nonword lists, and hence, their error profile for word lists should resemble healthy adults' error profile for nonword lists (i.e., an increase of phonologically related nonword errors resulting from phoneme substitutions and phoneme migrations, Treiman & Danis, 1988).

A second question concerned the relationship between serial order information and learning of new phonological information. Starting with Baddeley, Gathercole and Papagno (1998), several researchers have suggested that STM memory plays a crucial role in long-term learning of new phonological information (e.g., Burgess & Hitch, 1999; Cumming, Page & Norris, 2003). If short-term memory for serial order is preserved in semantic dementia, then this raises the possibility that patients might also achieve relatively normal learning of new serial order information and new phonological item information. This issue was investigated in our final experiment.

CASE DESCRIPTIONS

AT

AT was first seen by the Cambridge research team in February 1999 (aged 64), when he had approximately a 5-year history of difficulty in retrieving words. His problem had become much worse in the preceding year. He also complained of difficulty in comprehension, especially when people spoke rapidly. He was a well-educated man who had retired from a responsible university position in 1991 (due to carcinoma of the bladder). An interview with his wife established that, having previously been devoted to intellectual pursuits, he had changed over recent years into a much narrower, more rigid and humourless individual. AT reported that he could no longer read for interest/pleasure due to his comprehension difficulty and had begun to spend much of his time doing jigsaw puzzles. MRI (October 1999) revealed marked bilateral but asymmetric anterior temporal lobe atrophy, more severe on the left.

On presentation, he had well preserved general cognitive abilities including orientation, visuo-spatial abilities, executive function, episodic memory and comprehension of syntax (TROG score = 75/80). His digit span was 8F, 5B. His word span (for open word lists) was 4. His anomia was profound: 17/64 correct on the relatively easy object naming test in the Cambridge semantic battery. Single word repetition was preserved. His score on the ACE (Addenbrooke's Cognitive Examination, an extended mini-mental state examination:

Mathuranath et al., 2000) was poor, 58/100[1], owing to his complete failure on all components assessing language, factual knowledge or verbal memory.

Follow-up since 1999 has documented substantial deterioration, especially in all semantic and language abilities. At the time of the experimental testing reported below, AT could name only 5/64 pictures of common objects in our semantic battery and could only produce 2 animal names (cat and dog) in category fluency.

WM

WM presented in April 1998 (aged 51) with a 2.5 year history of gradually increasing difficulty in finding words, with more recent deterioration in speech comprehension. She was a well-educated woman and still working in a laboratory. She had high-level general cognitive abilities including preserved orientation, visuo-spatial abilities, executive function, episodic memory, arithmetic and comprehension of syntax (TROG = 80/80). Her speech was fluent without syntactic or phonological errors but with some anomia and word-finding pauses. Digit span was 8F, 7B. Her word span (for open word lists) was 4. Her anomia was still mild on our relatively easy naming test (59/64 correct) but already very marked on the more difficult Graded Naming Test (2/30, which is far below her pre-morbid abilities). Single word repetition was preserved. MRI and SPECT (May 1998) revealed anterior left-temporal atrophy and hypoperfusion. Her ACE score was 84/100. On follow-up, there has been progressive deterioration of all semantic test performance and, at the time of experimental testing for the present study, her ACE score had dropped to 55/100, mainly due to poor performance on all aspects of language ability and verbal memory.

[1] The cut-off score of the ACE is 88, with 93% sensitivity and 71% specificity for dementia.

EXPERIMENT 1

SEMANTIC KNOWLEDGE AND ITEM AND SERIAL ORDER RECALL

Experiment 1 investigated immediate serial recall (ISR) for words with high or low imageability ratings. We were specifically interested in the overall rate of item and order errors, as well as their distribution as a function of word imageability. We wanted to determine whether the patients' recall of serial order would be preserved or impaired, and whether item recall would interact with the ease of redintegration, as indexed by word imageability. High imageability words should be easier to reconstruct as they are supposed to have richer and more stable semantic representations and should be more resistant to semantic degradation.

Method

ISR of high- and low-imageability words. Fifty high imageability and 50 low imageability monosyllabic words were selected, matched for log frequency taken from the CELEX database (Baayen, Piepenbrock, & Gulikers, 1995) (high imageability words, mean log frequency = 1.9, range: 1.1 – 3.2; low imageability words: 2.0; range: 1.2-3.1) and grammatical ambiguity[2] (degree of grammatical ambiguity: 1.8 for low imageability words and 1.6 for high imageability words; range 1-3 in each case). Imageability status of the words was determined by combining imageability ratings from the MRC Psycholinguistic Database (Coltheart, 1981) and more recent ratings by Bird, Franklin and Howard (2001). Where a word appeared in both databases, we used the average. Both databases report ratings in the range 100 (low imageability) to 700 (high imageability). This procedure was used in order to

[2] The grammatical ambiguity values provided here represent the average number of different grammatical classes a same word can be a part of ; the majority of words in both lists could be either nouns or verbs.

obtain a large pool of monosyllabic stimuli from which we could select experimental word lists matched on number of phonemes and frequency. Low imageability words had a mean imageability rating of 348 (range: 191-407) and high imageability words had a mean imageability rating of 599 (range: 560-633). The patients were presented with ten 5-word sequences in each condition (e.g., low imageability: stress, ease, fact, choice, hint; high imageability: cow, ice, sky, boy, nurse). For the controls (N=11, mean age = 67), there were eight lists of 6-word sequences in each condition, in order to make overall performance levels more comparable to the patients[3]. Each word occurred only once during the task. The high and low imageability lists were presented in a blocked design. Order of presentation of the high and low imageability lists randomly varied between participants. Participants were asked to repeat the sequences in correct serial position. The stimuli were recorded onto Digital Audio Tape by a male speaker of British English. They were then transferred to computer at a sampling rate of 22050 Hz, where they were edited and copied onto CD. Stimulus presentation was by means of a portable CD player connected to hi-fi speakers. Lists of stimuli were presented at a rate of one item per second. Participants' responses were tape recorded for later checking and error analysis. Participants were also instructed to say 'blank' when not knowing an item for a given position.

Error analysis. Different error types were defined for categorizing the patients' incorrect responses: (1) Blend error = an error where the phonological components of the response are identifiable, recombined segments from stimulus items. (2) Phonologically related nonword error = a nonword that shares 50% of its phonemes with target items but the other segments do not obviously originate in the list. (3) Unrelated nonword error = a nonword sharing fewer than 50%

[3] A sequence length of 6 words is the standard sequence length used in experiments exploring the influence of imageability on immediate serial recall in healthy adults (e.g., Walker & Hulme, 1999). This relatively long sequence length is chosen in order to reach the limits of STM capacity and hence increase the reliance on long-term semantic knowledge during performance on this task. However, for patients with impaired semantic knowledge, this would have proven too difficult given that a number of the words to be recalled will not be

of its phonemes with the target list. (4) Word error = a semantically related word, whole-word intrusion or perseveration; (5) Order error = a target item recalled in the wrong serial position; (6) Omission error. Due to a very low error rate in two control participants, their data were not used for error analysis.

Results and discussion

In terms of overall level of recall, AT scored at the low end of the normal range for ISR of both high- and low-imageability words, whereas WM's scores were below this range in both conditions (Table 1). Like the controls, both patients showed an advantage in ISR for high-imageability words, although the size of the effect was at the lower end of the control range (controls: $t(10) = 3.76$, $p < .01$) (see Table 3). However, for both types of word lists (see Table 2a), the patients showed an abnormal profile, in the number of item and order errors produced. First, both patients made significantly more item errors than controls, including phonological blends and both types of nonword responses. Second, serial order errors were very rare for the patients. Although the majority of errors produced by controls were order errors, neither AT nor WM produced a single order error for low-imageability words. For high-imageability words, the number of errors was also surprisingly small given the very large number of errors made by controls in this condition. Thus for both types of words, virtually everything that the patients recalled was produced in correct serial position. Identical results were obtained when considering error proportions rather than absolute values (see Table 2b).

< INSERT TABLES 1, 2a, 2b AND 3 ABOUT HERE >

A first finding of this experiment is that imageability, a semantic factor, influenced performance in patients with SD roughly to the same extent as in control participants. One

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known anymore and hence the limits of STM capacity will be reached earlier. Preliminary testing had shown that might have predicted a reduction of the word imageability effect for the patients, given their deficits in the semantic representations from which imageability effects must arise. Alternatively, one could argue that the gradual degradation process should have a disproportionate impact on the sparser representations of abstract, low-imageability words than on the richer semantic space of a concrete, imageable concept. By the latter reasoning, one would predict a decline in item STM performance for both high and low imageability words that nevertheless maintains the normal advantage for high imageability words. This is what was observed in the present study.

A second finding relates to the difference between recall of item and of serial order information in both SD patients. We observed almost no order errors in either word condition, suggesting that processes underlying retention of serial order information operate independently from those that support retention and/or redintegration of item information. One could argue that the low proportion of order errors was simply a consequence of the patients' loss of word knowledge. Put simply, did the patients make fewer order errors because they recalled fewer words? This seems rather unlikely for several reasons. First, patient AT still showed an abnormally low rate of order errors even for the low imageability lists where his overall recall performance was quite similar to that of controls (.58 vs. .65). Second, although a reduction in quantity recalled should perhaps lead to a reduction in order errors, there is no reason to anticipate that it would yield a nearly complete disappearance of order errors as was the case in Experiment 1. Experiment 2 will further explore this issue by comparing recall performance for ISR tasks using a closed item set and hence maximizing the probability of order errors.

Finally, it could be argued that blend errors are also a kind of serial order error, but at the phoneme level, where phoneme onsets (or nuclei or codas) of two different items are

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a sequence length of 5 words for the patients was a more appropriate length avoiding floor effects.

reordered (phoneme onset of item 1 becomes phoneme onset of item 2). Accordingly, we recalculated order errors to include both word order errors and blend errors. As can be seen at the bottom of Table 2b, both AT and WM still showed a smaller proportion of these combined order errors than controls, especially for high-imageability words, although the difference between controls' and patients' error rates is reduced when considering absolute number of combined order errors (Table 2a). Even if blend and word order errors were both the consequence of failure of the same serial order mechanism, the pattern of errors remains strikingly different between patients and controls, in that almost all the controls' combined errors corresponded to misplacing a whole word whereas virtually all of the patients' combined errors involved misplacing a phoneme or other sub-word segment. This latter type of error resembles the pattern in healthy adults when recalling nonword lists (Treiman & Danis, 1988).

EXPERIMENT 2

ITEM AND SERIAL ORDER RECALL FOR CLOSED ITEM SETS

In the previous experiment, we used lists where the items were sampled from an open set of words. Experiment 2 used lists sampled from closed word sets: this procedure maximizes the likelihood of order errors as the items are the same in the different trials, and only their serial position changes. The results from Experiment 1 would be reinforced and extended if the new procedure still yields a major discrepancy between the proportions of item and order errors for word ISR in the SD patients relative to controls. We also introduced an additional variable, namely phonological similarity. Order errors normally appear at a high rate for phonologically similar word lists. If patients with SD still make significantly fewer order errors than controls for phonologically similar word lists, this would provide yet further support for preserved retention of serial order information in SD.

Method

ISR of phonologically similar and dissimilar words. Stimulus materials consisted of 10 lists of five phonologically similar words (ram, map, cat, mat, ham) and 10 lists of five phonologically dissimilar letters (soap, nail, leaf, duck, pen). The words in the two conditions were reasonably well matched for frequency (mean CELEX log frequency similar = 1.4, range: 1.1-1.9; dissimilar = 1.2, range: .8-1.8) and concreteness (similar = 593.2, range: 571-606; dissimilar = 557.6, range: 513-615; MRC Psycholinguistic Database, Coltheart, 1981). There were two practice trials. The phonologically similar and dissimilar trials were presented in a blocked design. Order of presentation of the phonologically similar and dissimilar word blocks randomly varied between participants. Participants were asked to recall the sequences in correct serial order. Control data were collected from a sample of 13 control subjects with a mean age of 55 years (range: 50-60 years). As in Experiment 1, stimulus presentation was by means of a portable CD player connected to hi-fi speakers. Lists of stimuli were presented at a rate of one item per second. Participants' responses were tape recorded for later checking and error analysis.

Results and discussion

The results of Experiment 2 are presented in Table 4. In controls, the advantage for phonologically dissimilar over similar lists was significant, $t(12) = 7.52$, $p < .0001$. AT and WM also showed a phonological similarity effect of similar size to the controls (see Table 3). In terms of accuracy, AT's performance on phonologically dissimilar words was at the low end of the control range, but otherwise both patients were below the normal range.

< INSERT TABLE 4 ABOUT HERE >

Error analysis. The errors in word ISR from Experiment 2 are shown in Table 5a (absolute number of errors) and Table 5b (proportions). On both measures, AT and WM made significantly more item errors (blends and phonologically related or unrelated nonwords) than controls in the phonologically dissimilar word condition, but not for phonologically similar words. On the other hand, the number and proportion of order errors for the patients was either similar to or significantly lower than in controls. As in the preceding experiment, we also conducted an analysis of combined errors (blends + item order errors). In that case, neither the proportions nor absolute levels of order errors were smaller in the patients than in controls, although once again the contributions of whole-word and word-segment movements were notably different.

< INSERT TABLES 5a AND 5b ABOUT HERE >

Overall, if we consider the relative proportions of error types, the results support the dissociation of item and order information already observed in Experiment 1, at least for the phonologically dissimilar word lists. For the phonologically similar word lists, the actual rate of order errors may have been lower than reported for the patients: due to the phonological similarity of the items, some errors scored as order errors might in fact have been blend errors[4]. The pattern of results of Experiment 2 confirms those obtained in Experiment 1, by suggesting normal or maybe even supra-normal recall of serial order information. Once again, the good serial order recall performances cannot be simply attributed to the fact that patients recalled fewer words, because order errors were still rare even for conditions where patients and controls were close with respect to overall recall performance (e.g., phonologically dissimilar words in patient AT and controls).

[4] For example, for a target sequence such as ‘map, cat, mat, ham, ram’ and a response such as ‘mat, cat, map, ram, ham’ we scored 4 order errors; however, ‘mat’ in serial position 1 of the response sequence could also have been a blend error resulting from the combination of the onset of ‘map’ and the coda of ‘cat’; the same applies to ‘order’ errors ‘map’, ‘ram’ and ‘ham’ in the response sequence.

When we consider blend errors as order errors at the phoneme level and combine them with word order errors, the patients and controls presented more similar numbers of order errors, but for different reasons: for the patients, almost all of these were order errors at the phoneme level (i.e., blend errors), with the reverse pattern, i.e. almost all order errors at the word level, for controls. The patients' blend errors are almost certainly attributable to their impaired word knowledge: the decayed STM traces for words in the list can no longer be reconstructed (as they are in normal participants) with reference to corresponding word representations in lexico-semantic LTM, and thus the reconstruction process must rely instead on whatever phonological segments are available in STM. An alternative view might be that blend errors reflect impaired STM for serial position information at the phoneme level. If this was so, then the patients should also show impaired recall of non-word lists where redintegration processes are much less likely to play a role. Among other factors, this possibility was further explored in Experiment 3.

EXPERIMENT 3

ITEM RETENTION CAPACITIES FOR PHONOLOGICAL AND LEXICO-SEMANTIC INFORMATION

Experiment 3 explored the influence of sublexical and lexico-semantic knowledge on STM for item information. If poor verbal STM performance in SD is related only to degraded lexico-semantic knowledge, then we should still expect normal recall performance for information that is not influenced by lexico-semantic knowledge. For example, general knowledge about the typical phonological properties of the language should have a normal impact on verbal STM performance. This was explored by comparing nonword recall for nonwords that differed at the level of diphone phonotactic frequency. A number of studies have shown that nonwords containing diphones that occur frequently in the native language of the participants give rise to better recall performance than nonwords with low frequency diphones (e.g., Gathercole, Frankish, Pickering , & Peaker, 1999; Majerus & Van der Linden, 2003; Majerus, Van der Linden, Mulder, Meulemans, & Peters, 2004).

Two interpretations of the phonotactic frequency effect currently co-exist. Gathercole et al. (1999), Majerus et al. (2004) and Thorn and Frankish (2005) have argued that this effect reflects the influence of sublexical phonological knowledge about the statistical properties of the language. On the other hand, Roodenrys and Hinton (2002) suggest that the phonotactic frequency effect may also reflect lexical phonological knowledge, as nonwords with frequent phonotactic patterns typically have a larger phonological neighbourhood (number of familiar words differing from the nonword's phonological form by only one or two phonemes) than nonwords with less frequent phonotactic patterns. Exploring this effect in patients with SD provides a particularly convenient opportunity to tease apart these two different interpretations. If the phonological LTM contribution to nonword STM were mainly based on word form knowledge, then we might expect a reduced effect in SD patients, whose word form knowledge is impaired (Knott et al., 1997; Knott, Patterson, & Hodges, 2000; Papagno & Capitani, 2001; Patterson et al., 1994; Rogers, Lambon Ralph, Hodges & Patterson, 2004). On the other hand, if the LTM phonological contribution to STM is sublexical, then the effect in SD should be comparable to that observed in healthy participants. Indeed, when STM support from lexical and semantic levels of language representations is degraded as in SD, reliance on phonological levels of language representations might be normal or even increased. In the latter case, we might expect larger phonotactic frequency effects in nonword recall for patients than controls, providing that phonotactic frequency is based on sublexical rather than lexical knowledge.

A further set of tasks in Experiment 3 assessed retention capacities for both high and low phonotactic frequency nonwords using single-item delayed repetition and single-item delayed recognition. The two single-item tasks were used (in addition to ISR) because they provide a purer index of phonological item retention, independent of any demand to retain 'word'-level serial order information.

Experiment 3 also included a final task that directly confronted differential sensitivity to lexico-semantic and phonological item information: a delayed probe recognition task for word stimuli including both phonological and lexico-semantic foils. If lexico-semantic knowledge is degraded, then the patients might rely more heavily on phonological information, and therefore be influenced by phonological foils to a greater extent than controls.

Method

General procedure. As in the previous experiments, the materials for all tests were recorded onto Digital Audio Tape by a male speaker of British English and presented by means of a portable CD player connected to hi-fi speakers. In all tasks, lists of stimuli were presented at a rate of one item per second. In all tests involving a filled retention interval, the interval was 5 seconds, and subjects were required to count backwards from 95 during the delay. In all tasks involving verbal output, participants' responses were tape recorded for later checking and error analysis. All tasks were also administered to the same controls as in Experiment 2.

ISR of high and low phonotactic frequency CVC nonword lists. This task used 32 high and 32 low phonotactic frequency CVC nonwords (see Appendix). Stimuli were classified as high or low phonotactic frequency according to the type and token frequencies of the CV*, *VC and C*C diphones in the CELEX corpus of spoken English (Baayen et al., 1995). The diphone frequencies are given in Table 6. The nonwords were presented in 4-item sequences. There were 8 trials for each nonword condition. Each item only occurred once during the task.

Two practice trials preceded the experimental trials. The high and low phonotactic frequency nonword conditions were presented in blocked design. Order of presentation of the high and low phonotactic frequency nonword blocks varied randomly between participants. Subjects were asked to recall the sequences in correct serial order.

< INSERT TABLE 6 ABOUT HERE >

Delayed repetition of high and low phonotactic frequency nonwords. This task used 40 high and 40 low phonotactic frequency nonwords. As in the preceding task, phonotactic frequency was based on the type and token frequencies of constituent CV*, *VC and C*C diphones in CELEX (see Table 6). Each nonword was presented in isolation, followed by a 5-second delay during which the participant counted aloud backwards. At the end of the delay, the experimenter tapped sharply on the desk, indicating that the participant should repeat the target nonword. There were 4 practice trials. High and low phonotactic frequency nonwords were presented in a blocked design. Order of presentation of the high and low phonotactic frequency nonword blocks varied randomly between participants.

Delayed recognition of high and low phonotactic frequency nonwords. Twenty-four high and 24 low phonotactic frequency target nonwords were created. A target, presented in isolation, was followed after the 5-sec filled delay by a probe nonword which was either identical to the target nonword (12 trials), or differed from the target in its initial consonant (4 items), vowel (4 items) or final consonant (4 items). In each condition, mean diphone frequency for target and negative probes was similar (see Table 6). Participants were asked to say “Yes” or “No” depending on whether the probe was the same as the target. There were an additional 4 practice trials. High and low phonotactic nonwords were presented in a blocked design. Order of presentation of the high and low phonotactic frequency nonword blocks varied randomly between participants.

Delayed word probe recognition task with phonological and semantic foils. In this task, 72 sequences of three monosyllabic words were presented, and were each followed by a probe word after a filled delay of 5 seconds. The probe word was either identical to one of the words in the list (N=36), phonologically related (sharing the rhyme: N=12), semantically related (approximate synonym: N=12), or unrelated (N=12). Participants had to indicate whether the probe word had occurred in the target list. The different probe types were matched for word frequency, imageability and grammatical ambiguity (mean degree of grammatical ambiguity was 2 (range: 1-3) for each type of probe item). Each serial position in the three-word list was probed equally often for each condition. As this was a relatively long task, it was split in two halves that were presented on different test sessions. Response latencies between the end of presentation of the probe word and onset of the participant's response were measured from a digitised recording of the test session.

Results and discussion

Nonword ISR, delayed repetition and delayed recognition

Accuracy of performance. The patients' performance was within the normal range for all nonword measures, though sometimes at the lower end (see Table 7). Phonotactic frequency. Both the patients and the controls performed more poorly on low than high phonotactic frequency nonwords in all three tasks manipulating this factor (see Table 7). For controls, the phonotactic frequency effects were significant, by paired t-tests, in each of the three tasks (ISR: $t(12) = 8.12$, $p <.0001$; delayed repetition: $t(12) = 6.72$, $p < .0001$; delayed recognition: $t(12) = 4.42$, $p <.001$). For patient WM the phonotactic frequency effects for all tasks were of similar magnitude to those observed in controls. For patient AT the effect was actually significantly larger than in controls for nonword ISR (see Table 3).

Error analysis. Error analysis (Table 8) was performed on those tasks that yielded a sufficiently high number of errors, i.e. the nonword ISR and the nonword delayed repetition task. For ease of presentation, errors were also collapsed over the high and low phonotactic frequency conditions as no differences were observed in type of errors produced. Most errors made by both patients and controls were phonologically related or unrelated nonwords. Most importantly, patients made no more order or blend errors in nonword ISR than controls.

< INSERT TABLES 7 AND 8 ABOUT HERE >

Delayed probe recognition task

Accuracy. AT's success in rejecting words that had not been presented in a target sequence was within the control range for all foil types, but he also incorrectly rejected a number of real targets, indicating a "no" response bias (Table 9). WM exactly matched the control mean for accepting correct targets, and made no more errors to semantic or unrelated foils than an average normal subject, but gave more false positive responses to phonologically related foils than even the most error-prone control participant. Additional and somewhat finer-grained information is available from the RTs for the participants' correct responses. By this measure, WM, and to some extent AT, showed particular sensitivity to phonologically related foils (Table 9). Normal participants were substantially slower to reject foils in this category than unrelated foils, but WM was significantly slower still. Although AT was not significantly slower than controls, his reaction time difference was at the upper range of control performance. AT also showed significantly slower reaction times for the rejection of semantically related foils.

< INSERT TABLE 9 ABOUT HERE >

An influence of phonological knowledge, as measured by the effect of phonotactic frequency, was observed in the two patients. It was even significantly increased in patient AT for nonword ISR. As noted earlier, if the significant effect of phonotactic frequency generally observed in nonword recall were attributable more to the lexical neighbourhood than to sublexical phonological knowledge, then one might expect a reduced phonotactic frequency effect in SD patients because of their disrupted knowledge of phonological word forms. This should be especially noticeable for high-phonotactic frequency nonwords. The fact that the patients showed normal, or even increased, phonotactic frequency effects is thus more consistent with the view that this effect is mediated largely by general phonological knowledge about the language at the subword-level, and therefore also that such knowledge is largely preserved in SD. On the whole, the patients' performance was normal for nonword ISR, nonword delayed repetition and nonword delayed recognition, in terms of both accuracy and error profiles, indicating that retention of phonological item information is preserved in the two patients. Furthermore, the fact that the rate of blend errors in nonword recall was similar for the patients and controls suggests that the increased number of blend errors observed for the patients' word recall in Experiments 1 and 2 is indeed due to deficient word knowledge and not to impaired STM for phonemic serial order information.

EXPERIMENT 4

LEARNING OF NEW SERIAL ORDER AND ITEM INFORMATION

In the final part of this study, we explored the two SD patients' ability to learn new item and serial order information. Baddeley and colleagues have established that a well-functioning verbal STM system is a prerequisite for learning new phonological forms (e.g. Baddeley, Papagno & Vallar, 1988; Baddeley et al., 1998). More recently it has been argued that it is specifically the serial order component that is critical for learning new phonological information (e.g., Cumming, Page & Norris, 2003; Gupta & McWhinney, 1997; Gupta, 2003). Some of these accounts also suggest that STM is of more general importance for learning sequences as, for example, in the Hebb effect (e.g. Burgess & Hitch, 1999; Cumming et al., 2003). Individuals with preserved memory for serial order might therefore be expected also to have a preserved ability to learn new phonological information. However, long-term learning also requires long-term memory and, at least in the domain of lexico-semantic knowledge, this is clearly impaired in SD. In patients with an eroding lexical/semantic system, preserved serial order STM may be insufficient to support long-term learning of phonological word forms. Indeed, a previous study of SD has shown relatively poor learning of word lists as measured by free recall or even recognition (Graham, Patterson, Powis, Drake & Hodges, 2002). Furthermore, maintenance of previously known or new vocabulary appears to require constant drill and is subject to rapid forgetting once practice stops (Graham, Patterson, Pratt & Hodges, 1999). However, these previous studies assessed learning for meaningful verbal information, and it may be that difficulties at the level of semantic processing depressed learning.

In this study, we explored learning for new phonological information without any major contribution of semantic level processing. Although this is a somewhat artificial experiment, it is, at the methodological level, the purest way to test the link between preserved serial order storage abilities and learning of new phonological information. Phonological learning was assessed via free recall following repeated presentations of lists of CVC nonwords with high- vs. low-diphone frequencies. Finally, we also assessed more directly whether learning of new serial order information in SD is preserved to the same extent as is STM for serial order information, via a Hebb digit learning task.

Method

CVC nonword list learning. This task used two lists of five CVC nonwords, one of high diphone frequency items and the other with low diphone frequencies (see Appendix).

Diphone frequencies were computed using the spoken language corpus of the CELEX database (see Table 6). There were 6 learning trials for each condition. The nonwords were presented at a rate of 1/sec in different orders on each learning trial. After each presentation, the participants were asked to recall as many items as possible in any order. The control subjects were the same as in Experiment 1.

Hebb learning. This task used digit lists titrated to the individual patients' spans by adding one item. AT's digit span was 6 and hence his list-length for the Hebb learning experiment was 7; for WM, the corresponding values were 7 and 8. Two thirds of trials consisted of random digit sequences, whereas on every third trial, the same digit sequence was repeated. After the eighth repetition, a new sequence was presented and then repeated every third trial. The control group comprised 6 adults with a mean age of 65 years (range: 56-72).

Results and discussion

Learning lists of nonwords. The nonword learning task was clearly difficult, and even the age-matched controls were still far from achieving perfect recall on trial 6 for each of the two nonword sets (see Table 10 and Figure 1). In general, however, the learning curves in Figure 1 for normal participants showed relatively consistent, monotonically increasing functions. AT and WM were impaired relative to controls on almost all measures: only one – AT's score on the high-diphone CVC nonwords – was within the control range. AT's learning curves were nevertheless either erratic or flat, showing little evidence of significant learning between the first and the sixth learning trial in any condition (see Figure 1). WM's performance revealed a little more incremental learning than AT's, though she too was very poor at these tasks.

< INSERT TABLE 10 AND FIGURE 1 ABOUT HERE >

As expected, controls were better at learning the list of high than low phonotactic frequency words, $t(10) = 6.08$, $p < .001$). The patients showed the same effect (Table 10), though WM's benefit for higher-diphone frequency CVCs was not large. The pattern of errors for patients and controls was very similar (Table 11). Errors consisted mainly of nonword blend errors.

< INSERT TABLE 11 ABOUT HERE >

The Hebb effect. Both AT and WM showed performance in the normal range in this task (Table 10). They showed a normal Hebb effect, i.e. a notable advantage in ISR for digit sequences that repeated every third trial as compared to novel random sequences (AT: Δ = .11; WM: Δ =.41; controls: mean Δ = .19, range: .10-.32). In the case of WM, this advantage was even significantly stronger than in controls ($t=2.91$, $p <.05$).

Although, in retrospect, it would have been better to choose a less difficult phonological information learning task yielding better control performance, the results at least suggest that the ability to encode serial order information is not sufficient to produce normal learning of new phonological information. Both AT and WM were impaired at learning nonword lists, despite their preserved capacity to learn and retain serial order. The implications of these data for current models of STM will be discussed in the following section.

GENERAL DISCUSSION

The purpose of this study was to investigate the impact of degraded lexico-semantic knowledge on short-term retention capacities for item and serial order information in two patients with SD. In Experiment 1, we observed significantly impaired performance for item recall of high and low imageability word lists, combined with good-to-excellent performance for recall of order information. Unlike the control subjects, and independent of the semantic characteristics of the stimulus items, the SD patients essentially never recalled a whole word in the wrong position in ISR for words. Experiment 2 replicated these findings, using phonologically similar and dissimilar word lists sampled from closed sets which typically generate a high rate of order errors in healthy controls. Once again, the patients showed very low rates of serial order errors, while item recall was impaired. Experiment 3 examined STM performance for item recall more closely, by differentiating STM for phonological and lexico-semantic item information: the patients showed performance in the normal range for recall of nonwords, with a normal or increased influence of sublexical factors such as phonotactic frequency on nonword recall. The patients were also more sensitive to phonological than lexico-semantic item information in a delayed probe recognition task with appropriately selected distractors. Finally, Experiment 4 demonstrated that, despite their good memory for phonological item and serial order information, the patients were extremely poor at learning new phonological information (in free recall of short nonword lists) while their acquisition of serial order information in the Hebb paradigm was completely preserved.

Overall, the results of the present study are in line with the assumption that poor verbal STM performance for word lists in SD reflects the failing support of lexico-semantic knowledge, which is, by definition, impaired in SD. The patients' recall of word lists resembles healthy controls' performance when recalling nonwords. This conclusion is supported by the occurrence in the patients' word-list recall of blend errors, where segments from two or three words of the target STM list are recombined into words, or more often nonwords, that had not been in the target STM list. Healthy controls generally make this type of error only when recalling either lists composed entirely of nonwords (Treiman & Danis, 1988) or lists of mixed words and nonwords (Jefferies, Frankish & Lambon Ralph, 2006). By contrast with this evidence for significantly reduced impact of lexico-semantic knowledge on STM, we observed a normal influence of phonotactic frequency on the patients' STM, reflecting their retained knowledge of typical sound patterns in the language. Furthermore, recall of serial order information was also normal in both patients. Hence, the only type of information for which patients with SD showed poor recall was lexico-semantic item information, precisely the type of information for which underlying knowledge is degraded (see also Jefferies et al., 2005, for related results).

At a theoretical level, the present data lend considerable support to current STM models that treat language knowledge as a major determining factor of STM performance (e.g., Baddeley et al., 1998; Burgess & Hitch, 1999; Gupta, 2003; N. Martin & Saffran, 1992; R. Martin et al., 1999). The results also stress a distinction between processes involved in recalling item information (which are shared with language processing) and those underlying recall of serial order information (e.g. Brown et al., 2000; Burgess & Hitch, 1999; Gupta, 2003), as shown by remarkably preserved order recall but impaired lexico-semantic item recall. Finally, our data argue for a dynamic interplay of processes involved in phonological item information, lexico-semantic item information and order information. For example, in a number of instances, it appeared that the patients' serial order recall was not only preserved but was even better than in controls (although this depended somewhat on the both the task and the order measures used). A similar phenomenon was observed when distinguishing phonological and lexico-semantic item information. In Experiment 3, the patients showed an increased sensitivity to phonological information in a delayed probe recognition task and to phonotactic frequency for nonword recall. The differential impairment of lexico-semantic retention capacities versus phonological retention capacities is also consistent with models distinguishing separate phonological and semantic STM buffers, each buffer being determined by input from respective levels of language representations (e.g. R. Martin et al., 1999). In the model proposed by R. Martin et al., however, there is no separate mechanism for storing serial order information, which is considered an inherent property of the phonological and semantic

STM buffers. With respect to this latter point, our data are more supportive of models proposing distinct item and order storage mechanisms.

In the interactive activation model of Martin and Saffran (1992), STM recall reflects the temporary activation of phonological, lexical and semantic language representations which are connected via feedforward and feedback links. When the decay rate of such activation of language representations is abnormally increased in the implemented model, then phonological representations, activated first during oral presentation of a verbal STM list, will be more degraded than lexical and semantic representations at the moment of recall. In that case, lexico-semantic factors have a greater impact on STM recall, as evidenced by increased lexicality effects and even semantic paraphasias. This is indeed the hallmark of patients suffering from deep dysphasia, a severe repetition-type aphasic disorder (e.g., Martin & Saffran, 1992; Majerus, Lekeu, Van der Linden, & Salmon, 2001). In this regard, the Martin and Saffran model is similar in spirit to our suggestion of a dynamic trade-off between different types of information contributing to STM. This model, however, cannot account for the differential impact that serial order and item information might have on STM recall, as it lacks any explicit mechanism for maintaining serial order information. Models incorporating precise and explicit mechanisms for both item and serial order information should be more useful in this respect, but they will need to be adapted in order to account for the complex trade-offs that may emerge between these different mechanisms in the case of pathology.

Finally, our data have implications for the relationship between capacities for serial order information and phonological learning. A number of recent computational models have proposed that the capacity to retain serial order information is responsible for the link consistently observed between verbal STM and new word learning abilities (Burgess & Hitch, 1999; Gupta & MacWhinney, 1997; Gupta, 2003). When a new word form has to be learned, the different phonemes have to be retained in their correct serial order and these serially ordered phonemes have to be transformed into a more stable long-term memory trace. For the authors cited above, STM capacities for serial order information play a crucial role during this process. In the present study, although our patients had (at the very least) normal ability to retain both serial order and phonological information in STM tasks, their learning of new phonological sequences, one of the first steps when learning new word forms, was impaired. This cannot be explained in terms of a more general serial order learning problem, because Experiment 4 demonstrated normal learning of serial order information in the Hebb paradigm using material for which SD patients have good lexical and semantic knowledge, namely single-digit numbers (Jefferies et al., 2004b). The implication here is that the ability to retain serial order may be necessary but is not sufficient for learning of new phonological information. A well-functioning and stable phonological network into which the new phonological sequences forms can be incorporated as new lexical representations is also required. At the sublexical phonological level, this network is most probably intact in the patients, as normal phonotactic frequency effects were observed in both STM and nonword learning tasks. At the lexical level, however, this network is almost certainly abnormal in SD, as patients with SD show impaired performance in many tasks requiring word form knowledge (Knott et al., 1997, 2000; Papagno & Capitani, 2001; Patterson et al., 1994; Rogers et al., 2004).

To conclude, this study explored the qualitative changes that arise in serial and item STM as a result of degradation of lexico-semantic knowledge. In the context of impaired lexico-semantic knowledge, retention of list-level serial order and phonological information seem to become increasingly important determinants of verbal STM performance. More generally, our study supports the view that capacities for recall of order information are most probably distinct from capacities underlying recall of item information.

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Appendix

Nonwords used in the ISR task in Experiment 3 and in the nonword list learning task in Experiment 4.

ISR: High phonotactic frequency nonwords

Trial 1: lHs, bWl, fKm, hNv

Trial 2: rDl, bLd, hu:l, seNd

Trial 3: sWv, dC:m, gDv, lNf

Trial 4: dBLn, saNf, nHtG, wLk

Trial 5: GNl, hKm, sHv, riJ

Trial 6: lLd, dDm, saNl, wNd

Trial 7: su:l, neNs, wHm, hBLt

Trial 8: gM:v, wHJ, mu:l, lA:t

ISR: Low phonotactic frequency nonwords

Trial 1: lDb, nWE, tGKG, bHp

Trial 2: nNdF, gu:b, vNr, zeNg

Trial 3: zA:n, fCNp, zDb, lM:r

Trial 4: vBLtG, GaNb, fHp, gLs

Trial 5: ku:g, JHl, mKn, tCNf

Trial 6: laLm, pu:b, faLp, wBLdF

Trial 7: tNdF, mLf, heNJ, zaNb

Trial 8: lM:G, sA:g, fDJ, sLb

Nonword list learning : High phonotactic frequency nonwords

/fCs/, /hNv/, /sM:k/, /waim/, /kHn/

Nonword learning: Low phonotactic frequency nonwords

/baidF/, /gaLp/, /hLg/, /tCif/, /zDb/

Table 1

Correct responses for ISR of high and low imageability words in Experiment 1

	Imageability	
Tasks	High	Low
ISR (proportion)		
AT	0.64	0.58
WM	0.52*	0.42*
Control mean (range)	0.81 (0.67-0.98)	0.65 (0.50-0.81)

Note. The results represent correct recall in correct serial position

* $p < .05$ (modified t-test; Crawford & Garthwaite, 2002)

Table 2a

Raw error scores for the SD patients and controls (mean, range) for ISR of high and low imageability words in Experiment 1

	High imageability			Low imageability		
Error types	AT	WM	Controls	AT	WM	Controls
Blend	3*	5*	0.6 (0-3)	4*	11*	1.1 (0-3)
Phon. related nonword	2*	6*	0	2*	4*	0
Unrelated nonword	0	6*	0	1*	0	0
Word error	5	6	4 (0-8)	2	8	5 (0-11)
Order	1*	2*	10.5 (4-17)	0*	0*	11.1 (4-19)
Omission	8	0	4.8 (0-12)	12	6	11.6 (7-19)
Blend + Order	*4(*)*	*7*	*11.1 (4-17)*	*4(*)*	*11*	*12.2 (5-21)*

Note. Blend = an error where the phonological components of the response are identifiable, recombined segments from stimulus items. Phon. related nonword = a nonword that shares 50% of its phonemes with target items but the other segments do not obviously originate in the list. Unrelated nonword = a nonword sharing less than 50% of its phonemes with the target list. Word error = semantically related words, intrusions and perseverations.

* $p < .05$; (*) $p = .07$ (modified t-test; Crawford & Garthwaite, 2002)

Table 2b

Percentage[1] of various error types for the SD patients and controls (mean, range) for ISR of high and low imageability words in Experiment 1

	High imageability			Low imageability		
Error types	AT	WM	Controls	AT	WM	Controls
Blend	16*	20*	3 (0-8)	19*	38*	4 (0-9)
Phon. related nonword	11*	24*	0	9*	14*	0
Unrelated nonword	0	24*	0	6*	0	0
Word error	26	24	21 (0-33)	9	28	18 (0-33)
Order	5*	8*	53 (33-80)	0*	0*	38 (16-51)
Omission	42*	0	23 (0-36)	57	20	40 (22-65)
Blend + Order	*21**	*28**	*56 (33-82)*	*19**	*38*	*42 (20-57)*

* $p < .05$ (modified t-test; Crawford & Garthwaite, 2002)

[1] percentage of each error type relative to the total number of errors actually produced by each patient

Table 3

Sizes* of imageability effects and phonotactic frequency assessed in Experiments 1-3.

Tasks	AT	WM	Control mean (range)
Word imageability effects			
Word ISR (Exp. 1)	3	4	8,18 (3-13)
Word ISR – strict serial order (Exp. 1)	2	4	9,19 (-2-21)
Phonological similarity effects			
Word ISR (Exp. 2)	23	9	16,38 (-1-30)
Phonotactic frequency effects			
Nonword ISR (Exp. 3)	14°	6	7,30 (4-11)
Delayed nonword repetition (Exp. 3)	4	5	4,15 (1-8)
Delayed nonword recognition (Exp. 3)	3	5	2,00 (-1-5)

* the values reported in this table represent the difference between the scores obtained in the two conditions of a given task (e.g., High Imageability word recall – Low Imageability word recall)

°patient's difference score significantly larger than controls' difference scores ($p < .05$; modified t-test; Crawford & Garthwaite, 2002).

Table 4

ISR performance for phonologically similar and dissimilar word lists in Experiment 2

	Condition	
Tasks	Similar	Dissimilar
Word ISR (max=50/condition)		
AT	13*	36
WM	14*	23*
Control mean (range)	27.62 (15-37)	44.00 (34-50)

Note. The results represent correct recall in correct serial position

* $p < .05$ (modified t-test; Crawford & Garthwaite, 2002)

Table 5a

Raw error scores of various error types for the SD patients and controls (mean and range) in ISR of phonologically similar and dissimilar words in Experiment 2

	Phonologically similar			Phonologically dissimilar		
Error types	AT	WM	Controls	AT	WM	Controls
Blend	11	13	3.67 (0-19)	8*	15*	.25 (0-1)
Phon related nonword	0	0	0	0	2*	0
Unrelated nonword	0	0	0	0	3*	0
Word error	4	2	1 (0-5)	1	2	.13 (0-1)
Order	12	16	13.33 (8-23)	1*	4	8 (4-16)
Omission	10	5	4.33 (0-12)	3	1	1 (0-7)
Blend + Order	*23*	*29*	*17 (10-34)*	*9*	*19**	*8.25 (5-16)*

Note. See table 2a for a description of error types. * Results significantly different from control performance (modified t-test, p < .05; Crawford & Garthwaite, 2002).

Table 5b

Percentage of various error types for the SD patients and controls (mean and range) in ISR of phonologically similar and dissimilar words in Experiment 2

	Phonologically similar			Phonologically dissimilar		
Error types	AT	WM	Controls	AT	WM	Controls
Blend	30	36	16 (0-54)	61*	56*	3 (0-11)
Phon related nonword	0	0	0	0	7*	0
Unrelated nonword	0	0	0	0	11*	0
Word error	11	6	5 (0-23)	8	7	1 (0-13)
Order	32*	44	60 (39-92)	8*	15*	85 (53-100)
Omission	27	14	19 (0-56)	23	4	11 (0-46)
Blend + Order	*62*	*80*	*72 (56-100)*	*69*	*71*	*88 (53-100)*

Note. See table 2a for a description of error types. * Results significantly different from control performance (modified t-test, p < .05; Crawford & Garthwaite, 2002).

Table 6

Phonotactic frequencies of the nonwords used in Experiments 3 and 4.

	Diphone frequency measures					
	Type			Token		
	CV*	*VC	C*C	CV*	*VC	C*C
ISR						
HF nonwords	188	136	86	38436	30529	16961
LF nonwords	44	29.22	15.59	1964	1328	695.8
Delayed repetition						
HF nonwords	111	137	75.6	24849	29267	19577
LF nonwords	36.03	30.78	17.78	1585	1269	983.1
Delayed recognition						
HF nonwords – targets	209	143	108	32623	23165	13449
LF nonwords – targets	36	31	19	1690	1089	1101
HF nonwords – foil	212	158	118	37325	45794	17846
LF nonwords – foil	55	25	14	2185	666	650
Learning						
HF nonwords	138	161	92	49395	26377	18424
LF nonwords	29	11	15	791	434	513

HF : high phonotactic frequency: LF : low phonotactic frequency

Table 7

Number of correct responses of the nonword tasks in Experiment 3

	Phonotactic frequency	
Task	High	Low
Nonword ISR (max=32/condition)		
AT	22	8
WM	18	12
Control mean (range)	20.70 (15-28)	13.38 (7-23)
Nonword delayed repetition (max=40/condition)		
AT	24	20
WM	28	23
Control mean (range)	31.00 (24-36)	26.85 (20-34)
Nonword delayed recognition (max=24/condition)		
AT	23	20
WM	24	19
Control mean (range)	22.92 (18-24)	20.92 (17-23)

Note. For ISR, the results represent correct recall in correct serial position.

* $p < .05$ (modified t-test; Crawford & Garthwaite, 2002)

Table 8

Number of errors (proportion of errors below) for various error types for the SD patients and controls (mean and range) in Experiment 3

	Nonword ISR			Nonword delayed repetition		
Error types	AT	WM	Controls	AT	WM	Controls
Blend	10	10	8.85 (1-16)	5	8	4.85 (1-8)
	.31	.28	.29 (.14-.48)	.14	.30	.21 (.08-.33)
Phon. related nonword	12	12	10 (1-19)	14	12	10 (3-18)
	.38	.33	.36 (.07-.66)	.40	.44	.48 (.19-.69)
Unrelated nonword	4	13	5.46 (0-15)	1	6	2.39 (0-6)
	12	36	.18 (0-.39)	.03	.22	.13 (0-.25)
Word error	0	1	1.69 (0-6)	1	0	1.38 (0-3)
	0	.03	.06 (0-.14)	.03		.07 (0-.23)
Order	0	0	0.46 (0-4)	-	-	-
			.01 (0-.09)			
Omission	6	0	3.62 (0-17)	14*	1	1.62 (0-6)
	.19	0	.10 (0-.56)	.40*	.04	.11 (0-.23)

Note. See table 2a for a description of error types. * $p < .05$ (modified t-test; Crawford & Garthwaite, 2002)

Table 9

Numbers of errors and reaction times in word delayed probe recognition in Experiment 3

		Foil type		
	Targets (out of 36)	Phonolog. foils (out of 12)	Semantic foils (out of 12)	Unrelated foils (out of 12)
Number of errors				
AT	9*	2	0	0
WM	2	6*	1	0
Control mean (range)	2.18 (0-5)	2.09 (0-5)	0.73 (0-3)	0.18 (0-1)
Reaction time differences[1]				
AT	/	796	573*	/
WM	/	1497*	70	/
Control mean (range)	/	510 (104-843)	130 (-42-367)	/

Note. Errors to targets are incorrect “no” responses (misses) and errors to different types of foils are incorrect “yes” responses (false positives).

[1]Reaction time differences (msec) between phonological and unrelated foils as well as semantic and unrelated foils are presented, calculated on correct responses only.

* $p < .05$ (modified t-test; Crawford & Garthwaite, 2002)

Table 10

Proportion of items recalled, summed over the 6 learning trials, for the nonword learning task, and proportion correct recall for the Hebb learning task in Experiment 4

Tasks	AT	WM	Control mean (range)
HF nonword learning (max=30)	.40	.17*	.61 (.30-.80)
LF nonword learning (max=30)	.07*	.07*	.35 (.20-.57)
Hebb learning – random sequences	.71	.41	.58 (.36-.72)
Hebb learning – repeated sequences	.82	.83	.77 (.53-.85)

HF : high phonotactic frequency: LF : low phonotactic frequency

Table 11

Percentage of various error types for the SD patients in the nonword learning task in Experiment 4

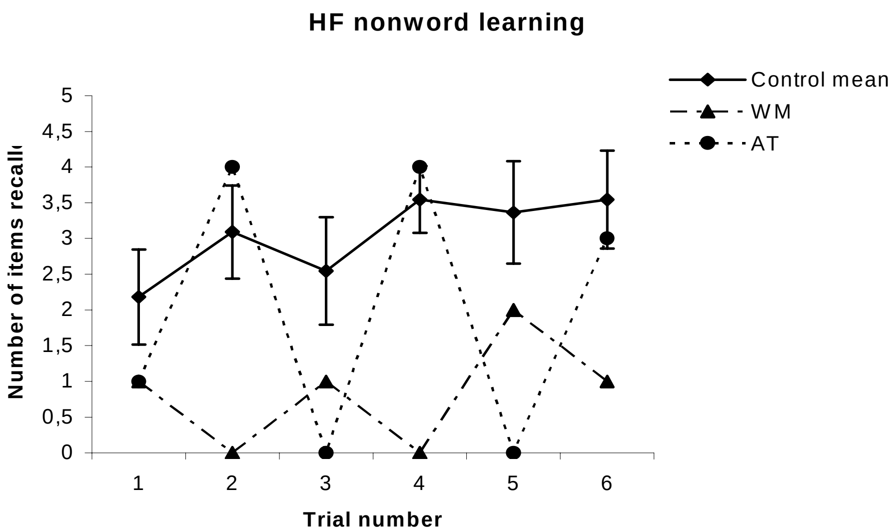
	HF and LF nonword		
Error types	AT	WM	Controls
Blend	9	25	10 (0-30)
	.20	.47	.32 (0-.63)
Phon. related nonword	8	7	6.63 (0-15)
	.18	.13	.21 (0-.37)
Unrelated nonword	8	7	1.9 (0-8)
	.18	.13	.06 (0-.19)
Word error	4	9	7.19 (0-12)
	.09*	.17	.25 (0-.35)
Omission	16*	5	4.72 (0-13)
	.35	.10	.17 (0-.53)

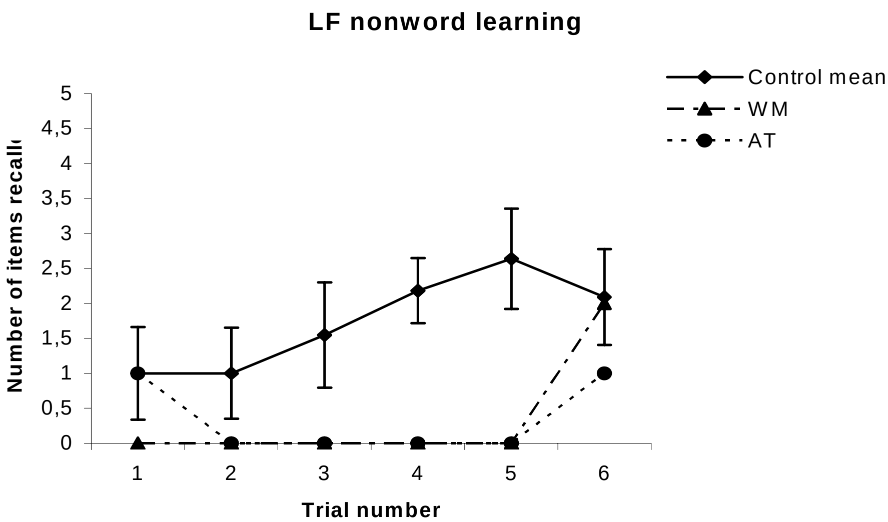
Note. See table 2a for a description of error types. * $p < .05$ (modified t-test; Crawford & Garthwaite, 2002). HF : high phonotactic frequency: LF : low phonotactic frequency

FIGURE LEGENDS

Figure 1. Learning curves for the nonword list learning tasks. HF : high phonotactic frequency: LF : low phonotactic frequency

Figure 1.


HF nonword learning
Control mean
WM
AT
Number of items recall
Trial number
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
5
1
2
3
4
5
6


LF nonword learning
Control mean
WM
AT
Number of items recall
Trial number
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
5
1
2
3
4
5
6