DISSOCIATING SHORT-TERM MEMORY AND LANGUAGE IMPAIRMENT: THE IMPORTANCE OF ITEM AND SERIAL ORDER INFORMATION

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ABSTRACT

BACKGROUND: Selective verbal short-term memory (STM) deficits are rare, and when they appear, they are often associated with a history of aphasia, raising doubts about the selectivity of these deficits. Recent models of STM consider that STM for item information depends upon activation of the language system, and hence item STM deficits should be associated with language impairment. By contrast, STM for order information is considered to recruit a specific system, distinct from the language system: this system could be impaired in patients with language-independent STM deficits.

AIM: We demonstrate here the power of the item-order distinction to separate STM and language impairments in two brain damaged cases with STM impairment and a history of aphasia.

METHODS & PROCEDURES: Recognition and recall STM tasks, maximizing STM for either item or order information were administered to patients MB and CG.

OUTCOMES & RESULTS: Patient MB showed mild phonological impairment. As predicted, associated STM deficits were characterized by poor item STM but preserved order STM. On the other hand, patient CG showed no residual language deficits. His STM deficit was characterized by poor order STM but perfectly preserved item STM.

CONCLUSIONS: This study presents the first double dissociation between item and order STM deficits, and demonstrates the necessity of this distinction for understanding and assessing STM impairment in patients with and without aphasia.

221 words

INTRODUCTION

Verbal short-term memory (STM) impairments are a very frequent characteristic of aphasic syndromes, and are among the most persistent deficits in patients with aphasia (e.g., N. Martin, Saffran & Dell, 1996; Majerus, Van der Linden, Poncelet & Metz-Lutz, 2004). However, despite extensive research, the nature of these deficits and their relation to the language processing impairments in these patients remain a matter of debate. An influential view is that verbal STM impairments reflect an independent deficit, in the sense that they are not caused by underlying deficits in language representations but rather that they reflect impairment to a specific verbal STM processing system (e.g., Hamilton & R. Martin, 2007; R. Martin, Lesch & Bartha, 1999; Saffran & Marin, 1975; Warrington, Logue & Pratt, 1971; Warrington & Shallice, 1969). Other authors however consider that verbal STM impairments are the consequence of underlying language processing impairments, based on the assumption that the language processing system is an integral part of the cognitive substrate of verbal STM (e.g., N. Martin & Saffran, 1992). We will briefly review the evidence supporting both of these positions. We will then introduce the distinction between STM for item information and STM for order information as a new means of investigating verbal STM deficits and their degree of dependency on language impairment.

The proposal that verbal STM impairments reflect independent deficits is theoretically driven by early modular accounts of verbal STM, considering that verbal STM capacity is defined by the capacity of a temporary buffer (e.g., the phonological store of the phonological loop model by Baddeley and Hitch, 1974), which is independent from language processing systems, and by the intervention of strategies such as articulatory rehearsal for preventing decay of representations stored in the temporary buffer. Although of a more interactive nature, R. Martin and colleagues also proposed a model containing two temporary buffers, one dedicated to the temporary storage of phonological information, and another one dedicated to the temporary storage of semantic information (R. Martin, Shelton & Yaffee, 1994; R. Martin et al., 1999). The main argument in favor of this position is the observation of a handful of patients that appear to show poor STM for phonological and/or semantic information, while apparently presenting no associated language impairment that could explain these deficits (e.g., Basso, Spinnler, Vallar & Zanobio, 1982; Majerus et al., 2004; R. Martin et al., 1994; Saffran & Marin, 1975; Vallar & Baddeley, 1984; Warrington et al., 1971; Warrington & Shallice, 1969).

On the other hand, psycholinguistic approaches of STM consider that temporary activation of long-term memory language representations is a fundamental part of STM (e.g., Baddeley, Gathercole & Papagno, 1998; R. Martin et al., 1999). The most extreme example of this position is probably the interactive spreading activation model proposed by N. Martin et al. (1996), considering that verbal STM does not exist as an independent system, but is merely the emergent property of activation and decay processes within the language network. In this framework, verbal STM impairments will result from structural damage to the language network, preventing activation of language representations and hence also their usage in verbal STM tasks, leading to both language processing and verbal STM deficits. Verbal STM impairments can also result from rapid decay of language activations; if the decay rate is severely abnormal (i.e., too fast), both verbal STM and language processing impairments will appear; if the decay rate is impaired more mildly, the duration of activation of language representations may still be sufficient for accurate performance in most single word processing tasks, but will be insufficient when representations have to be maintained over a longer time period, as is the case in verbal STM tasks and other multi-word language processing tasks. This position is supported by the fact that the vast majority of patients presenting “selective” verbal STM are in fact aphasic patients which have partly recovered from their single word processing difficulties but still present poor verbal STM (see Majerus, 2009, for a review). Majerus (2009) also showed for these patients a strong correlation between the severity of their verbal STM impairments and the severity of residual language impairment. N. Martin et al. (1996) further showed that single word processing impairments can re-appear or become more severe if a delay is inserted between stimulus input and response output. Hence, at least some patients with so-called selective STM deficits may in fact present residual language processing deficits, taking the form of an abnormally increased decay rate of activation in the language system. Further evidence for this psycholinguistic approach also stems from studies in healthy adults and children, showing that the richer and more easy-to-activate a linguistic representation of a word is, the greater the likelihood that this word will be correctly recalled in verbal STM tasks. Indeed, word frequency, lexicality and word imageability effects are consistently observed in immediate serial recall tasks (e.g., Gathercole, Frankish, Pickering & Peaker, 1999; Hulme, Maughan & Brown, 1991; Majerus et al., 2004; Walker & Hulme, 1999).

In the light of these contrasting but empirically difficult-to-distinguish theoretical positions, the present study introduces a distinction which is at the core of many more recent models of verbal STM. This is the distinction between STM for item information and STM for order information. STM for item information refers to the phonological, lexical and semantic characteristics of the items to be stored in a STM task. STM for order information refers to the serial order in which the items have been presented. Like psycholinguistic approaches of STM, recent models of STM consider that language activation is at the heart of verbal STM; however and critically, the intervention of language activation is restricted here to the temporary representation of item information (Burgess & Hitch, 1999, 2006; Gupta, 2003; Majerus & D’Argembeau, 2011). On the other hand, order information is represented by a specific serial order processing and maintenance system, connected to but distinct from the language system, although authors disagree on the precise mechanisms involved (Brown, Hulme & Preece, 2000; Burgess & Hitch, 1999; Gupta, 2003; Henson, 1998; Majerus & D'Argembeau, 2011). Some authors consider that order information is coded via temporal/context based mechanisms, where each item is associated to a different state of the temporal/context signal (Brown et al., 2000; Burgess & Hitch, 1999; Gupta, 2003). At recall, order information is retrieved by retrieving the temporal/context signals towards which each item was associated during encoding. Other authors consider that order information is encoded via spatial referents: Henson (1998) considers the existence of two markers, the start node marking the beginning of the STM list and the end node marking the end of the STM list. Early items will be marked maximally by the start node and minimally by the end node, and vice versa for items in later serial positions. Items from the middle of the list will be associated with medium level strength with both types of nodes. For these models, the standard serial position effects (primacy and recency effects) are thought to arise from the existence of more distinctive serial position codes for start-of-list and end-of-list items or enhanced inter-position interference for mid of list items. Furthermore, selective impairment for early or late serial positions may be possible if we assume that start nodes and end nodes can be damaged separately. In sum, in the light of these different models, language impairment should indeed lead to difficulties for STM, but this mainly for the maintenance of item information. At the same time, the theoretical existence of genuine 'selective' verbal STM deficits is possible but these deficits should be characterized by specific impairment at the level of STM for order information.

There is increasing empirical support for the proposed distinction between STM for item and STM for order information, and for the dependency of item information on the quality of the language network. Studies in healthy adults have shown that language knowledge reliably affects recall of item information but not order information: stimuli with richer lexical or semantic representations (e.g., high frequency words vs. low frequency words; concrete vs. abstract words) lead to higher recall performance in immediate serial recall tasks at the level of item information (as measured by item errors: omissions, paraphasias, intrusions) but not at the level of order information (as measured by order errors: transpositions of items within the list) (e.g., Majerus & D'Argembeau, 2011; Nairne & Kelley, 2004; Poirier & Saint-Aubin, 1995; Walker & Hulme, 1999). Functional neuroimaging studies have also shown that tasks maximizing STM for item information activate superior temporal, temporo-parietal and inferior temporal areas involved in phonological and semantic processing, relative to tasks maximizing STM for order information which involve fronto-parietal areas to a higher extent (Majerus et al., 2006a, 2010). Furthermore patients with semantic dementia, presenting a progressive loss of semantic representations, show preserved STM for order information, but impaired STM for item information, and this especially for semantic item information (Majerus, Norris & Patterson, 2007a). Finally, although no study has directly explored order and item STM in patients with deep dysphasia, these language-impaired patients also most probably present impaired item information processing capacities. Deep dysphasia is characterized by poor single word repetition with a strong sensitivity to lexical and semantic factors and severely reduced STM spans. Both language and STM deficits have been interpreted to stem from an abnormally increased decay rate at the level of phonological representations during input word processing tasks, leading to poor STM, severely impaired nonword repetition and poor word repetition, especially for low frequency and low imageability words. Given that phonological activation decays at an abnormally increased rate, patients will increasingly rely on the levels that remain somewhat activated at the moment of response selection, i.e. the last-to-be activated, semantic level, leading to an enhanced impact of semantic factors on both STM and single word processing tasks (N. Martin et al., 1996). This conjoined deficit in STM and language processing tasks is most probably characterized as stemming from impairment at the level of processing and maintaining phonological item information in the language network.

The aim of the present study was to demonstrate that, by adopting the distinction between STM for item information and STM for order information, STM deficits and language processing deficits can be deconfounded, and a clearer understanding of the nature of verbal STM impairments can be achieved. On the one hand, patients may present verbal STM impairments as a consequence of their associated language impairments: in that case, especially STM for item information should be impaired. On the other hand, if the verbal STM impairment results from deficits which are independent from language processing deficits, then especially difficulties at the level of storing order information in STM tasks should be observed. In the present study, we provide the first description of a double dissociation between STM for item information and STM for order information. We will show that patient MB presents a severe deficit for maintaining item information, in association with a language profile similar to deep dysphasia. The anomic patient CG on the other hand presents a ‘specific’ STM deficit characterized by preserved STM for item information but impaired STM for order information. In three experiments, we will establish the STM profiles for each patient. In a final experiment, we explore the wider consequences of item and order STM impairments, by assessing new word learning abilities in both patients. Recent studies indicate that order STM capacities are particularly strong predictors of new word learning performance, and some of the theoretical models discussed here propose that order STM allows for the sequential refreshing of the new string of phonemes to be learned, favoring the creation of robust and accurate long-term memory representations for the new word form (Gupta, 2003; Majerus et al., 2006b, 2008a). Hence patients with order STM impairment should also be impaired in new word learning tasks.

CASE DESCRIPTIONS

Patient MB

MB is a 46-year-old French-speaking right-handed man, who had worked as a metal worker. In June 2008, he suffered a cerebro-vascular accident; a CT scan indicated damage to the left temporo-parietal area; angio-MRI further indicated small nodular lesions in left and right parietal cortical and subcortical areas. His initial profile was most close to conduction aphasia, with important difficulties in repetition and many phonological approaches in spontaneous speech and object naming. As most patients with conduction aphasia, he also showed reduced STM spans.

In September 2009, at the start of this study, his language profile was further explored. At this time, MB showed no difficulties in object naming anymore, but speech rate was still impaired. Nonword repetition was also strongly impaired; repetition errors were characterized by phoneme substitutions (96% of errors); 4% of errors were phoneme inversion errors, where the serial positions of phonemes migrates within a nonword. Furthermore, MB showed an increased advantage for repeating nonwords containing high phonotactic frequency patterns, as compared to nonwords of low phonotactic frequency (see Table 1 for details of performance). Perceptual analysis, as assessed by a minimal pair discrimination task (e.g., baba vs. bada), was at the lower end of control performance for stimuli presented at normal speech rates (MB: .86; control range: .85-1.00); however, stimuli presented at accelerated speech rates, which put greater demands on rapid acoustic analysis, led to unambiguously normal performance levels (MB: .72; control range: .61–.95). On the other hand, when inserting a delay of 2000 ms between the two syllables to be judged, performance was clearly impaired, controls showing near-to-perfect performance on this task (MB: .89, control range:

.95-1.00). Semantic levels of processing were preserved as indicated by ceiling performance on a word definition task. At the level of STM performance, MB presented a weak digit span and significantly impaired performance in a word immediate serial recall task, for both item recall (items recalled, independently of serial position) and order recall (items recalled in correct serial position). Furthermore, MB showed an increased effect of word imageability in the immediate serial recall task, with an advantage of 15 items for item recall of high versus low imageability words, while this difference was on average 7 items in the control population (range: -4-12). Reading performance was normal, as well a performance on neuropsychological tasks testing sustained and selective attention capacities. In sum, patient MB showed a profile of impaired performance on phonological processing and verbal STM tasks, with increased semantic effects on STM tasks. Furthermore, perceptual tasks were characterized by weak performance for stimuli presented at standard speech rates, impaired performance when inserting a delay between the stimuli to-be-judged, but normal performance for stimuli presented at accelerated speech rates. This profile is in line with the predictions of a phonological decay impairment, phonological judgments being more difficult for stimuli that need to be maintained for a longer duration and hence are more subject to decay, and semantic effects being increased during maintenance of verbal information (for similar profiles, see also patient CB, Croot, Patterson & Hodges, 1999; patient NC, N. Martin & Saffran, 1992; patient BJ, Majerus, Van der Kaa, Renard, Van der Linden & Poncelet, 2005; patient CO, Majerus, Lekeu, Van der Linden & Salmon, 2001).

< INSERT TABLE 1 ABOUT HERE >

Patient CG

CG is a 66-year-old French-speaking right-handed man who had worked as a financial planner. He suffered a head injury in April 2009; a computerized tomography (CT) scan, made immediately after admission to hospital, showed damage to the anterior left temporal lobe as well as left hemispheric subarachnoid hemorrhage with a filling of the sylvian valley anteriorly. Initially, CG presented with word finding difficulties as well as impaired verbal STM spans.

At the time of this study, CG's main complaint related to difficulties to follow a conversation and to read for a long time. His performance on phonological and semantic processing tasks were at normal levels (see Table 1). In the nonword repetition tasks, most errors were phoneme substitutions (85%); the other 15% of errors were phoneme inversions which is a significantly higher proportion than in patient MB (χ^2=7.04, p<.01). Normal performance levels were also observed for speech rate. However, verbal STM performance remained poor. Forward digit span was at the minimum of control range. In the word immediate serial recall tasks, he showed performance in the control range for item recall measures, but performance was impaired when order recall was also taken into account. This was confirmed when directly comparing the item and the item+order recall measures: the performance decrement for order measures, relative to the item only measures, was 14 items for high imageability word lists (control mean: 12, range: 4-17) and 24 for low imageability lists (control mean: 15, range: 8-21). This indicates the possibility of increased difficulties for processing order information in STM in patient CG. In contrast to patient MB, CG showed normal word imageability effects in the immediate serial recall tasks (for the item recall measure[1]), a normal phonotactic frequency effect in nonword repetition and normal performance in all conditions of the minimal pair discrimination task. Finally, reading

[1] The decrease of performance for the item+order measure when comparing immediate serial recall for high and low imageability lists may further suggest an increased word imageability effect in this condition. On the other hand, this performance decrement may also result from the combined effect of maintaining the more difficult-to-process low imageability items and impaired serial order processing. The impact of word imageability on item and order STM will be more directly addressed in Experiment 2.

performance was normal, as well a performance on neuropsychological tasks testing sustained and selective attention capacities. In sum, patient CG showed mildly impaired verbal STM performance, and this mainly for measures challenging the maintenance of order information.

Control participants

For the probe recognition tasks in Experiment 1 and the closed pool immediate serial recall task in Experiment 2, each patient's performance was compared to that of a control group of healthy adults matched for age (Control group 1, N=10, age range: 59-65 years; Control group 2, N=10, age range: 45-55 years). For the open pool immediate serial recall task in Experiment 2 and the tasks in Experiments 3 and 4, which were collected at later time points of this study, each patient's performance was compared to that of a single control group of age-matched healthy adults (Control group 3, N=10, age range: 45-64 years). Like the patients, the controls were native French speakers and had been raised in a monolingual environment. They had been recruited from the general adult population of the urban and suburban area of the city of Liège. Participation to this study was subject to written informed consent by each participant.

EXPERIMENT 1 – ITEM AND ORDER PROBE RECOGNITION

The first experiment assessed item and order STM capacities in patients CG and MB by using serial order and item probe recognition tasks, allowing the assessment of STM capacities independently of productive language requirements. In the item probe recognition task, short word sequences (one item per second) were presented visually, followed by an item corresponding to one of the items in the list or differing from one of the items by a single grapheme/phoneme. Negative probes differing from the target by a minimal amount were used in order to increase retention demands at the item level. The structure of the serial order probe recognition task was identical to the item probe recognition task, except for the probe trials consisting of the presentation of two items of the memory list. The probe items were organized from left to right, and the participants had to decide whether the item on the left had occurred before the item on the right in the memory list. For positive and negative probe trials, items from adjacent serial positions were presented in order to probe memory for fine-grained serial order representations. Both tasks had been adapted from studies by Henson, Hartley, Burgess, Hitch and Flude (2003); Majerus, Poncelet, Van der Linden and Weekes (2008a) and Majerus et al. (2006a, 2010) which aimed at dissociating item and order retention processes in healthy adults. These tasks have been successfully used in previous studies to demonstrate dissociation between order and item STM capacities in a neurodevelopmental population suffering from a 22q11.2 microdeletion syndrome (Majerus, Van der Linden, Braissand & Eliez, 2007b). Finally, in fMRI neuroimaging studies, they have been shown to reliably distinguish between fronto-temporal networks involved in item STM and parieto-fronto-cerebellar networks involved in order STM (Majerus et al., 2006a, 2008b, 2010). In the present experiment, we explored whether patients CG and MB show a dissociation between performance on item and order probe recognition tasks.

Methods

Material

The STM lists were sampled from a pool of 30 pairs of words that differed by a single phoneme and by a single letter (e.g., charbon–chardon, masque–marque). This enabled us to increase the difficulty of the item STM conditions by constructing negative probes that differed only very minimally from the target word: negative probe trials consisted in the presentation of one member of the minimal pair in the memory list and the other member in the probe array. Mean lexical frequency was matched within the minimal word pairs: for the first and second words of the pairs, mean lexical frequency was 49.93 (range: 0.61–482.77) and 49.05 (range: 0.91–410.26), respectively (Lexique2 database, New, Pallier, Brysbaert & Ferrand, 2004). For the order condition, the probe trials always contained two adjacent words of the target stimulus list, but they were presented either in the same or the reversed order. For the different trials, the stimuli were pseudorandomly sampled from the stimulus set of 60 words with the restriction that the two words of a minimal pair could never occur together in the same trial, except for the negative probe trials in the item STM conditions where one word of the pair occurred in the target list and the other in the probe array. There were an equal number of positive and negative probe trials, probing equally all item positions.

Procedure

All conditions were presented on a mobile workstation running Matlab 6.1 and the Cogent toolbox (UCL, http://www.vislab.ucl.ac.uk/cogent.php) for stimulus presentation. Each STM trial consisted of the sequential, visual presentation of four words, a fixation cross and an array of two probe words (see Figure 1 for timing details). Participants indicated within 5000 ms if the probe words were matching or not the target information in the memory list, by pressing the “O” key for ‘yes’ responses or the “I” key for ‘no’ responses. In the order STM condition, the participants judged whether the probe word presented on the left of the screen had occurred before the probe word presented on the right, relative to the order of presentation of the two words in the memory list. In the item condition, the participants judged whether the probe word (presented twice in order to match the amount of information presented for item and order probe stimuli) matched one of the items in the memory list (see Figure 1). There were 40 trials in each condition. Before starting the experiment, there were 10 practice trials for familiarizing the participants with each of the STM tasks. The different STM conditions were presented in blocks.

< INSERT FIGURE 1 ABOUT HERE >

Statistical analyses

For each patient, performance on individual measures was compared to his respective control group, by using modified t-tests (Crawford, Garthwaite, Howell & Venneri, 2003). Modified t-tests give an inferential estimate of the distance between the score of a single case and the range of scores of the control group estimated at the population level. If p<.05, this signals individual performance significantly outside the control range (i.e., for $N_{controls} = 10$, this equals to performance at least 2 standard deviations below or above mean performance in the control group, for a two-tailed significance test). Furthermore, Z-scores were computed as an estimate of effect size.

Results and discussion

For response accuracy, patient MB showed severely impaired performance in the item probe recognition condition (Z-score = -5.00), and mildly impaired performance in the order probe recognition condition (Z-score = -2.17) (see Figure 2a for Z-scores and Table 2 for mean performance in controls and patients). Patient CG showed performance in the normal range for both probe recognition conditions. On the other hand, when considering response times, patient CG showed significantly slowed response times for the order probe recognition condition (Z=2.64) but not for the item probe recognition condition (Z= 1.05) (see Figure 2b for Z-scores and Table 2 for mean performance in controls and patients). Patient MB showed response times of a similar size to those of controls for both probe recognition conditions. In other words, patient MB was as fast as controls in responding in his task, but he made many more errors than controls, and this especially in the item condition.

< INSERT FIGURE 2 AND TABLE 2 ABOUT HERE >

The results reveal increased difficulties in the item STM condition for patient MB. Although he also showed weak performance in the order STM condition, it should be noted that the order probe STM task used here, while minimizing item STM processes, is not a perfectly pure order STM task given that items also have to be processed and stored to some extent. Although the order STM condition did not probe item information, if encoding and maintenance of items is impaired, order encoding processes operating on these items will also get disturbed. In other words, the retention of order information is conditional to the retention of item information. Hence, it is not surprising that given the severe item STM limitations in patient MB, his performance in the order probe recognition will also suffer to some extent. On the other hand, patient CG showed perfectly preserved performance in the item STM condition, for both accuracy and response times, but he showed selective difficulties in the order STM condition, as shown by his significantly impaired response times in this condition.

EXPERIMENT 2 – IMMEDIATE SERIAL RECALL

In Experiment 2, we assessed MB's and CG's profile on standard immediate serial recall tasks for word lists. In standard immediate serial recall tasks, item and order STM are distinguished by determining the rate of item errors (omissions, intrusions, paraphasias) and order errors (items recalled in an incorrect serial position) (e.g.: Poirier & Saint-Aubin, 1996; Nairne & Kelley, 2004). We determined the proportion of order errors relative to all items recalled. This score reflects a more direct measure of order STM since it takes into account differences in overall item recall performance, contrary to Experiment 1. Two types of immediate serial recall tasks were administered. A first task used a closed pool of items; this procedure is sensitive to order recall, but less sensitive to item recall given that the same items are repeatedly used (e.g., Romani, McAlpine, & R. Martin, 2008). A fixed length was used given that this task was part of a larger experiment exploring the impact of dual tasking on item and order recall (results not reported here); a length of 6 items was chosen in order to ensure a sufficient number of error rates, word spans being about 3 and 4 items in patients MB and CG, respectively, based on the performance on the preliminary immediate serial recall task reported in the background testing section). A second task used an open pool of items, increasing sensitivity for item recall measures, while remaining sensitive to order recall (e.g., Majerus, Poncelet, Elsen, & Van der Linden, 2006). This task also varied the degree of word imageability, by using high and low imageability word lists. Semantic knowledge underlying the word imageability effect has been shown to influence item recall to a higher extent than order recall (Nairne & Kelley, 2004; Romani et al., 2008). Hence, patient MB, considered to present a decay-based language impairment, should be particularly sensitive to semantic factors in this task, as already suggested by his performance on the immediate serial task reported in the background testing. The present task used lists of variable and increasing sequence length up to seven items in order to take into account potential differences in overall performance levels between both patients. Given the results of Experiment 1, in both immediate serial recall tasks used here, we predict a significantly increased rate of item errors in patient MB and a significantly increased rate of order errors in patient CG. Furthermore, for the second immediate serial recall task, patient MB should show an increased word imageability effect, and this particularly for item error rates.

Methods

Material

Closed lists - We selected a stimulus set of 11 two-syllable words. The words were selected to be concrete and of high frequency in order to avoid difficulties with stimulus identification in our patients. The words contained four or five phonemes, they were all nouns and word frequency ranged between 64 and 104 (New, Pallier, Ferrand & Matos, 2001). 6-word sequences were generated by randomly sampling from the stimulus set.

Open lists - Two sets of 108 words were constructed. The high and low imageability words had a rating of >4 and <3, respectively, relative to a rating scale ranging from 1 to 6

(Hogenraad & Orianne, 1981). Both sets were matched for word length and contained 1-, 2- and 3-syllable words; mean word length was 1.8 syllables in each list. Both sets were also matched for word frequency [t(214)=1.749, n.s.; Content, Mousty, & Radeau, 1990]. The words of each set were randomly assigned to lists ranging from 2 to 7 items, with four lists per sequence length.

Procedure

Closed lists - The stimuli were presented in sequences of 6 words in the center of the screen of a mobile workstation, each word being presented for 1250 ms. After the final word of each sequence, a question mark appeared, requiring the participants to recall all the words in their order of presentation. *Open lists* – The procedure was the same, except that the lists were presented auditorily in sequences of increasing length.

The participants' responses were recorded on digital disc for later transcription and scoring. For both tasks, we determined the proportion of order errors (an item is recalled in a wrong serial position) relative to the amount of items recalled, as well as the proportion of item errors (omissions, paraphasias, intrusions) relative to the total number of items to be recalled. Please note that for the closed list, the control groups were the same as those for the Experiments 1 and 2. For the open lists, collected at a later time of this study, the control group was the same as in Experiments 3 and 4 (for further details, see the Case description section).

Results and discussion

Closed lists - As shown in Table 3 and Figure 3, MB presented a higher proportion of item errors, as compared to controls, this difference being marginally significant. The proportion of order errors was within control range. CG presented no significantly different performance relative to controls in this analysis.

< INSERT FIGURE 3 AND TABLE 3 ABOUT HERE >

Next, we performed an analysis of serial position effects by calculating for each serial position, the proportion of items correctly recalled as well as the proportion of items recalled in correct serial position. Overall, this analysis (see Figure 4) showed for MB and CG a marked primacy effect and a mild or absent recency effect. We should note that the recency effect was however also reduced in controls. A reduced recency effect is often observed when stimuli are presented visually in immediate serial recall tasks (Watkins & Watkins, 1977; Tan & Ward, 2008). When considering performance on a position-by-position basis, patient MB showed significantly impaired performance for positions 5 and 6 ($Z = -3.98$ and $Z = -3.35$, respectively), and this only for the item recall measure, as expected from the previous analyses. However, in this more fine grained analysis, patient CG also showed significant impairment: recall performance for the final position was significantly reduced (position 6; $Z = -2.81$), and this specifically for the order recall measure. No final item was recalled in correct serial position, despite the fact that he recalled as many final items as controls. In other words, patient CG presented a mild recency effect for item recall, but the recency effect was reversed for order recall. This result further suggests that patient CG has restricted capacities for processing order information.

< INSERT FIGURE 4 ABOUT HERE >

Open lists – As shown in Table 4, patient MB showed an increased rate of item errors, and this most significantly for the low imageability word condition; the rate of order errors was very low. This time, a strong reverse effect of error type was also observed for patient CG: his proportion of item errors was in the normal range for both high and low imageability conditions, but the proportion of order errors was very highly increased in both conditions. Furthermore, when calculating the size of the imageability effect ($effect = \frac{\text{High Imageability} - \text{Low Imageability}}{High\ Imageability}$), only MB showed a significantly increased imageability effect, and this only for the proportion of item errors (see Table 4). Note that controls did not present a reliable imageability effect in this task; the imageability effect in immediate serial recall tasks in healthy adults has been shown to be among the weakest long-term memory effects on STM, relative to lexicality and word frequency effects, and large sample sizes are needed to document this effect in healthy controls (Majerus & Van der Linden, 2003).

< INSERT TABLE 4 ABOUT HERE >

As for the closed list task, we also analysed performance as a function of serial position. In order to increase the reliability of this analysis, serial positions were collapsed over the different trials and sequence lengths. As shown in Figure 6, MB's item recall performance was most significantly impaired for positions 3, 4 and 5 (Z=-4.27 for position 5 in the high imageability list; Z=-4.17, and Z=-3.53, for positions 3 and 4, respectively, in the low imageability list). On the other hand, MB's order recall performance was comparable to controls; note that no order recall measure was computed for position 7 in the high imageability list since MB did not recall any item from this position. When considering patient CG, the reverse was observed. CG showed perfectly preserved item recall performance for all serial positions, but order recall performance decreased sharply as a function of increasing serial position, with virtually no item recalled in correct position for final list positions, despite recalling as many items as controls (Z=-4.68 for position 6 in the high imageability list; Z=-4.46, Z=-3.35 and Z=-4.12, for positions 4, 6 and 7, respectively, in the low imageability list).

INSERT FIGURE 6 ABOUT HERE

The results from the present experiment provide evidence for a double dissociation between item recall and order recall performance, with patient MB showing a specific impairment for item recall performance and patient CG for order recall performance. This is particularly clear for the results obtained from the open list recall task, where lists of variable length were administered and hence provided a better potential for capturing and exploring atypical STM performance in patients showing at the start different individual levels of performance. In this task, patient CG presents perfectly preserved item recall, and this for any serial position, while order recall decreases very strongly as a function of increasing serial position. Furthermore, results from the open list recall experiment also provide more robust evidence for an item STM impairment in MB; this is most probably due to the increased sensitivity of open list immediate serial recall tasks to item STM processes (Romani et al., 2008). At the same time, we should acknowledge that the comparison of the results between closed and open lists has to be considered with caution given that open and closed lists were administered at different time points and further varied in presentation modality and list length. Finally, this experiment further documents the interdependency between language processing and STM processing in patient MB, by highlighting an increased influence of semantic factors on recall performance, and this most specifically for item recall performance.

EXPERIMENT 3 – SERIAL ORDER RECONSTRUCTION

Experiments 1 and 2 showed that patient CG has specific difficulties in processing order information in STM, these difficulties appearing mainly in positions in the second half of a STM list (Experiment 2). In order to further characterize order STM performance in patient CG, we administered a serial order reconstruction task using, as in the open list recall task of the previous experiments, lists of increasing length in order to gain a more complete picture of serial order processing limitations in this patient. This task assessed order STM in the purest possible manner, since the only type of errors that were possible to make were order errors. The serial order reconstruction task consisted of the presentation of lists up to 8 items. In order to maximize order recall and to reduce item processing requirements at its most minimal level, the participants knew in advance which items would be presented: for lists of length 4, the lists were sampled from the digits 1 to 4; for lists of length 5, the lists were sampled from the digits 1 to 5 and so on. Moreover, at the moment of recall, the digits, printed on cards, were given to the patient and he used the cards to arrange them according to the order of presentation of the digits. Hence, the only possible errors in this task were order errors, item information being available during all stages of the task, contrary to standard digit span tasks where both item and order information have to be maintained and retrieved. This task has been shown to reliably measure order STM with no ceiling effects in high performing adults (Majerus et al., 2008a).

Methods

Material

The serial order reconstruction task consisted of the auditory presentation of digit lists of increasing length. The lists, containing 3–8 digits, were sampled from digits 1 to 8. For list length 3, only the digits 1, 2, and 3 were used. For list length 4, only the digits 1, 2, 3, and 4 were used, and so on for other list lengths. The lists were recorded by a female voice and stored on computer disk, with a 500-ms inter-stimulus interval between each item in the list (mean item duration: 540 (±139) ms).

Procedure

The sequences were presented via high quality loudspeakers connected to a PC that controlled stimulus presentation by running E-Prime software (version 1.0, Psychology Software Tools). They were presented with increasing length, with six trials for each sequence length. At the end of each trial, the participants were given cards (size: 5 · 5 cm) on which the digits presented during the trial were printed in black font. The number of cards corresponded to the number of digits presented and were presented in numerical order to the participants. The participants were requested to arrange the cards on the desk horizontally following their order of presentation. For each list length, we determined the proportion of items correctly reconstructed.

Results and discussion

As expected, patient CG showed significantly impaired performance (see Table 5) in the serial order reconstruction task, performance dropping sharply from list length 6 onwards (length 5, Z = .00; length 6, Z= -3.55; length 7, Z= -2.5; length 8, Z= -4.44). This is in line with the accurate order recall performance up to serial position 5 observed during the closed list word immediate serial recall task in Experiment 2. In contrast, patient MB showed performance levels identical or higher to mean performance of the control group for all list lengths in this task.

< INSERT TABLE 5 ABOUT HERE >

As for Experiment 2, we performed an analysis of serial position effects by calculating for each serial position, the proportion of digits correctly reconstructed. This analysis was restricted to list lengths 6, 7 and 8, which showed the most variable performance in both patients and the control group; as shown in Table 5, patients and controls were close to or at ceiling performance for earlier list lengths in this task. Like in experiment 2, CG showed a marked primacy effect and an absent or negative recency effect, except for list length 6 where he also showed a recency effect (see Figure 7). As in Experiment 2, patient CG was impaired for the final positions in the longest lists: positions 5, 6 and 7 for list length 7 and positions 6, 7 and 8 for list length 8 (see Table 6 for Z-scores). Furthermore, for list length 6, in addition to end-of-list positions 4 and 5, impairment was also observed for positions 2 and 3. Patient MB on the other hand showed no impairment for any serial position.

< INSERT FIGURE 7 AND TABLE 6 ABOUT HERE >

Experiment 3 provides further robust evidence for important difficulties in STM for order in patient CG. Although the measures used in Experiment 1 and 2 to probe order STM provided good estimates of order STM processes, they were not pure order STM measures since also item information had to be processed. The task used in Experiment 3 was the purest with respect to order STM requirements since item information was available at all stages during the serial order reconstruction task, and the only information to be encoded and maintained was order information. In addition, the high performance levels for patient MB in Experiment 3 confirm very clearly that the STM deficit in this patient is restricted to item STM.

EXPERIMENT 4 –WORD-NONWORD AND WORD-WORD PAIRED ASSOCIATE LEARNING

A final experiment assessed the functional impact of an order STM deficit on other verbal tasks such as new word learning. A number of studies have shown that order STM is a critical ability not only for temporary storage of verbal sequences, but also for learning of new verbal sequences such as vocabulary in native and foreign language. Majerus, Poncelet, Greffe and Van der Linden (2006b) and Majerus, Heiligenstein, Gautherot, Poncelet and Van der Linden (2009) showed that order STM was a better predictor of vocabulary development in children aged 4 to 7 years than item STM. Mosse and Jarrold (2010) also observed a similar finding in children with Down syndrome. Finally, Majerus, Poncelet, Elsen and Van der Linden (2006c) and Majerus et al. (2008b) showed that order STM is a strong predictor of new word learning capacities in monolingual and bilingual adults. Some of the recent models of STM discussed in the Introduction assume that the temporary storage and reactivation of the ordered sequence of phonemes that defines a new word is fundamental for long-term learning of this new word form (e.g., Burgess & Hitch, 2006; Gupta & MacWhinney, 1997; Gupta, 2003). Gupta and MacWhinney have proposed that order information is stored in a specific sequence memory, which encodes the order in which new phonemes have been activated in the language system via vectors linking the phonemes in the language system and the serial positions of the sequence memory; by reactivating these vectors, the new phoneme sequence can be replayed, and repeated activation of the new phoneme sequence will lead to the creation of more stable phonological representations in the language network via Hebbian learning mechanisms. In other words, order STM is considered by these models to be a determining building block of new word learning. Hence, if order information cannot be encoded correctly anymore, as is the case for patient CG in this study, the replay and refreshment of newly presented phoneme sequences will lead to erroneous reactivation in the language system, and hence to impaired new word learning abilities.

In order to test new word learning capacities in patient CG, we administered word-nonword paired associate learning tasks. We also administered a word-word paired associate learning condition, in order to rule out the possibility of a general learning impairment in patient CG. We expected CG to show poor performance on learning of the word-nonword pairs. MB also participated in this experiment. Given his more basic impairments at the level of language processing, interpreted as reflecting an abnormally increased rate of decay of activation in the language network, we expect both word-word and word-nonword paired associate learning to be impaired: the excessive decay of activations in the language network will prevent extended co-activation of the representations for the two items of a pair and, hence, will slow down learning of both the items and their associations. Four word-nonword learning pairs were administered and we were interested in rapid learning rates over five learning trials. Although one may consider that learning four word-nonword pairs is at the frontier between STM and long-term memory, we should note that nonword span for the type of stimuli used here (bisyllabic stimuli with complex syllable structures) typically is about two items, and hence even if the first recall attempt probably reflects read out from STM, the increment of recall performance over the five trials reflects the gradual learning of new phonological representations.

Methods

Material

Bisyllabic and phonologically dissimilar nonwords were constructed, based on the diphone frequency lists of French by Tubach and Boë (1990). The nonwords contained diphones that are frequent in French phonology. The following stimuli were constructed: /divfak/, /ʒɛzkɔl/, /kɪksɛ̃s/, /mastɑ̃s/; mean diphone frequency was 1005 (range: 192-2180). Each nonword was randomly paired with bisyllabic, familiar words: “médecine” (medicine), “beau-frère” (brother-in-law), “machine” (machine), “donner” (to give).

For the word-word paired associate control learning condition, four target words of identical syllabic structure as the nonwords were selected. They were: “dispute” (quarrel), “déclic” (trigger), “microbe” (germ), “lecture” (reading). They were paired to the following cue words: “déplaire” (to not like), “tartine” (piece of bread and butter), “chambre” (room), “chercher” (search).

Procedure

For each learning condition, the four pairs were presented orally by the experimenter. After the presentation of the four word-nonword/word pairs, the experimenter successively read aloud each of the four cue words in random order. After each cue-word, the participant was requested to recall the corresponding nonword/word. No feedback was given. Then the complete list of word-nonword/word pairs was presented again but in a different order, followed by a new cued recall session. This procedure was repeated five times. An entirely correct response was assigned one point. Responses where only one of the two CVC syllables was correctly recalled were credited half a point. The final score represented the total number of points for the five cued recall trials divided by the maximum possible score (=20). There was a break of 30 minutes between each learning conditions. The order of the different learning conditions was randomized between participants.

Results and discussion

Patient CG showed significantly impaired performance in the word-nonword paired associate learning condition ($p<.05$, $Z= -3.29$) (see Figure 7). However, he showed perfect performance in the word-word learning condition ($Z= 0.13$). On the other hand, patient MB was impaired in both learning conditions (word-nonword, $p<.05$, $Z= -3.09$ and word-word, $p<.05$, $Z= -4.8$). The learning curves for control participants showed monotonically increasing functions (see Figure 7). This was only observed in CG for the word-word paired associate learning condition. In the other condition, the learning curve was flat, with little evidence of learning between the first and the fifth learning trial. Some evidence of learning was observed for patient MB in both conditions, with performance on the fifth trial being higher than performance on the first trial, even if performance on the fifth trial remained significantly below control performance. With respect to errors produced during learning (by excluding omission errors which were the most frequent error type in both patients), MB produced one phonological paraphasia and one semantic paraphasia as well as four incorrect pairings (a correct target is recalled for the wrong cue word) in the word-word paired associate learning condition; CG only presented omission errors in this condition. For the word-nonword paired associate learning condition (by disregarding again omission errors), MB produced 7 phoneme substitution errors (e.g., /ʒeʀkɔl/ for / ʒezkɔl/), which is in agreement with his mild phonological impairment. Although CG also produced phoneme substitution errors (n=3), his most frequent error type after omissions were phoneme inversion errors (n=4), where the serial position of phonemes migrate within a target nonword (e.g., /di**sk**ɛ̃s/ for / ki**ks**ɛ̃s/). In controls, the most frequent errors types, after omissions were wrong pairings (N=1.7, SD=1.10) in the word-word learning task, and phoneme substitutions in the word-nonword learning task (N=1.5,SD=0.8). Phoneme inversions were observed in only three control participants, with a maximum of 2 inversion errors.

< INSERT FIGURE 8 ABOUT HERE >

GENERAL DISCUSSION

The aim of this study was to demonstrate the importance of distinguishing between item STM and order STM processes for understanding verbal STM deficits in brain injured patients and their relation to language impairment. In the light of recent models of STM, we considered that STM impairments can affect selectively item retention and order retention capacities; furthermore, item retention capacities should be closely related to the level of integrity of the language processing network, while order retention capacities should reflect a language-independent capacity. In the first three experiments, we obtained evidence for a double dissociation between item STM and order STM deficits. Patient MB showed impaired performance on item recognition and item recall while order recall was perfectly preserved; patient MB also showed associated deficits at the level of phonological processing and an increased impact of semantic variables on STM performance, and this especially for item recall. Patient CG showed preserved item recognition and item recall, but order recall was impaired, and this mainly for positions towards the end of the STM lists; patient CG, although initially language impaired, presented no residual language processing deficits at the time of this study. Finally, a fourth experiment documented impaired new word learning capacity in both patients CG and MB.

The nature of item STM impairments

In order to understand the nature of MB's item STM impairment, we first have to consider the nature of his residual language impairment. As presented in the Case description, MB showed a language profile very similar to other patients that have been considered to present a decay impairment of language activation. These patients are considered to correctly activate language representations, but the activations decay at a very fast rate. In repetition tasks, this will lead to a reduced impact of phonological variables and an enhanced influence of semantic variables since the phonological representations, activated first, will have decayed to a much higher extent than semantic representations at the moment of response selection and production. Patient MB showed indeed an abnormal phonotactic frequency effects in nonword repetition and enhanced imageability effects in word immediate serial recall tasks. Furthermore, he showed weak performance in discrimination tasks for stimuli with a longer acoustic duration and hence with a greater sensitivity for decay, while performance for acoustically accelerated stimuli was closer to control levels of performance.

According to the interactive spreading activation model by N. Martin et al. (1996), patient MB thus shows a deficit at the level of maintenance of activation in the language network. This deficit should automatically lead to impairment in verbal STM tasks which require maintenance over even longer durations than single word language processing tasks. This is indeed the case in patient MB. Importantly, the present study shows that this STM deficit is nevertheless restricted to the maintenance of item information. STM for order information is preserved, showing that language-based models of STM only account for item maintenance. Given that the capacity for processing order information is preserved, which is most clearly shown by MB's excellent performance on the serial order reconstruction task in Experiment 3 and normal range proportions of order errors in Experiment 2, the present data further support recent STM models which assume the existence of a distinct, specialized system dedicated to the processing and storage of order information (Burgess & Hitch, 1999, 2006; Brown et al., 2000; Gupta, 2003; Majerus & D'Argembeau, 2011).

MB also illustrates only one specific type of item STM impairment, where both STM and language impairment originate from abnormally increased decay rates in the language network. As such, MB is very similar to other STM patients with associated decay-based language impairment (patient CB, Croot, Patterson & Hodges, 1999; patient NC, N. Martin et al., 1996; patient BJ, Majerus et al., 2005; patient CO, Majerus et al., 2001). MB shows also a performance profile close to patient IR presented by Belleville, Caza and Peretz (2003). This patient also presented a mild phonological impairment, accompanied by a reduced impact of phonological variables but an enhanced influence of lexico-semantic factors on both STM and LTM, as well as poor word-nonword paired associate learning. Although the distinction between item and order was not explicitly addressed in patient IR, most experiments manipulated factors that targeted item processing, suggesting that his deficit at least involved STM for phonological item information, although it may not have been restricted to item STM. In addition, as noted in the Introduction, item STM will also be impaired in the case of structural damage to language representations. If language representations cannot be activated anymore due to loss or severe degradation, items cannot be processed anymore in both language and STM tasks. This has been documented in patients presenting progressive loss of semantic representations: these patients present severely impaired item recall for items with semantic content such as word list recall; furthermore, like patient MB, these patients can present perfectly preserved order recall in STM tasks (Majerus et al., 2007a). In sum, like some previously published cases of verbal STM impairment, MB illustrates the interdependency between STM and language impairment. Importantly, MB's profile clearly demonstrates that this interdependency only accounts for STM impairments at the level of maintaining item information.

Finally, it may seem surprising that patient MB presented also an important deficit for word-word paired associate learning. Given his enhanced reliance on lexico-semantic factors, one may argue that he could have linked the meanings of the words to be learned and hence achieved better learning performance than he did. However, the word-word pair associations were specifically chosen not to facilitate semantic bindings, in the sense that semantic bindings between target and cue words within pairs were as likely as between pairs. Hence the exact word forms had to be encoded, associated and maintained, which is more difficult in a language system where phonological representations decay rapidly, as we already detailed in the introduction section of Experiment 4.

The nature of order STM impairments

The most novel finding of this study is the first documentation of a case with a specific order STM impairment, patient CG. Before discussing the nature of CG's order STM deficit, we first have to rule out a number of alternative accounts of his STM profile. Given that CG's deficit was most consistently observed for positions towards the end of the STM lists, with a dramatic absence of recency effects, the question arises whether slowed articulatory rehearsal could have accounted for his profile. If articulatory rehearsal is slowed, items and positions cannot be refreshed efficiently, and this most strongly for the items occurring in final positions, where there is less time for rehearsal given the closeness to the recall stage. However, in that case, performance should have been impaired in end-of-list positions for recall of both order and item information : rehearsal allows for refreshing of both item and order information and blocking of articulatory rehearsal has been shown to affect both item and order recall, the effect of blocking not being reliably stronger for order recall (e.g., Baddeley, 1986; Henson et al., 2003). For patient CG the deficit was not only restricted to recall of order information, but recall of item information in final positions was at the same level as performance in control participants. Hence CG recalled item information as well as controls, across all serial positions, but he had specific difficulties in recalling end-of-list items in correct serial position. Finally, data from background testing clearly show that patient CG did not present slowed rehearsal rates, given his normal speech rate for repeating word pairs. On the other hand, patient MB showed a slowed speech rate, and yet he had no difficulties at the level of recall of order information.

Then, what is the nature of CG's order STM impairment? Why did he not present a generally increased rate of transposition errors, across all serial positions, as one may intuitively expect in a case of impaired STM for order? To understand CG's profile, we have to consider the predictions of STM models of serial order. A straightforward explanation can be derived from the start-end model proposed by Henson (1998). This model considers that order information is encoded relative to two markers: the start node, marking the start of the list, and the end node, marking the end of the list. Items in all serial positions will be associated to both nodes, but with different weights. The connection between the start node and the first item will be maximal, second-highest for the second item, and so on, with no or very minimal weight for final items, especially if there are many items in the list. The reverse will be true for connections with the end node: the weight of the connection with the final item will be maximal, second highest for the penultimate item, and so forth. Patient CG's profile corresponds to what would be predicted if the start node is functional but the end node is impaired or absent. In that case, order information for initial items can still be correctly processed, due to strong, decreasing and hence distinctive weights for items in the initial portion of the STM list. However, order information for final items will be severely impaired given that there will be no connection with the absent end node, and connection weights relative to the start node will be very minimal, or even zero for the final item in longer list. Hence, the likelihood of order errors should be highest for the most final items, and the likelihood of order errors in these positions should further increase with list length, as is the case in patient CG. If there are only three items in a list, all three items will have distinct connections with the start node; although the final item in these lists will have a lesser connection weight than the initial item, the connection weight will be far from zero given the reduced number of positions to be encoded, and hence the weight will be sufficient for correct order encoding and recall (this explanation is very similar to the primacy gradient account of serial order proposed by Page and Norris, 1996).

Other models of order STM consider that order information is coded via a moving context signal (Burgess & Hitch, 1999) or a moving temporal signal (oscillator; Brown et al., 2000), each item being connected to a different state of this signal as list presentation moves forward. Although CG's particular pattern of performance is more difficult to explain within these models, one could assume that the moving context or temporal signals are of limited capacity and, in case of impairment, stop working prematurely, before all items of a list have been encoded; in that case, initial positions and order information within short lists may still be represented accurately, but this will not be possible for end-of-list positions and order information for longer lists. An alternative possibility is that the processes associating items to moving context/temporal signals are functional, but they are slowed, leading to slowed encoding of order information as well as to slowed retrieval of order information. In this case, at the time of recall, items from initial STM list portions may have been associated to their context/temporal signal, but not yet the items from later STM list positions, leading to poor recall of order information for items in later list positions. This interpretation of a slowing of order processing is further supported by CG's response times which were specifically slowed for order recognition but not item recognition in Experiment 1.

An additional important issue is the relation of patient CG to other patients with selective verbal STM deficits, such as patient IL (Saffran & Marin, 1975) or patient PV (Basso et al., 1982). Is patient CG an atypical patient or is he representative of these other patients? In line with the theoretical framework adopted in this study, all patients with isolated verbal STM deficits which cannot be linked to underlying language impairment (e.g., excessive decay or structural damage) and item STM deficits, should present deficits for the retention of order information since maintenance of order information is the other core STM process, after temporary language activation. Given that STM for item and order information has been typically confounded in these studies, it is difficult to answer this question. However, there are at least two striking similarities between patient CG and other published cases of selective verbal STM impairment. First, most, if not all patients with selective STM impairment show serial position curves characterized by reduced or absent recency effects, just like patient CG (patient IL, Saffran & Marin, 1975; patient PV, Basso et al., 1982; cases 1, 2 and 3, Warrington et al., 1971). At the same time, it is difficult to interpret these findings since item and order recall were typically confounded, and hence it is difficult to know whether the reduced or absent recency effects characterize item recall, order recall or both. For example, impaired item recall processes, such as pathological phonological decay could also lead to absent recency effects, by considering that especially items from recency positions are supported by phonological activation while items from primacy positions are supported to a larger extent by semantic activation (e.g., Martin & Saffran, 1997). On the other hand, in the present study, we clearly show that patient CG presents reduced recency effects exclusively for order recall, but not for item recall. Second, like other STM patients, CG is dramatically impaired in learning new word forms (e.g., patient PV); we should however note that new word learning difficulties in these other patients could have resulted from other deficits like associated phonological impairment. Hence, relative to these two core characteristics of patients with selective STM deficits, we argue that patient CG presents a profile close to other patients with selective STM impairment although this does not directly imply that these other patients also presented selective order STM impairment.

Conclusion

Although dissociations between STM for order and STM for item information have been reported before (Majerus et al., 2007a; Majerus, Metz-Lutz, Van der Kaa, Van der Linden & Poncelet, 2007c), the present study is the first to document a double dissociation between these two STM capacities. On the one hand, the association between item STM and language impairment in patient MB supports 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). On the other hand, the dissociation between impaired item STM and preserved order STM in MB, and the reverse dissociation in patient CG support recent STM models which distinguish order STM systems from language-based item STM processes (Brown et al., 2000; Burgess & Hitch, 1999; Gupta, 1999; Majerus & D'Argembeau, 2011). Future research has to determine to what extent order STM deficits are the core impairment in most patients with selective, language-independent verbal STM deficits. Future research also has to consider how these deficits can be rehabilitated.

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Table 1. Performance on short-term memory and language background.

		MB	CG	*Controls*
Verbal STM tasks	Digit span			
	Direct order	**4**	**4**	*4-7* [a]
	Indirect order	3	3	*3-6* [a]
	Speech rate (ms) [1]	**930**	640	*450-770* [b]
	Immediate serial recall [2]			
	High imageability word lists			
	Items recalled	**73**	88	*81-101* [c]
	Items recalled in correct position	**64**	**74**	*75-87* [c]
	Low imageability word lists			
	Items recalled	**58**	82	*74-101* [c]
	Items recalled in correct position	**47**	**58**	*65-85* [c]
Language tasks	Minimal pair discrimination [3] (accuracy) :			
	Standard speech rate	.86	.93	*.85-1.00* [d]
	Accelerated speech rate	.72	.83	*.61–.95* [d]
	Intra-stimulus delay	**.89**		*.95-1.0* [b]
	Non-word repetition [4] (accuracy) :			
	High phonotactic frequency	**.40**	.72	*.67-.95* [e]
	Low phonotactic frequency	**.27**	.67	*.67-.97* [e]
	Picture naming [5] (accuracy)	.94	.95	*.89 – 1.00* [f]
	Word definition [6] (accuracy)	1.00	1.00	*.97 – 1.00* [a]
	Word reading [7] (accuracy)	1.00	1.00	.99 - 1.00 [b]
Neuropsychological tasks	Trail Making Test [8]			
	Part A (ms)	/	63	*30-74*
	Part B (flexibility - ms)	/	137	*71-185*
	Flexibility [9] (accuracy- percentile)	34	/	
	Phasic Alertness [9]			

	(accuracy – percentile)	50	42
	Go – nogo [9] (accuracy - percentile)	96	

(1) Speech rate : this task assessed articulatory rehearsal speed by presenting two monosyllabic French words (‘banc’, ‘main’) to be repeated 5 times as fast as possible; the score represents the mean time taken to repeat the two words (by dividing the total time by 5)

(2) Lists of increasing length (2-7 items; 4 lists per length); maximum score: 108 items; task adapted from Majerus & Van der Linden (2003).

(3) Minimal pair discrimination for nonsense syllables differing by a single consonant (e.g. [bada]) and presented at standard or accelerated speech rates, or having a delay of 2000 ms inserted between the two syllables to be judged.

(4) Non-word repetition for nonwords with high or low phonotactic frequency patterns, all nonwords having a CVCCVC structure (e.g., /kubtal/ vs. /ʃubmyf/ ; /60 items per condition); task from Majerus et al. (2004).

(5) Standardized picture naming task from Bachy (1987); this test contains a total of 90 objects, the target names varying in word frequency (high, medium or low frequency) and word length (1 syllable, 2 syllables, 3 syllables).

(6) Standardized word definition task adapted from the Protocole Montréal-Toulouse d’examen linguistique de l’aphasie (Nespoulous, Joanette, Lecours, 1992). 18 words are presented auditorily and the patient has to produce a synonym word and produce a short definition. The target words vary in lexical frequency (high, medium, low) and syllable length (1 syllable, 2 syllables, 3 syllables).

(7) Word and nonword reading task, the stimuli differing in the number of syllables; the words further varied as a function of orthographic regularity. Total number of stimuli: N = 60.

(8) Trail Making Test (Soukup, Ingram, Grady & Schiess, 1998) – standardized norms

(9) TAP – Test zur Prüfung der Aufmerksamkeit (Zimmermann & Fimm, 2009) – standardized norms

[a] N = 20, age range 45-65, [b] N = 10, age range 45-65, [c] N = 20, age range 50-70, [d] N = 45, age range 45-65, [e] N = 12, age range 55-65, [f] N = 60, age range 40-65

Boldface type: patient scores ≤ 2 standard deviations below control mean

Table 2. Performance on the item and order probe recognition tasks (Experiment 1).

		MB	*Controls*	CG	*Controls*
Item					
	Accuracy	.67*	*.87 (.04)*	.82	*.85 (.05)*
	Response time (ms)	2037	*1922 (477)*	2143	*1875 (255)*
Order					
	Accuracy	.70 (*)	*.83 (.06)*	.82	*.88 (.07)*
	Response time (ms)	2288	*2599 (464)*	3325*	*2676 (246)*

* $p < .05$, (*) $p = .068$, modified t-test (Crawford et al., 2003)

Table 3. Error proportions in the closed list immediate serial recall task (Experiment 2).

	MB	*Controls*	CG	*Controls*
Item errors	.48(*)	*.25 (.11)*	.26	*.33 (.08)*
Order errors	.29	*.37 (.15)*	.42	*.49 (.15)*

(*) p = .077, modified t-test (Crawford et al., 2003)

Table 4. Error proportions in the open list immediate serial recall task (Experiment 2).

	MB	CG	*Controls*
Error proportions			
High imageability			
Item	.32 (*)	.19	*.20 (.06)*
Order	.03	.21 ***	*.07 (.02)*
Low imageability			
Item	.40 ***	.24	*.19 (.04)*
Order	.03	.23 **	*.06 (.04)*
Imageability effect size			
Item	.12 *	.06	*-0.01 (.05)*
Order	.04	.03	*.01(.06)*

******* $p < .001$, ****** $p < .005$, ***** $p < .05$

(*) $p = .088$, modified t-test (Crawford et al., 2003)

Table 5. Order error proportions as a function of list length in the serial order reconstruction task (Experiment 3).

	MB	CG	*Controls*
List length			
3	0	0	*1 (0)*
4	0	0	*1 (0)*
5	0	.07	*.06 (.06)*
6	0	.36*	*.09 (.06)*
7	.05	.60*	*.15 (.10)*
8	.15	.56*	*.29 (.11)*

* p < .05, modified t-test (Crawford et al., 2003)

Table 6. Patient Z-scores for the serial position analysis of the serial order reconstruction task, as a function of list length and serial position (Experiment 3).

		Serial position							
		1	2	3	4	5	6	7	8
	List length								
MB	6	0.00	.47	0.71	1.39	1.22	0.00		
	7	0.47	0.00	0.22	1.20	1.45	0.61	0.32	
	8	-0.46	0.32	1.13	1.84	1.05	0.87	0.87	-1.90
CG	6	0.00	-4.27	-2.85	-2.31	-2.45	0.00		
	7	0.47	0.00	-1.27	-2.33	-3.73	-3.95	-15.5	
	8	-0.46	-0.32	0.00	-0.56	-1.05	-2.6	-2.6	-11.4

FIGURE LEGENDS

Figure 1. Schematic drawing of task design for the item and order probe recognition task in Experiment 1 (a negative probe is shown for each condition).

Figure 2. Patient Z-scores for recognition accuracy (a) and response times (b) in the item and order probe recognition task (Experiment 1).

Figure 3. Patient Z-scores for error proportions in the closed list immediate serial recall task (Experiment 2).

Figure 4. Item and order recall accuracy as a function of serial position in the closed list immediate serial recall task (Experiment 2). (a) Patient MB (b) Patient CG. * $p < .05$, modified t-test (Crawford et al., 2003).

Figure 5. Patient Z-scores for error proportions in the open list immediate serial recall task (Experiment 2).

Figure 6. Item and order recall accuracy as a function of serial position in the open list immediate serial recall task (Experiment 2). (a) High imageability (b) Low imageability. * $p < .05$, modified t-test (Crawford et al., 2003).

Figure 7. Patient Z-scores for recall accuracy as a function of serial position and list length in the serial order reconstruction task (Experiment 3). * $p < .05$, $^{(*)}$ $p = .05$, modified t-test (Crawford et al., 2003).

Figure 8. Learning curves for the word-word and word-nonword paired associate learning conditions (Experiment 4). * $p < .05$, modified t-test (Crawford et al., 2003).

Figure 1.

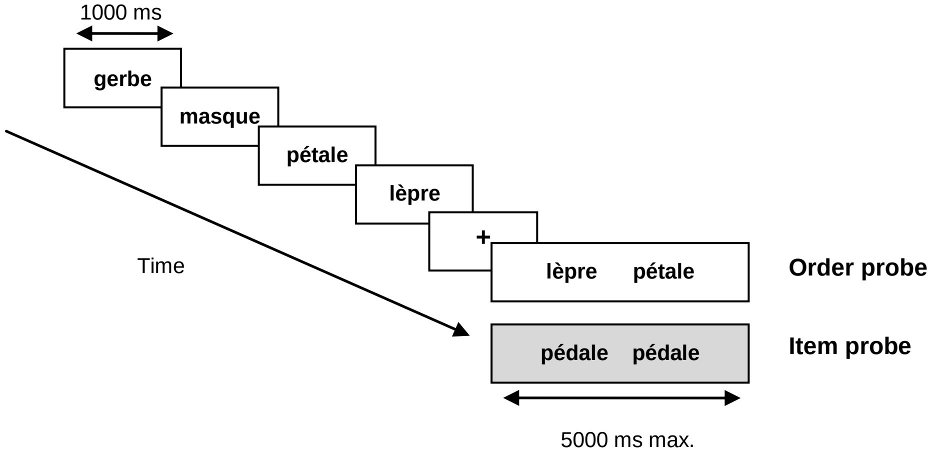
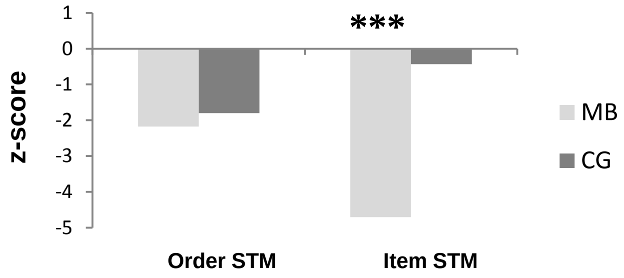

1000 ms
gerbe
masque
pétale
lèpre
+
lèpre pétale
Order probe
pédale pédale
Item probe
Time
5000 ms max.

Figure 2.

(a) **Accuracy**



(b) **Response time**

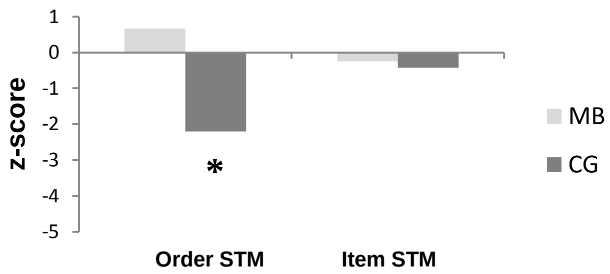


Figure 3.

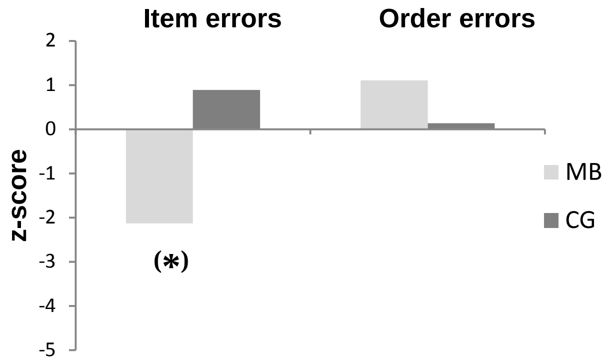


Figure 4.

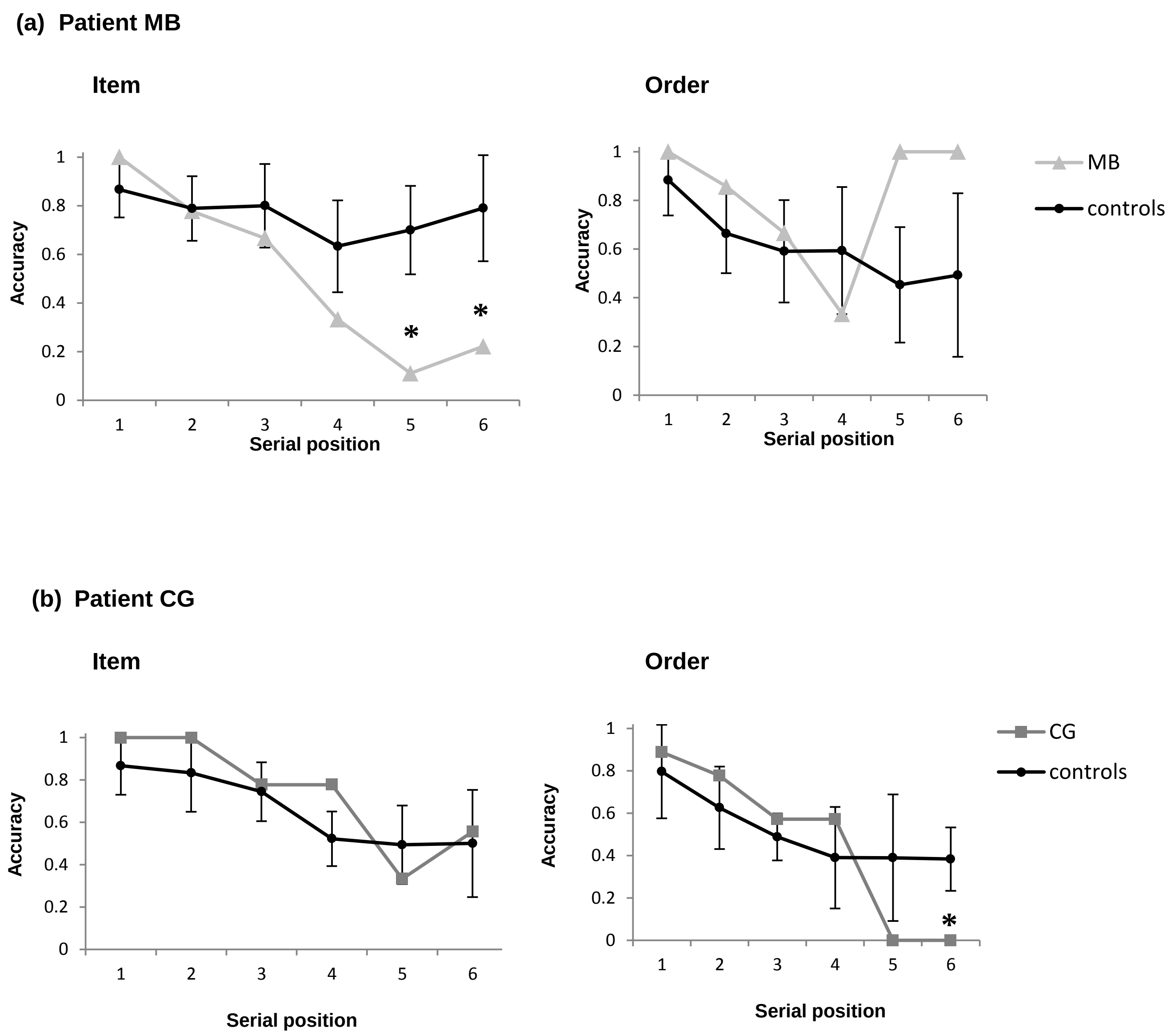

(a) Patient MB
Item
Order
Accuracy
Serial position
1
0.8
0.6
0.4
0.2
0
1 2 3 4 5 6
*
*
MB
controls
(b) Patient CG
Item
Order
Accuracy
Serial position
*
CG
controls

Figure 5.

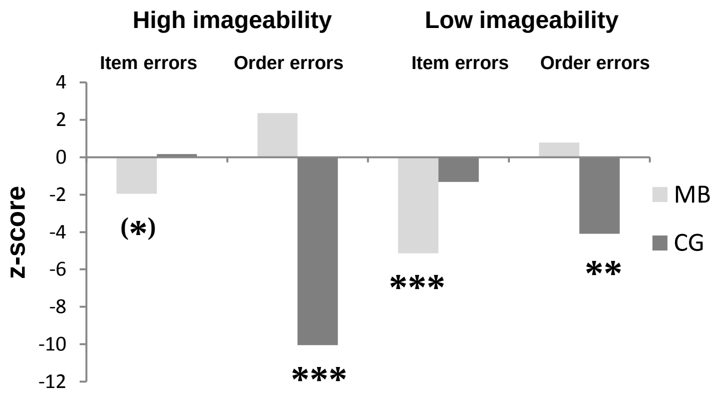

High imageability
Low imageability
Item errors
Order errors
Item errors
Order errors
4
2
0
-2
-4
-6
-8
-10
-12
z-score
(*)
***
***
**
MB
CG

Figure 6

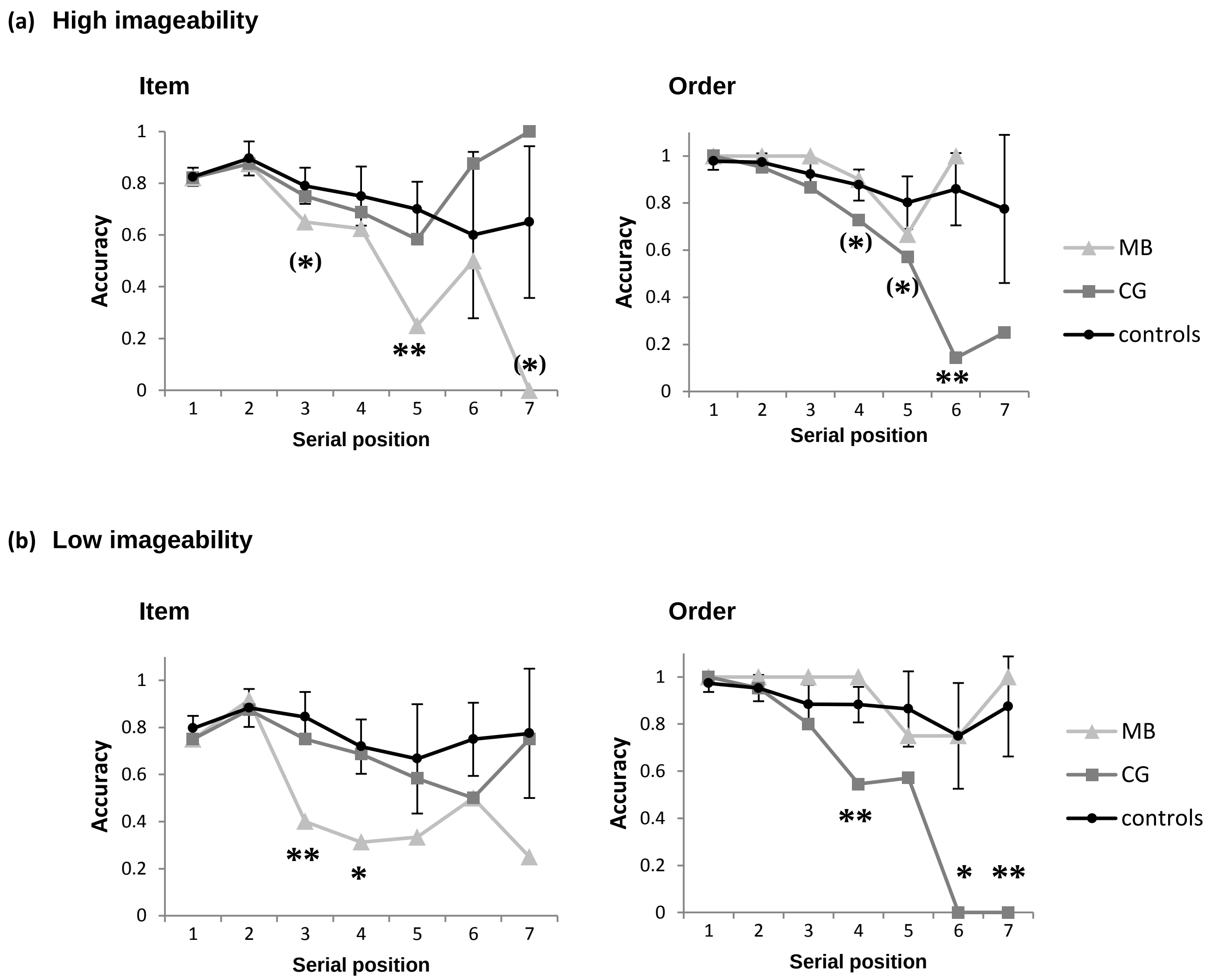

(a) High imageability
Item
Order
Accuracy
Serial position
(*)
**
(*)
(*)
(*)
**
MB
CG
controls
(b) Low imageability
Item
Order
Accuracy
Serial position
**
*
**
*
**
MB
CG
controls

Figure 7.

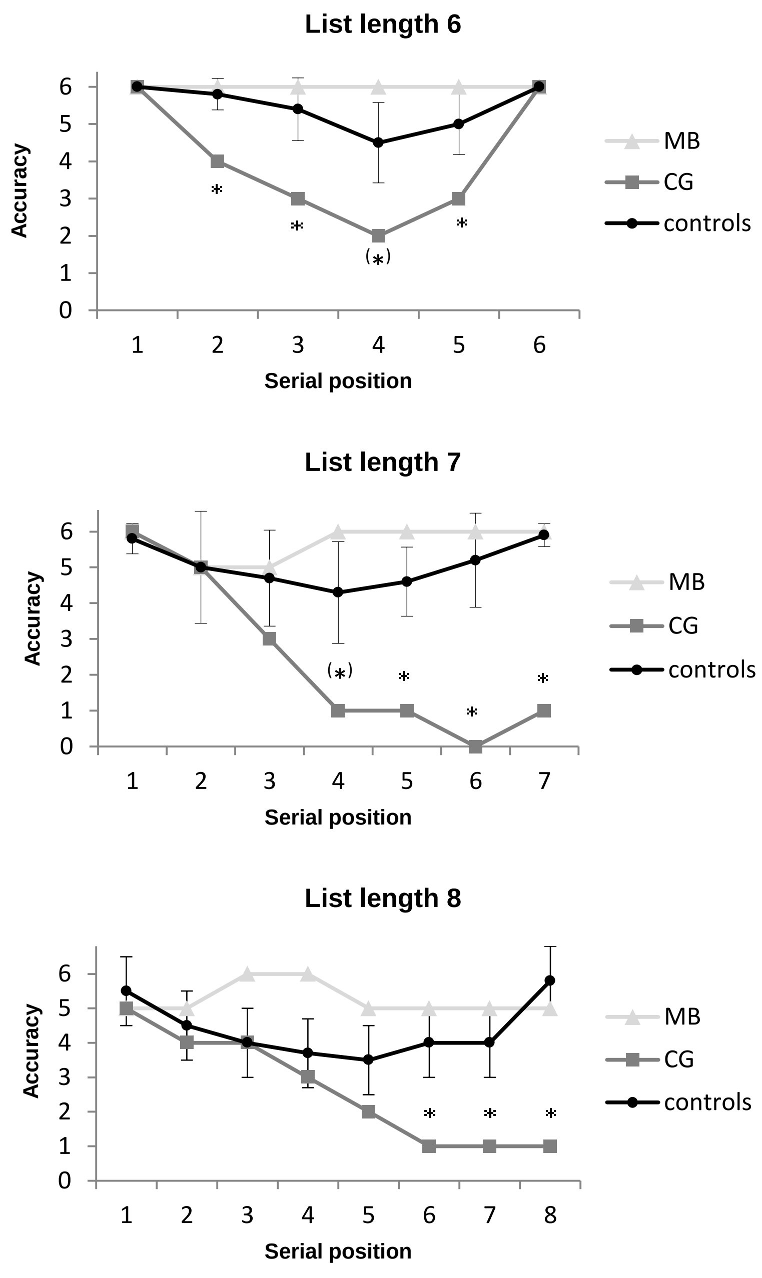
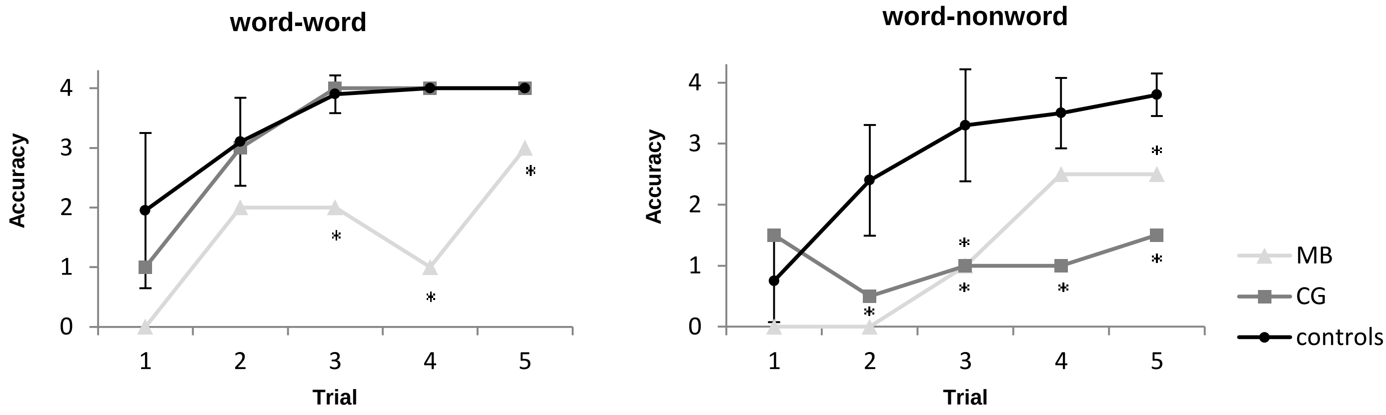

List length 6
Accuracy
Serial position
MB
CG
controls
List length 7
Accuracy
Serial position
MB
CG
controls
List length 8
Accuracy
Serial position
MB
CG
controls

Figure 8.


word-word
Accuracy
Trial
word-nonword
Accuracy
Trial
MB
CG
controls