

Phonological short-term store impairment after cerebellar lesion: A single case study

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Abstract

The cerebellum is a recent addition to the growing list of cerebral areas involved in the multifaceted structural system that sustains verbal working memory (vWM), but its contribution is still a matter of debate. Here, we present a patient with a selective deficit of vWM resulting from a bilateral cerebellar ischemic lesion. After this acute event, the patient had impaired immediate and delayed word-serial recall and auditory-verbal delayed recognition. The digit span, however, was completely preserved. To investigate the cerebellar contribution to vWM, four experiments addressing the function of different vWM phonological loop components were performed 18 months after the lesion, and results were compared with normative data or, when needed, with a small group of matched controls.

In Experiment 1, digit span was assessed with different presentation and response modalities using lists of digits of varying lengths. In Experiment 2, the articulatory rehearsal system was analyzed by measurement of word length and articulatory suppression effects. Experiment 3 was devoted to analyzing the phonological short-term store (ph-STs) by the recency effect, the phonological similarity effect, short-term forgetting, and unattended speech. Data suggested a possible key role of the semantic component of the processed material, which was tested in Experiment 4, in which word and nonword-serial recall with or without interpolating activity were analyzed.

The patient showed noticeably reduced scores in the tasks that primarily or exclusively engaged activity of the ph-STs, namely those of Experiment 3, and good performance in the tests that investigated the recirculation of verbal information. This pattern of results implicates the ph-STs as the cognitive locus of the patient's deficit. This report demonstrates a cerebellar role in encoding and/or strengthening the phonological traces in vWM.

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1. Introduction

Working memory is a form of temporary storage of information that is needed for performing a wide range of cognitive skills (Baddeley, 2003). This mechanism allows the temporary maintenance and manipulation of a limited amount of information. According to the Baddeley–Hitch model (Baddeley & Hitch, 1974), the working memory system does not have a unitary functional architecture but comprises a limited capacity attentional controller (central executive) and two subsystems

that temporarily store visual-spatial information (visuospatial sketchpad) or acoustic-verbal information (phonological loop).

The phonological loop is further divided into two independent components: the phonological short-term store (ph-STs), which is involved in immediate retention of verbal information; and the rehearsal system, which refreshes phonological information to prevent its rapid decay (Salamè & Baddeley, 1982). If verbal material is presented in spoken form, access to the ph-STs is direct and obligatory. If verbal material is presented visually (through written stimuli or pictures), then it needs to be recoded into phonological code by means of the rehearsal process before accessing the ph-STs (Levy, 1971; Sperling, 1963). Thus, the rehearsal process has two functions: to refresh phonological traces and to translate visual stimuli into a phonological code.

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Recirculation of the memory trace, provided by the rehearsal system, is supposed to take place between the ph-STS and the so-called phonological output buffer (Vallar, Basso, & Bottini, 1990), a working memory space in which phonological segments are temporarily stored to allow the programming of various output processes (Burani, Vallar, & Bottini, 1991). Evidence from various fields of neuroscience demonstrates that the working memory system has discrete neural correlates within the left frontal and parietal cortical areas (Paulesu, Frith, & Frackowiak, 1993; Silveri & Cappa, 2003; Vallar, Di Betta, & Silveri, 1997; Vallar & Papagno, 1995). Moreover, some data indicate that subcortical structures are also involved in working memory functions. Specifically, neuroimaging studies have demonstrated that the cerebellum is one of the most consistently activated regions within a network that includes the inferior frontal lobe, the supplementary motor area, the premotor cortex, and the parietal lobe (Andreasen et al., 1995; Chen & Desmond, 2005b; Chein & Fiez, 2001; Desmond, Gabrieli, Wagner, Ginier, & Glover, 1997; Grasby et al., 1994; Kirschen, Chen, & Schraedley-Desmond, 2005; Li et al., 2004; Paulesu et al., 1993).

In addition to neuroimaging data, lesion studies demonstrating mild impairment of verbal working memory (vWM) tasks in patients affected by cerebellar lesions provide further support for a cerebellar role in working memory. (Justus, Ravizza, Fiez, & Ivry, 2005; Ravizza, McCormick, Schlerf, Ivry, & Fiez, 2006; Silveri, Di Betta, Filippini, Leggio, & Molinari, 1998).

Consistent with the proposals advanced in Silveri et al.'s (1998) neuropsychological study, most neuroimaging studies hypothesise a cerebellar role in the rehearsal process, arguing that the cerebellum, in conjunction with the inferior frontal lobe and the supplementary motor area, is part of a circuit that sustains articulatory rehearsal mechanisms, whereas the inferior parietal lobe is the locus of the ph-STS (Chein & Fiez, 2001; Grasby et al., 1994; Paulesu et al., 1993; Petrides, Alivisatos, Meyer, & Evans, 1993). This assumption is consistent with the hypothesis that the cerebellum controls speech production at the interface of the subvocal rehearsal process and motor execution (Silveri et al., 1998).

However, articulatory rehearsal does not seem to provide a complete account of cerebellar involvement in verbal working memory. Significant activation is still observed in the right cerebellar hemisphere when the rehearsal control condition is subtracted from the working memory task (Awh et al., 1996), suggesting that the cerebellum performs functions in addition to, or instead of, articulatory rehearsal. Contrary to the rehearsal hypothesis, Chein and Fiez (2001) found no cerebellar activation during the maintenance phase of a delayed recall task; however, they described primary activation during encoding and retrieval working memory phases.

Lesion studies have also questioned the notion that the cerebellar role is confined exclusively to rehearsal mechanisms. The requirement to speak while trying to remember verbal material in a working memory task is detrimental to recall, because articulatory mechanisms are unavailable for rehearsal (articulatory suppression) (Baddeley, Thomson, & Buchanan, 1975). Unlike patients with prefrontal cortex lesions (Goerlich, Daum,

Hertrich, & Ackermann, 1995; Vallar et al., 1997), patients with cerebellar damage show normal suppression effects (Ravizza et al., 2006; Silveri et al., 1998).

This evidence questions the selective influence of the cerebellum on rehearsal and supports the idea proposed by Ravizza et al. (2006) of a more complex cerebellar contribution to both storage and rehearsal working memory mechanisms. According to this hypothesis, two different cerebro-cerebellar networks – i.e., one for articulatory rehearsal and one for phonological storage – have been described (Chen & Desmond, 2005b). Articulatory rehearsal refers to the frontal-superior cerebellar articulatory control system, in which the superior cerebellar hemisphere receives input from frontal areas via the medial pontine nuclei; phonological storage refers to the parietal-inferior cerebellar system in which the inferior cerebellar hemisphere receives input from parietal areas involved in the ph-STS via the lateral pontine nuclei (Chen & Desmond, 2005b). Until now, however, no evidence of selective damage of the ph-STS with preservation of rehearsal mechanisms in patients with cerebellar damage has been demonstrated.

To detail the cerebellar contribution to verbal working memory, the function of different vWM phonological loop components was addressed in a patient with vascular bilateral cerebellar lesions.

2. Case description

BB, a 54-year-old, right-handed male banker with 18 years of formal education, was admitted to the Neurology Ward of the Catholic University of Rome in August 2002. His symptoms included the sudden appearance of tinnitus, sensory abnormalities on the left side of the face, and dizziness with nausea and vomiting. The patient was alert and oriented in time and place; a physical examination revealed ataxia of gait, dysmetria of the left limbs, and horizontal torsional nystagmus.

MRI showed two T1 hyperintense areas in the left postero-inferior cerebellar hemisphere (lobule VIIIA) and in the right antero-superior cerebellar regions (lobule V), confirming the diagnosis of ischemic stroke. The extent of the lesions was characterized by lobular parcellation according to Schmahmann, Doyon, Toga, & Petrides's (2000) atlas (Fig. 1). All extracerebellar structures were completely spared.

After 9 days, the patient was moved to Santa Lucia Rehabilitation Hospital in Rome, at which time a general neuropsychological examination was performed. It showed that intelligence (Raven, 1947), constructional praxia (Rey, 1968), and frontal lobe abilities (Caltagirone et al., 1995) were within the normal range. Spontaneous speech was spared. Verbal and visuospatial spans (Orsini et al., 1987) were normal, as were visual immediate recall abilities (Rey, 1968).

A test of memory and learning (Reynolds & Bigler, 1995) revealed impairment of short-term and delayed auditory free recall, as well as divergent results on delayed recognition. In the latter test, the patient presented with a disproportionate deficit in the auditory-verbal modality, with normal performance in the visual-verbal modality. No further testing was carried out at that

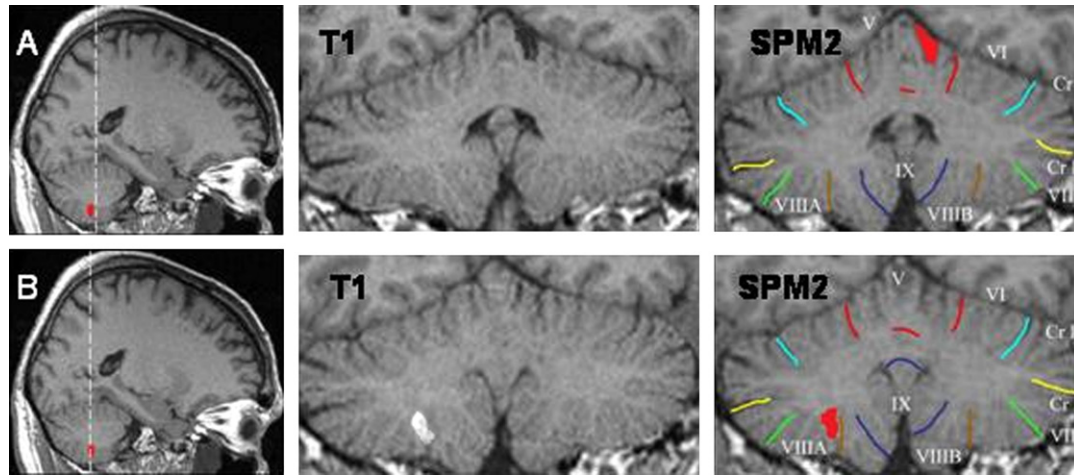


Fig. 1. T1-weighted not-normalized MRI and T1-weighted MPRAGE-normalized SPM2 (Welcome Department of Cognitive Neurology, London, UK) images showing ischemic lesions localized in the right lobule V (A) and in the left lobule VIII A (B). Lobules are defined according to Schmahmann, Doyon, Toga, and Petrides (Schmahmann et al., 2000).

time. The patient's scores, adjusted for age and education, are summarised in Table 1.

3. General neuropsychological assessment

BB came under our observation 18 months after the stroke. At that time, his neurological examination revealed only slight gait ataxia. His cognitive level and neuropsychological profile were investigated. Four normal control subjects, matched for age (mean age: 54 years) and education (18 years), were also tested; the neuropsychological profiles of BB and the control subjects are reported in Table 2.

Table 1
Neuropsychological examination at time of lesion

Tasks		Cut-off
Cognitive profile		
Raven-coloured matrices	28.6	18.96
Memory tasks		
Span		
Digit forward	6	7 ± 2
Digit backward	5	5 ± 2
Spatial forward	6	7 ± 2
Spatial backward	5	5 ± 2
Visuospatial memory		
Rey's complex figure	24	22 ± 4.9 ^a
Words serial recall (TOMAL)		
Free immediate recall	5	7
Free delayed recall	5	7
Verbal cues recognition	0	
Visual cues recognition	9	
Constructional praxia tasks		
Rey's complex figure	33	32 ± 1.8 ^a
Executive tasks		
Analogy	18	18

^a Mean raw score values from Rey (1968).

BB's total, verbal, and performance IQs were within the normal range according to the WAIS-R (Wechsler, 1997), and his linguistic and praxic abilities were intact as measured by the phonemic word fluency task (Borkowsky, Benton, & Spreen, 1967) and by "Mental Deterioration Battery" (Caltagirone et al., 1995). His performance on the immediate visual recognition test was similar to those of the controls (Caltagirone et al., 1995). He made a few omissions on the double line cancellation task (Zazzo, 1980), suggesting a mild defect in visual exploration ability.

BB's performance on the word-serial recall task, extrapolated from TOMAL (Reynolds & Bigler, 1995), showed that he had clearly recovered from the acute phase. In immediate and delayed free recall, BB recalled 11 and 12 of 12 items, respectively, and thus, delayed recognition was not tested (Table 2).

Spatial and verbal span were measured using Corsi's block-tapping test (Orsini et al., 1987) and immediate repetition of digits (Orsini et al., 1987), words, and nonwords (Miceli, Laudanna, & Burani, 1994). BB's scores were normal for block-tapping and repetition of digits and words. However, the patient's performance of nonword stimuli retrieval was impaired, exhibiting clear differences from controls. When manuality-handedness was assessed by the Edinburgh Inventory (Oldfield, 1971), the patient obtained a score of 10/10 in favour of his right hand.

In summary, the patient's neuropsychological profile 18 months after the acute event confirmed intact praxis and visuospatial and verbal fluency abilities, as reported in the acute phase. A mild, previously undiscovered deficit in visual exploration was present. The patient's performance on the word-serial recall task showed recovery with scores comparable with those of controls.

His verbal span task performance, however, was intriguing. In fact, while BB's performance was completely preserved on the digit and word span tasks, his nonword span score was clearly impaired. This observation, indicating a possible defect in vWM, propelled us to further investigate the function of vWM components.

Table 2
Neuropsychological examination at 18 months after stroke

Tasks	Controls					Cut-off
	BB	C1	C2	C3	C4	
Cognitive profile						
WAIS-R						
Total IQ	116	116	130	124	128	
Verbal IQ	119	106	125	122	123	
Performance IQ	108	127	130	124	130	
Memory tasks						
Span						
Digit forward	6	6	6	7	6	7 ± 2
Digit backward	5	4	5	5	4	5 ± 2
Spatial forward	6	6	6	6	5	7 ± 2
Spatial backward	5	4	5	5	4	5 ± 2
Word	4	4	4	4	4	
Nonword	2	4	4	3	3	
Visual recognition						
Immediate picture recognition	18.4	19.2	20.4	19.4	20.6	13.85
Words serial recall (TOMAL)						
Free immediate recall	11	6	11	8	9	7
Free delayed recall	12	10	11	11	10	7
Verbal cues recognition	^a	1	1	1	2	
Visual cues recognition	^a	1	^a	^a	^a	
Visuospatial tasks						
Double line cancellation	9	10	13	11	13	12
Constructional praxia tasks						
Copying drawings	9.9	8.9	10	11.9	11.1	7.18
Copying drawings with landmarks	67.4	64.4	64.6	68.6	68.8	61.85
Linguistic tasks						
Word fluency	41.6	28.2	37.6	41.6	40.2	17.35

^a Not tested according to TOMAL protocol. Test is not performed if in the preceding recall tasks 12 out of 12 words are already recalled.

4. Experiment 1: digit span

Evident or mild digit span deficits have been reported in cerebellar patients (Maddox, Aparicio, Marchant, & Ivry, 2005; Ravizza & Ivry, 2001; Silveri et al., 1998; Witt, Nuhsman, & Deuschl, 2002). Digit span is the traditional method for measuring phonological short-term memory capacity (Vallar et al., 1990; Vallar & Papagno, 1995), consisting of immediate serial recall of digit sequences of increasing length. The score is the length of the longest correctly recalled sequence. In verbal serial recall tasks, stimuli can be administered in the auditory modality (wherein digits are spoken by the examiner) or in the visual modality (by presenting a series of black digits printed on white cards).

Independent of the presentation condition, two recall modalities can be used: verbal repetition and pointing recognition. When a repetition response is required, the subject has to repeat the stimuli verbally (auditory-verbal or visual-verbal). When a pointing response is required, the subject has to indicate the proposed sequence among alternatives (auditory-pointing or visual-pointing). According to different presentation or recall modalities, different components of the phonological loop can be tested. In fact, while auditory input has direct obligatory

access to the ph-STs, visual material requires two additional operations: phonological recoding (grapheme-to-phoneme conversion) and articulatory rehearsal.

Thus, patients with a ph-STs deficit present with a disproportionate impairment of the auditory span compared with the visual span, and response modality does not affect performance (Vallar et al., 1997).

Conversely, since verbal visual stimuli must be recoded by the rehearsal system into a phonological code to gain access to the ph-STs (Shallice & Vallar, 1990), a deficit of articulatory rehearsal is indicated by improved performance in the pointing procedure after verbal presentation of stimuli than after visual presentation (Silveri et al., 1998). Furthermore, a comparison between verbal repetition and pointing recognition allows assessment of the phonological output buffer, a component of rehearsal (Vallar et al., 1997). The memory advantage of the pointing modality over the verbal repetition modality indicates a reduced capacity of the phonological output buffer (Vallar et al., 1997).

In summary, different performance patterns can identify specific loci of impairment of the vWM system. Therefore, we can identify: (i) *the ph-STs impairment pattern*, characterized by a pathological auditory-verbal span, associated with an auditory-

verbal span lower than the visual-verbal span, and lack of an advantage with pointing responses; (ii) *the rehearsal component defect pattern*, characterized by a visual-verbal span lower than the auditory-verbal span, with possible mild impairment of the auditory-verbal span; (iii) *the phonological output buffer impairment pattern*, characterized by an advantage with pointing responses versus verbal responses in every input modality.

Digit span was assessed using lists of digits of various lengths with different presentation and response modalities.

4.1. Methods

4.1.1. Participants

BB's digit span performance was compared with those of the controls reported in Vallar, Corno, and Basso (1992). These controls were 12 normal subjects with a mean age of 50.52 years (range 25–74) and a mean educational level of 10.08 (range 4–17) years.

4.1.2. Materials

The span task was administered using lists of digits in various presentation and response modalities. The stimuli set consisted of 5 sequences of 1, 2, 3, 4, 5, 6, or 7 digits. No digit was presented twice within a sequence.

4.1.3. Design and procedure

The digit span task was administered under four different conditions: (1) auditory-verbal (the patient repeated the sequence spelled out to him by the examiner); (2) visual-verbal (the patient repeated the sequence of digits visually presented one-by-one by the examiner); (3) auditory-pointing (the patient indicated the sequence of digits spelled out by the examiner among various alternatives printed on white cards randomly displayed on the table); (4) visual-pointing (the patient indicated the sequence of digits visually presented one-by-one by the examiner among various written alternatives). The digits included in each series were given to the patient at a presentation rate of one digit per second. If the patient did not correctly recall at least one of the sequences, subsequent longer list was not administered.

The span score was computed by the “ $K+x$ ” scoring system proposed by Zhang and Simon (1985) and used by Vallar et al. (1992) in an Italian population study. Sub-score K was the length of the longest sequence correctly recalled in 5 of 5 (100%) lists. Sub-score x was the number of correctly recalled sequences 1 item longer than K . Since each correctly recalled sequence was worth 0.20, the x sub-score ranged from 0 to 0.80 (0 to 4 of 5 sequences correctly recalled).

4.2. Results

BB's performance, reported in Table 3, was normal compared with those reported in same-age control subjects (Vallar

et al., 1992). No advantage was found for the auditory modality over the visual modality. Immediate repetition of digits was completely correct for both auditory and visual presentation. A slightly higher span was detected in the visual-pointing condition than in the auditory-pointing condition.

In Experiment 1, BB's digit span was preserved. A slight advantage emerged in the visual-pointing modality with respect to all other conditions, demonstrating good phonological recoding. Thus, BB's digit span data did not pinpoint the functional locus of the deficit. In the next two experiments, we specifically investigated the different components of the phonological loop.

5. Experiment 2: articulatory rehearsal system assessment

In Experiment 2, we addressed the function of the articulatory rehearsal system by analysing the word length effect and articulatory suppression.

Since the articulatory rehearsal system is a time-limited loop that recirculates information stored in the ph-STG, long words require more time to be articulated and thus are recalled less frequently than short words (Baddeley et al., 1975). This effect is described as the *word length effect* (Baddeley et al., 1975). In normal subjects, the word length effect is a good indicator of the efficiency of the articulatory rehearsal system.

Articulatory suppression refers to the disruption of verbal material retention in immediate memory span tasks by means of continuous uttering of an irrelevant speech sound. This effect is due to the interference of uttering on rehearsal activity and is considered an indirect index of the rehearsal process function (Baddeley, Lewis, & Vallar, 1984; Levy, 1971; Murray, 1968; Peterson & Johnson, 1971). In the case of a nonoperative rehearsal process, no articulatory suppression is expected (Silveri et al., 1998). Conversely, a strong suppression effect indicates intact recirculation of verbal information (Vallar et al., 1997).

5.1. Methods

5.1.1. Participants

In addition to BB, four control subjects, matched to the patient for age (mean age: 54 years) and education (18 years), were subjected to the word length effect test.

Table 3
BB's span performances in different conditions

Conditions	Auditory-verbal	Auditory-pointing	Visual-verbal	Visual-pointing
BB span	6.80	6.80	6.60	7
Controls (Vallar et al., 1992)	5.52	5.95	5.64	5.41
Sequence length	Percentage of correct responses			
1	100	100	100	100
2	100	100	100	100
3	100	100	100	100
4	100	100	100	100
5	100	100	100	100
6	100	100	100	100
7	80	80	60	100

Span are computed following Vallar et al. (1992).

5.1.2. Materials

5.1.2.1. Word length effect. To investigate the word length effect, a modified version of the original test developed by Brizzolara, Casalini, Chilosi, and Cipriani (2002) was administered. The adapted version consisted of two lists of two- or four-syllable words (Lists 1 and 5 of the original version) of high-use frequency, presented in either auditory or written form.

5.1.2.2. Articulatory suppression. Stimuli consisted of sequences of 7 digits each. No digit was presented twice within a sequence. A total of 4 blocks of 20 series of items were given to the patient. The response set material comprised 10 digits (from 0 to 9) printed in random positions on a white card.

5.1.3. Design and procedure

5.1.3.1. Word length effect. Items for this test were organised in progressively longer series (2–6 items). For each list (1–5), the examiner administered each string of words at a rate of one per second. The subject had to repeat the items in the order in which they were presented. If he succeeded, strings of words of increasing length were presented. If the subject failed to repeat a string, a second series of the same length was administered. If the subject failed again, the test was discontinued.

The span was established as the length of the last correctly recalled string. In the auditory presentation modality, the stimuli were read aloud by the examiner; in the visual presentation modality, the strings of words were printed on white cards and shown to the subject.

The patient's two- and four-syllable word spans were compared by frequency distribution test (χ^2 -value).

5.1.3.2. Articulatory suppression. This task was articulated in two sessions. In each session, BB received two blocks of stimuli presented under two different conditions (I+ and I−) in an ABBA design. In the articulatory suppression condition (I+), the patient was requested to continuously pronounce a nonsense word (blah), starting before the examiner presented each auditory list of digits and stopping after immediate recognition of the stimuli in the presentation order. Recognition was executed by pointing to the digits of the white response board (Baddeley et al., 1984). The pointing response was necessary because of the continuous uttering of verbal speech throughout the task.

In the control condition (I−), the patient was not engaged in any concurrent activity. According to Vallar et al. (1997), for articulatory suppression, one must use a digit list length for which at least 70% correct recognition was scored in the standard auditory-pointing span task. Thus, a list of 7 digits was administered to BB (see Table 3). Correctly recognised sequences by BB under the suppression and control conditions were compared by frequency distribution test (χ^2 -value).

5.2. Results

5.2.1. Word length effect

The patient presented no length effect with auditory stimuli; on the contrary, his performance on long words exceeded that for short words, suggesting a paradoxical word length effect. The word length effect was absent in two out of the four control subjects; i.e., their scores did not depend on the length of the presented stimuli. The remaining two controls presented a normal word length effect; i.e. their scores were better with shorter than longer words. Conversely, both BB and control subjects exhibited normal length effects with visual verbal stimuli. In the visual verbal condition, BB's span was significantly higher for two-syllable words than for four-syllable words ($\chi^2 = 9.86$, d.f. = 1, $p = 0.00$). The results for BB and control subjects are reported in Table 4.

5.2.1.1. Articulatory suppression. BB correctly recognised 24 of 40 auditory sequences under the suppression condition (60%)

and 33 of 40 under the control condition (82.5%) ($\chi^2 = 4.94$, d.f. = 1, $p = 0.02$).

The presence of a word length effect with visual stimuli and of noticeable articulatory suppression demonstrates good functioning of the rehearsal process. However, the lack of a word length effect in the auditory modality may raise doubts about this finding.

In any case, two of the control subjects did not perform better with longer auditory words; further, there are reports on the absence of the word length effect in patients with preserved rehearsal systems and impaired ph-STS (Silveri & Cappa, 2003; Vallar et al., 1997). This finding has been interpreted as a strategic choice, because rehearsing the material did not improve memory performance in the presence of a dysfunctional ph-STS (Vallar et al., 1997).

Interestingly, BB not only failed to show any word length effect in the auditory presentation, he also had a slight advantage with longer words. Different authors (Silveri et al., 1998; Vallar & Cappa, 1987; Vallar et al., 1997) have ascribed this paradoxical word length effect to the 'trace decay plus rehearsal' theory (Baddeley, 1990; Baddeley & Hitch, 1974; Brown & Hulme, 1995; Schweickert, Guentert, & Hersberger, 1990; Stigler, Lee, & Stevenson, 1986). According to this concept, a partially decayed item can be recalled by reconstructing its phonological trace. This process may be length-sensitive—for example, when a phonological segment is lost, reconstruction has to rely on the remaining segments. Therefore, long items are expected to be easier to reconstruct than short items.

6. Experiment 3: phonological short-term storage assessment

In Experiment 3, we assessed the function of the ph-STS by analysing recency and phonological similarity effects, short-term forgetting, and unattended speech.

In immediate free or serial recall of auditory lists, normal subjects typically present a U-shaped performance, with higher retention of the initial items (*primacy effect*) and final items (*recency effect*) than of the intermediate ones. Retention of the initial and intermediate stimuli primarily engages the articulatory process, whereas recalling the final ones involves the ph-STS in particular (Vallar & Papagno, 1986). Within this model, impaired recall of initial and intermediate stimuli is considered the expression of an inefficient rehearsal process. Conversely, a reduced recency effect is indicative of a ph-STS impairment (Vallar & Papagno, 1986).

Phonological similarity effect refers to the tendency of normal subjects to have longer spans for phonologically dissimilar letters than for phonologically similar letters in both auditory (Baddeley, 1966; Conrad, 1964; Wickelgren, 1965) and visual (Silveri et al., 1998) presentations. This effect is linked to the interference generated by phonological similarity in the ph-STS (Baddeley & Hitch, 1974) and is not observed when the ph-STS is defective (Vallar et al., 1997).

Short-term forgetting is the effect of a verbal interpolating activity on the ability to recall verbal stimuli. The interpolat-

Table 4
Word length effect according to input modality

Word length (syllables)	Sequence length									
	Auditory-repetition					Visual-repetition				
	BB	C1	C2	C3	C4	BB	C1	C2	C3	C4
2	4	4	4	5	6	6	6	6	5	6
4	5	4	4	4	4	4	5	5	4	5

ing activity is supposed to prevent the articulatory rehearsal mechanism by minimizing its contribution to recall. Thus, when subjects are engaged in an interfering activity, their ability to recall stimuli is considered an index of ph-STS function (Brown, 1958; Peterson & Johnson, 1971; Peterson & Peterson, 1959).

In the auditory-verbal modality, the listened material directly accesses the ph-STS; thus, the rate of forgetting during an interpolating activity is negligible when the ph-STS is efficient. On the other hand, when the ph-STS is defective, the rate of forgetting is marked, even after brief interfering activity (Shallice & Vallar, 1990).

Another index of ph-STS function is the interference of irrelevant speech on immediate verbal recall (*unattended speech*). In the auditory modality, both the stimuli to be recalled and unattended speech have direct access to the ph-STS, with no contribution of rehearsal (Salamè & Baddeley, 1982). Thus, at the ph-STS level, unattended speech interferes with the material to be recalled. When the ph-STS is impaired, irrelevant speech does not alter immediate verbal recall (Vallar et al., 1997).

6.1. Methods

6.1.1. Participants

For the recency effect, BB's performance was compared with those of the Italian normative group described by Capitani, Della Sala, Logie, and Spinnler (1992). In particular, for the control group we selected subjects with demographic characteristics similar to those of BB. They included 63 healthy subjects, whose ages ranged from 50 to 59 years, and whose education level varied from less than 3 to over 13 years (Capitani et al., 1992).

For the phonological similarity effect and short-term forgetting, four healthy subjects matched for age (mean age 54 years) and education (18 years) were tested using the same procedure adopted for the patient.

6.1.2. Materials

6.1.2.1. Recency effect. For free recall, following Silveri et al. (1998), 5 series of 10 words controlled for length and word frequency were administered.

6.1.2.2. Phonological similarity effect. A modified version of the original test developed by Brizzolara et al. (2002) was used. The adjusted version consisted of two series of two-syllable words (Lists 3 and 4 of the original version) arranged in progressively longer sequences (2–6 items). Stimuli consisted of phonologically similar and phonologically dissimilar words, which were administered in the verbal or the visual modality.

6.1.2.3. Short-term forgetting. Brown–Peterson's paradigm was used (Brown, 1958; Peterson & Peterson, 1959). In this task, 30 three-consonant strings, randomly generated among other phonologically dissimilar letters (F, M, Q, R, S, H, Z), were presented.

6.1.2.4. Unattended speech. The effect of unattended speech was evaluated in 7-digit sequences. Unattended speech consisted of taped two- and three-letter nonsense syllables and included a variety of C–V arrangements (CV, CCV, CVC)

presented at one syllable per second, following the protocol of Burani et al. (1991).

6.1.3. Design and procedure

6.1.3.1. Recency effect. This test consisted of five consecutive immediate free-recall trials. In the first immediate trial, the examiner presented 10 words orally at 1 every 2 s. Immediately after the presentation, the subject was asked to recall as many words as possible. Following Silveri et al. (1998), we considered the recollection of the first 2 items a measure of the primacy effect, and the recollection of the last 2 items a measure of the recency effect.

6.1.3.2. Phonological similarity effect. These test items were organised in progressively longer series (2–6 items). Each string of words was presented at one word per second, and immediately after presentation, the subject had to repeat each series of words in the correct order. If he succeeded, a longer series was presented. Conversely, if the subject failed on a sequence, a second series of the same length was administered. The test was discontinued when the subject failed on two successive same-length strings. The span was calculated as the number of items in the longest correctly recalled string. In the auditory modality, the stimuli were read aloud by the examiner; in the visual modality, printed strings of words were presented on white cards.

6.1.3.3. Short-term forgetting. The examiner presented three-consonant strings in the auditory modality. The subject had to repeat the consonant sequence of each string in the same order in which it was administered. The task was presented under two conditions. In the first condition, the subject had to respond after varying intervals (5, 10, and 20 s) without engaging in any concurrent task.

In the second condition, the response was given after different intervals (5, 10, and 20 s), which were filled by an interpolated activity (interference). In the interference condition, the subject was instructed to serially subtract 3 starting from a number randomly chosen between 100 and 999.

There were five trials for each of the six experimental conditions (three retention intervals \times two concurrent tasks). For each condition, the score was calculated as the total number of letters correctly recalled (range 0–15). BB's performance without or with 5 s of interpolating activity was compared by frequency distribution test (χ^2 -value).

6.1.3.4. Unattended speech. The taped unattended speech was started before auditory presentation of the digit sequences and continued throughout the memory task. In this paradigm, we used the digit sequence length at which the patient reached at least 70% correct recognition in the standard auditory-pointing span task (see Table 3). The task was conducted in two sessions. In each session, the patient received two blocks of stimuli to compare interference (I+) and control conditions (I–) in an ABBA design: interference (I+), control (I–), control (I–), and interference (I+). The span procedure was auditory-verbal. BB's performance with or without auditory interference was compared by frequency distribution test (χ^2 -value).

6.2. Results

6.2.1. Recency effect

In the immediate free recall of words, the patient remembered 8 of 10 stimuli in the first 2 positions (primacy effect), 16 of 30 items in the intermediate positions (3–8 positions), and 5 of

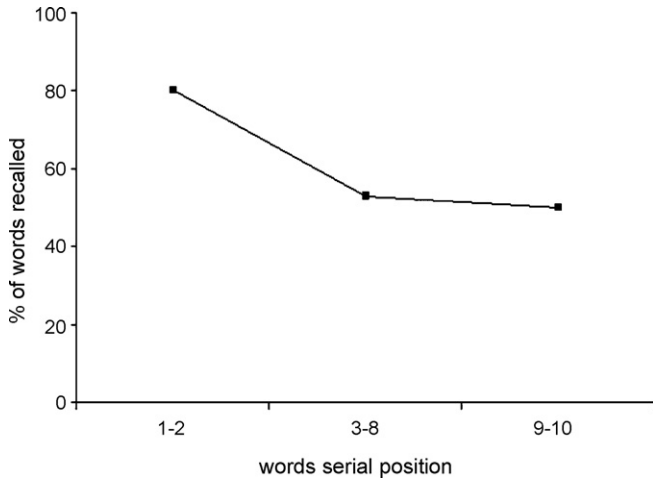


Fig. 2. BB's primacy and recency effects in the free recall of words: percentage of correct stimuli recalled according to their serial positions.

10 stimuli in the last 2 positions (recency effect). Thus, a clear advantage for the retention of the initial items (primacy effect) was observed compared with no advantage for the retrieval of the last stimuli (recency effect) on the list. The noticeable reduction in the recency effect is consistent with a defect in the ph-STs (Fig. 2).

6.2.2. Phonological similarity effect

BB did not show a phonological similarity effect in either the auditory condition or the visual condition, because his spans on phonologically similar and dissimilar words were comparable. Conversely, as expected, control subjects tended to recall phonologically dissimilar stimuli better than phonologically similar ones. It is worth noting that the relationship between ph-STs impairment and the similarity effect is not linear.

The absence of both auditory and visual phonological similarity effects (Silveri & Cappa, 2003), as well as presence of auditory but not visual phonological similarity effects (Vallar, Papagno, & Baddeley, 1991), has been reported in patients with ph-STs impairment. Based on the interpretations of Vallar et al. (1997) and Silveri and Cappa (2003), we assumed that the absence of an evident phonological similarity effect with auditory-verbal stimuli was indicative of a disorder of the ph-STs. Patient and control subject performances are reported in Table 5.

6.2.3. Short-term forgetting

In the free condition, patient performance after each interval did not differ from the controls (Fig. 3). During the interpolating

Table 5
Phonological similarity effect according to input modality

Stimuli	Sequence length									
	Auditory-repetition					Visual-repetition				
	BB	C1	C2	C3	C4	BB	C1	C2	C3	C4
Ph-similar	4	3	2	3	4	4	5	5	4	4
Ph-dissimilar	4	5	4	4	5	4	6	6	5	5

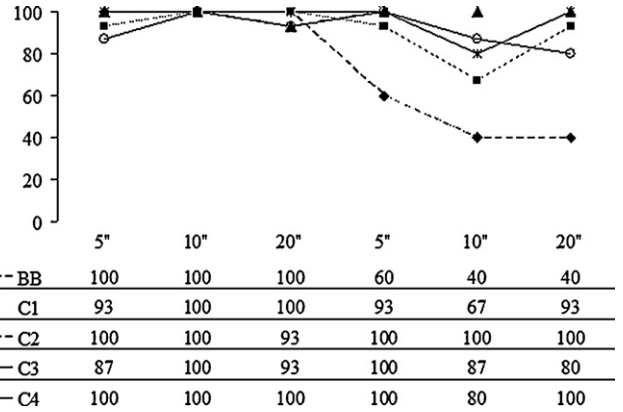


Fig. 3. Percentage of recalled auditory-verbal stimuli on Brown–Peterson paradigm in free condition and in suppression articulatory condition (time delay: 5 s, 10 s, 20 s).

task, the control performance remained substantially unchanged, while BB's rate of forgetting increased progressively (Fig. 3). The effect of the interferential activity was already evident within 5 s ($\chi^2 = 7.50$, d.f. = 1, $p = 0.00$), indicating quick forgetting of the material within a few seconds after presentation of the stimuli and confirming the hypothesis of an impaired ph-STs.

6.2.4. Unattended speech

BB showed no effect of unattended speech. He recalled 16 of 20 seven-item lists (80%) correctly during auditory interference and 18 (90%) of 20 under the control condition ($\chi^2 = 0.78$, d.f. = 1, $p = 0.37$).

The results of Experiment 3 confirm the absence of a phonological similarity effect with auditory input, a reduced recency effect in the auditory free recall of words, no effect of unattended speech, and a noticeable forgetfulness after 5 s of interference delay in the Brown–Peterson paradigm. Overall, the patient's performance is indicative of a defective ph-STs and a preserved rehearsal system.

However, the absence of a phonological similarity effect in the visual modality raises doubts about the function of the rehearsal system. On the other hand, it could also indicate a problem at the level of the ph-STs. It has been proposed that patients with a ph-STs impairment may strategically choose not to use the rehearsal mechanism, given that rehearsing material stored in a dysfunctional ph-STs does not significantly improve their performance (Vallar et al., 1997).

7. Experiment 4: lexical–semantic influence on verbal immediate serial recall

Results obtained in the previous experiments indicate that BB's deficit is confined to the ph-STs, while his use of the rehearsal process is normal. A defective ph-STs will conceivably affect both word and nonword spans. Nevertheless, BB demonstrated clearly defective performance with only nonword stimuli. How can BB maintain good word span performances if the ph-STs is defective?

An experiment was designed to investigate whether lexical–semantic coding represents a compensatory mechanism

that allows good word span performance. To this aim, word and nonword-serial recall tasks were administered, with a delay interval that was either filled or unfilled by an interpolated activity. Interpolated activity disrupts the subvocal rehearsal but not the support of lexical-semantic long-term knowledge to ph-STS performance. Thus, comparison of word and nonword scores during interference tasks will evaluate the influence of the lexical-semantic component on verbal immediate recall independently from the function of the rehearsal.

7.1. Methods

7.1.1. Participants

In addition to BB, four healthy subjects matched for age (mean age: 54 years) and education (18 years) were tested.

7.1.2. Materials

Three different sets of items were used. The first and second set of stimuli included 6 lists of two-syllable words each (semantically related or unrelated). Semantically related words belonged to the categories of food, vehicles, animals, body parts, clothes, and colours. The third set of stimuli consisted of 2 lists of nonwords comprising five- or six-letter strings.

7.1.3. Design and procedure

After a 20-s interval from the presentation, subjects had to repeat a series of auditory stimuli in the same order in which they had been administered. Each set of items was given under two different conditions. In the first condition, the response was requested after a delay filled by an interference activity (a counting task). In the second condition, the response was given after an interval unfilled by the interfering activity.

7.2. Results

When the task did not require interference activity and BB could normally refresh the stimuli, his performance was preserved using every list, independent of the presence of the semantic component. In fact, in the semantically related list, BB recalled 34 of 36 words (94%) compared with 34, 32, 32 and 31 stimuli (94%, 86%, 86%, and 89%, respectively) for the control subjects, and in the semantically unrelated list, he retrieved 27 of 36 words (75%) compared with 24, 24, 24 and 28 stimuli (67%, 67%, 67% and 78%, respectively) for the controls.

With regard to nonwords, BB recalled 7 of 8 items (87%), and control subjects recalled 6, 7, 7 and 7 of 8 items (75%, 87%, 87% and 87%, respectively). Conversely, when BB could not refresh the stimuli because of the interference activity, his performance was poor.

Overall, BB recalled fewer items than control subjects and showed a striking difference in nonword stimuli. Indeed, with interference activity BB recalled 26 of 36 semantically related words (72%) in comparison with 27, 32, 32, and 33 words (75%, 89%, 89%, and 92% respectively) in control subjects; 19 of 36

unrelated stimuli (53%) compared with 20, 21, 22 and 29 items (55%, 58%, 61% and 78%, respectively) in the normal subjects; and 1 of 8 nonwords (12%) compared with 4, 4, 5 and 5 stimuli (50%, 50%, 62% and 62%, respectively) for the controls.

The differences between BB's performance with word and nonword stimuli were further highlighted by frequency distribution test (χ^2 -value). BB recalled a significantly lower number of semantically related and unrelated words ($\chi^2 = 6.40$, d.f. = 1, $p = 0.01$ and $\chi^2 = 3.85$, d.f. = 1, $p = 0.04$) and nonwords ($\chi^2 = 6.25$, d.f. = 1, $p = 0.01$) when he was engaged in an interference activity than when he was not. Furthermore, taking into account both tasks performed with interference activity, BB's performance was significantly better with word (semantically unrelated or related) than with nonword stimuli ($\chi^2 = 4.28$, d.f. = 1, $p = 0.03$; $\chi^2 = 9.85$; d.f. = 1, $p = 0.00$), indicating an ameliorative effect of the semantic component. Patient and control scores are reported in Table 6.

The efficacy of the interpolating activity in reducing BB's word and nonword performances demonstrates the high efficiency of his rehearsal system and confirms that the ph-STS is the pathological locus of his vWM impairment. Furthermore, the difference between word and nonword recollection in the presence of interpolating activity demonstrates that lexical-semantic knowledge is able to support the phonological trace, even in an impaired ph-STS.

Different theories support the idea that long-term knowledge plays a role in the immediate recall of words. The interactive activation models (Martin, Lesch, & Bartha, 1999; Martin & Saffran, 1997) suggest that verbal short-term memory corresponds to the temporary activation of semantic and phonological representations in the language production system. "During immediate serial recall tasks all linguistic representations (including lexical and semantic representations) would be activated via bi-directional connections between levels of representations which in turn support recall performance" (Caza, Belleville, & Gilbert, 2002). Thus, when a word is presented verbally, its phonological representation is activated first, but activation then spreads to the corresponding semantic and lexical nodes (Forde & Humphreys, 2002).

In contrast to the view that long-term semantic representations normally form part of verbal short-term memory, "the redintegration theory" suggests that semantic memory only plays a role when information in short-term memory has been disrupted (Hulme et al., 1997). According to this theory, when a phonological trace is partially degraded, representations permanently stored in long-term memory can be recalled in order to "redintegrate" or "clean up" the trace in short-term memory (Poirier & Saint-Aubin, 1995; Schweickert, 1993; Walker & Hulme, 1999). This mechanism may explain why traces of

Table 6
Percentage of recalled stimuli in word (semantically related/unrelated) and nonword repetition with and without interference task

Conditions	Nonwords					Related words					Unrelated words				
	BB	C1	C2	C3	C4	BB	C1	C2	C3	C4	BB	C1	C2	C3	C4
Interference	12	50	62	50	62	72	92	89	89	75	53	55	78	58	61
No interference	87	75	87	75	71	94	94	86	86	89	75	67	78	67	67

words that have meaning-based features are more resistant to forgetting (Plaut & Shallice, 1993).

8. General discussion

The present findings demonstrate the presence of a vWM impairment in a patient with a lesion confined to the cerebellum due to a selective defect of the ph-STS with preservation of the rehearsal system function.

Directly after the cerebellar ischemic lesion, BB performed pathologically on immediate and delayed verbal serial recall and auditory recognition tasks. Because no lesions were detected in the supratentorial structures and because the only lesioned structure was the cerebellum, we can reasonably assume that the vWM impairment was related to the cerebellar damage.

BB presented with a vWM impairment with a normal verbal span. Justus et al. (2005) noted a largely preserved digit span in patients with degenerative or focal cerebellar damage, confirming previous observations that the digit span of degenerative cerebellar subjects was comparable with that of controls (Burk et al., 2003; Fabbro et al., 2004; Globas et al., 2003; Le Pira et al., 2002). Even when lower span scores were reported for cerebellar patients compared with controls, they were still within the normal range (Ravizza et al., 2006).

As expected with cerebellar lesions, BB's verbal recall deficits showed good recovery (Dunwoody, Alsagoff, & Yuan, 1997; Pollack, 1997; Silveri, Leggio, & Molinari, 1994; Silveri et al., 1998). At the time of our study, 17.6 months after the lesion, his performance on verbal serial recall tasks was within normal limits. However, even though span values were still normal for digit and word stimuli, a clear defect was present for nonword stimuli.

Because pathological performance on nonword stimuli can reflect vWM malfunction, we investigated BB's vWM system further by analysing each component of the phonological loop.

On digit span tasks (Experiment 1), BB's overall performance was normal. However, an advantage was present in the visual-pointing modality with respect to the other conditions, indicating good phonological recoding and questioning phonological output buffer functioning.

We found that the rehearsal process recirculated verbal information effectively (Experiment 2), as demonstrated by the strong effect of articulatory suppression and by the presence of a word length effect with visual stimuli. However, the lack of a word length effect with auditory stimuli raises doubts about the integrity of the rehearsal system.

Nevertheless, there is evidence supporting good rehearsal function in spite of the absence of a word length effect. Firstly, two of our control subjects did not present the auditory word length effect. Moreover, there are reports of patients with no word length effect who presented a selective deficit of the ph-STS with a preserved rehearsal process (see patient LA, in Silveri & Cappa, 2003; Vallar et al., 1997). This phenomenon has been interpreted as a strategic choice in the presence of a dysfunctional ph-STS, considering that rehearsing the material does not substantially improve memory performance (Vallar et al., 1997).

BB's pattern of ph-STS function (Experiment 3) was consistent with selective ph-STS impairment. The reduced recency effect in immediate free recall and the absence of a phonological similarity effect with auditory stimuli suggest a defect of the ph-STS. The insensitivity of BB's span to the interfering effect of unattended speech also indicates a ph-STS impairment (Vallar et al., 1997). In the Brown–Peterson paradigm, the interpolating activity prevents the operation of rehearsal (Brown, 1958; Peterson & Johnson, 1971; Peterson & Peterson, 1959). Consistent with the hypothesis of a ph-STS defect, in the free condition the patient was able to retain almost all auditory stimuli; however, his performance was poor even after only 5 s of interpolating activity.

In summary, BB's scores decreased noticeably on tasks that primarily or exclusively engaged activity of the ph-STS, while his performance was completely preserved on tests that investigate the recirculation of verbal information. This pattern of results implicates the ph-STS as the cognitive locus of the patient's deficit.

A possible limitation of the work, common to all single case studies, is the difficulty of providing statistically relevant data. In the present study, as in many other single case studies, caution is required when interpreting results, which will need confirmation from group studies.

BB's performance on verbal span tasks was normal for digit and word stimuli and markedly defective for nonword stimuli. This evidence supports the hypothesis that differential function of the ph-STS depends on characteristics of the material processed. In Experiment 4, word- and nonword-serial recall tasks with interpolating activity were performed. In this condition, BB's performance was significantly improved by the presence of meaningful items.

As already described, when the rehearsal mechanism is blocked by interpolating activities, the recall of auditory-verbal stimuli is considered a measure of ph-STS integrity (Graceffa, Carlesimo, Peppe, & Caltagirone, 1999). Because defective scores on nonword-serial recall tasks were obtained only when the rehearsal mechanism was blocked, this finding is surely linked to ph-STS impairment. The obvious difference between word and nonword stimuli is the semantic component. Therefore, it is conceivable to assume that lexical–semantic knowledge facilitates the retrieval of phonological information. In the case of BB, the data indicate that deficits are evident only if all of the ancillary mechanisms that support the ph-STS – i.e., rehearsal mechanisms and lexical–semantic compensation – are blocked.

Another aspect that deserves discussion is the dissociation between impaired performance in delayed auditory-verbal cued recognition and normal performance in visual cued recognition of the TOMAL. Several studies have demonstrated that concrete words are highly imaginable and promptly recalled from long-term memory (Davelaar & Besner, 1988; Paivio, 1966; Paivio, Yuille, & Smythe, 1966). According to the 'dual-coding' theory (Paivio, 1986), imaginable words can be stored by using both verbal and visual codes (Binder et al., 1997; Demb et al., 1995; Petersen, Fox, Posner, Mintun, & Raichle, 1988; Vanderberghe, Price, Wise, Josephs, & Frackowiak, 1996). Thus, concrete

words may rely on multiple forms of representation that facilitate their recollection (Baddeley, 2000).

Based on BB's performance, we hypothesise that the patient performed visual cued delayed recognition correctly by activating semantic components of the prefrontal cortex through the generation of perceptual and mental images. Thus, even if ph-STS impairment hindered BB's retrieval of phonological information, visual cues allowed him to generate a percept and a mental image of the concrete word. This mechanism cannot be active with auditory cues that require ph-STS activity; thus, delayed auditory-verbal cued recognition was impaired.

Functional neuroimaging data have consistently reported cerebellar activation in vWM tasks, but with differences in the lobular distribution of the activation foci. In 1996, Fiez and colleagues (Fiez et al., 1996) reported bilateral cerebellar activation in relation to short-term maintenance of verbal information; however, a subsequent report (Chein & Fiez, 2001) linked this to the first stage of the encoding phase, suggesting that it may not be engaged during rehearsal *per se*. Similarly, bilateral anterior and posterior cerebellar activation was described during digit span tasks under conditions of reduced rehearsal (Gerton et al., 2004).

Desmond et al. reported several foci of cerebellar activation in verbal working memory tasks (Desmond et al., 1997)—i.e., bilaterally in the superior cerebellar hemispheres, in the posterior vermis, and in the right inferior cerebellar hemisphere. On the basis of the cerebro-cerebellar connections, the authors connected activation of the right inferior cerebellar cortex to phonological store activity and activation of the superior cerebellar cortex to the articulatory control process.

Event-related fMRI data indicate that these two cerebellar regions are functionally different (Chen & Desmond, 2005a, 2005b). The right superior cerebellum (lobules VI/Crus1) was strongly activated during the initial encoding phase of a verbal working memory task, while the right inferior cerebellum (lobules VIIIB/VIIIA) showed the greatest activation during the maintenance phase (Chen & Desmond, 2005a, 2005b).

Discrepancies in neuroimaging data may arise from the existence of a distributed cerebellar network whose activation varies in relation to mnemonic load (Desmond et al., 1997; Zhang et al., 2003), input modality (Schumacher et al., 1996), or category (Ravizza et al., 2006), and particularly according to different phases of the working memory process (Chen & Desmond, 2005a, 2005b). Although neuroimaging data overall demonstrate the importance of the cerebellum in vWM, they do not allow clarification of the specific role of the different cerebellar folia in vWM functions (Justus et al., 2005).

BB presented two different foci of cerebellar damage—one localized in the left postero-inferior cerebellum (lobule VIIIA) and one in the right superior cerebellum (lobule V). Lobule VIIIA is within the area defined by several studies as involved in vWM (Chen & Desmond, 2005a, 2005b; Desmond et al., 1997). Although Chen and Desmond hypothesised right functional lateralization, this model has been contradicted by different reports that have indicated bilateral activation (Chein & Fiez, 2001; Fiez et al., 1996; Gerton et al., 2004). The importance of the inferior cerebellar lobe (without clear lateralization) in vWM is also sup-

ported by a recent study that did not find a correlation between the laterality of the damaged inferior cerebellar lobe and digit span performance (Ravizza et al., 2006).

The functional contribution of cerebellar processing to vWM requires further consideration. On the basis of neuroimaging (Paulesu et al., 1993; Petrides et al., 1993), as well as neurophysiological (Desmond, Chen, & Shieh, 2005) and neuropsychological studies (Silveri et al., 1998), the cerebellar role in vWM was first connected to the rehearsal process. However, the articulatory rehearsal hypothesis has been criticised on the basis of neuroimaging (Awh et al., 1996; Chein & Fiez, 2001) and neuropsychological observations (Justus et al., 2005; Ravizza et al., 2006), and accordingly, alternative hypotheses have been advanced.

Desmond and colleagues (Desmond, 2001; Desmond et al., 1997) proposed that the cerebellum serves as an interface between the ph-STS and articulatory rehearsal, comparing the output of subvocal articulation with the contents of the phonological store. Because smooth and rapid updating of the phonological store requires predictive control of the articulatory process, “the cerebellum could compute the discrepancy between actual and intended phonological rehearsal and use this information to update a feedforward command to the frontal lobe, thereby facilitating the phonological loop” (Desmond et al., 1997).

In a report on the motor theory of speech, which emphasizes the relationships between perception and action (Liberman & Mattingly, 1985), Ravizza et al. (2006) argued that cerebellar processing in vWM may be important for integrating acoustic/phonetic representations with articulatory representations and for correcting degraded sensory information. To this end, the cerebellum may provide a mechanism for creating more integrated and stronger memory traces, which are less prone to decay and error.

Ravizza et al. (2006) hypothesised a role of the cerebellum in vWM that was not limited to merely the rehearsal process but was also involved with the ph-STS. The present report is the first to demonstrate a selective impairment of the ph-STS, with sparing of the rehearsal process after cerebellar damage. Considering previous lesion studies that have reported selective impairment of the rehearsal component of the vWM, it is conceivable to hypothesise that also in vWM, cerebro-cerebellar interactions may act according to parallel segregated loops, as hypothesised for motor and cognitive functions (Middleton & Strick, 1997).

Further, as suggested also by Chen and Desmond (2005a), different cerebro-cerebellar loops support the functions of different cerebral modules. Therefore, isolated cerebellar lesions might affect one modular function with only discrete effects on performance as a whole.

How does this mechanism apply to the Baddeley's model of vWM? Each of the vWM cortical modules may receive in support selective cerebellar channels. If this is the case, differences in anatomical localisation of cerebellar damage can affect one channel while sparing the others. Thus, cerebellar patients may present different modalities of vWM impairment according to the topography of their lesion.

In this context, the discrepancy between the neuroimaging literature, which has shown consistent involvement of the cerebellum in vWM, and the neuropsychological literature, which has reported very little evidence of clear vMW impairment in patients with cerebellar damage, is readily apparent. In fact, in working memory function, as in other cognitive domains, cerebellar damage can be compensated by other neural systems that are still able to perform the function, but at a less efficient level.

Is the cerebellar contribution limited to verbal working memory or does it intervene also in spatial working memory? This question is interesting, and of relevance for general theories on the cerebellar functions. Present data do not allow us to directly address this topic. We observed normal verbal and spatial working memory performances in the general neuropsychological examination (see Tables 1 and 2). Nevertheless, when vWM has been addressed in detail, clear impairments have been demonstrated. Thus, it may be argued that spatial working memory impairments might also be revealed by a more detailed analysis. At present only few studies addressed the cerebellar role in spatial working memory with contrasting data. Studies in rodents reported various degrees of cerebellar involvement in spatial working memory (Mandolesi, Leggio, Graziano, Neri, & Petrosini, 2001; Martin, Escher, Goldowitz, & Mittleman, 2004) while excitotoxic lesions of deep cerebellar nuclei in monkeys did not affect spatial working memory (Nixon & Passingham, 1999). In humans, early functional imaging studies did not find cerebellar activation in spatial working memory tasks (Smith & Jonides, 1998) and the cerebellum has been suggested not to play a role in this function (Ivry & Fiez, 2000). Nevertheless, more recent functional imaging data indicated cerebellar activations associated with spatial working memory tasks (Haberecht et al., 2001; Koppelstaetter et al., 2008; Luna et al., 2002). Thus, cerebellum and spatial working memory appear promising fields for future research.

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