

Reduced phonological similarity effects in patients with damage to the cerebellum

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Abstract

Ten cerebellar patients were compared to 10 control subjects on a verbal working memory task in which the phonological similarity of the words to be remembered and their modality of presentation were manipulated. Cerebellar patients demonstrated a reduction of the phonological similarity effect relative to controls. Further, this reduction did not depend systematically upon the presentation modality. These results first document that qualitative differences in verbal working memory may be observed following cerebellar damage, indicating altered cognitive processing, even though behavioral output as measured by the digit span may be within normal limits. However, the results also present problems for the hypothesis that the cerebellar role is specifically associated with articulatory rehearsal as conceptualized in the Baddeley–Hitch model of working memory.

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1. Introduction

Researchers in cognitive neuroscience have in many cases looked to converging data from multiple methodologies when investigating a cognitive process of interest. The complementary perspectives of functional neuroimaging and cognitive neuropsychology are often employed in this regard; a strong case can be made for the involvement of a brain region in a given cognitive process when it is both metabolically active when healthy participants engage in the cognitive process, and when damage to this region disrupts the same cognitive process. Although the precise nature of this involvement may prove elusive to characterize, the brain region comes to be regarded as an essential com-

ponent of the system in question. When the two methodologies of neuroimaging and neuropsychology do not converge, however, even the most basic question of whether a given region is involved in a cognitive process is difficult to address.

One issue that must be kept in mind when making comparisons between data from neuroimaging and data from neuropsychology is that the two methods provide very different kinds of evidence about cognition. Neuroimaging studies have the potential to document *qualitative* aspects of cognitive processing that may not be evident from the behavioral outcome. In contrast, neuropsychological data—particularly that from standardized batteries that examine for gross impairment across a wide range of cognitive tasks—sometimes do not allow for such an observation. Identical behavioral outcomes may become falsely equated with identical cognitive processes, when this most cer-

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tainly is not always the case.¹ Neuropsychological studies must be designed such that the relevant qualitative as well as quantitative differences in a cognitive process may be observed.

A relative lack of convergence in the neuroimaging and neuropsychological literatures was a part of the motivation for the current study, which investigated the verbal working memory abilities of patients with damage to the cerebellum. As will be discussed below, the cerebellum is one of the most consistently activated regions in neuroimaging studies that employ verbal working memory tasks. However, a large reduction in verbal working memory capacity, for instance as measured by the digit span, is not typically reported in patients with cerebellar disorders. A possible explanation for this discrepancy is that although the verbal working memory system of these patients has been altered in a qualitative way, the altered system is nonetheless capable of producing near-normal behavioral output on standardized neuropsychological tests. For this reason, we wished to design a verbal working memory experiment that would go beyond simple measures of overall capacity and search for qualitative changes following cerebellar damage. The design that we chose not only allowed for the documentation of such a qualitative change in verbal working memory in our patient group, but also allowed us to examine a functional hypothesis, namely that the role of the cerebellum in verbal working memory is specifically articulatory rehearsal.

With this in mind, we shall first briefly review the Baddeley–Hitch multiple component model (e.g., Baddeley, 1986; Baddeley & Hitch, 1974), which is the dominant model of verbal working memory. Then we shall consider the relatively weak evidence from neuropsychology and the much more consistent evidence from functional neuroimaging regarding a cerebellar role in verbal working memory. Finally, we shall consider the ways in which the cerebellum may map onto the components of the Baddeley–Hitch model and motivate the design of the current neuropsychological study.

1.1. The Baddeley–Hitch model

In the Baddeley–Hitch model (e.g., Baddeley, 1986), working memory is divided into three components: a central executive that coordinates information processing in all modalities and two modality-specific systems, a visuospatial sketchpad and a phonological loop. The phonological loop is further divided into two subsystems: a phonological short-term store and an articulatory rehearsal mechanism. The phonological short-term store is thought to be the locus of input-based phonetic

representations and an output-based rehearsal process is thought to be required to refresh information in the store.²

A key feature of the Baddeley–Hitch model is that it posits separate phonetic and articulatory representations, rather than arguing that speech is immediately perceived in terms of articulation (i.e., motor theories of speech perception, e.g., Liberman & Mattingly, 1985). The primary psychological evidence for this separation comes from studies that have manipulated phonological similarity, word length, modality, and articulatory suppression. Phonologically similar words are more difficult to remember than phonologically dissimilar words (Conrad, 1964). This *phonological similarity effect* is believed to reflect conflicts that arise in the phonological short-term store. Additionally, words with many syllables are more difficult to remember than words with fewer syllables (Baddeley, Thomson, & Buchanan, 1975). This *word length effect* is believed to reflect the process of articulatory rehearsal, with increasing rehearsal demands for longer words. In support of this hypothesis, the word length effect disappears when articulation is suppressed, as for example when the participant must count repeatedly from one to three when perceiving and rehearsing the word list (Baddeley, Lewis, & Vallar, 1984). Interestingly, manipulations of input modality can further affect the phonological similarity effect, but not the word length effect under these conditions; articulatory suppression eliminates the word length effect regardless of whether the word list is heard or read, but eliminates the phonological similarity effect only when the words are read. This interaction between modality and articulatory suppression for the phonological similarity effect is the primary empirical basis for hypothesizing a distinction between phonetic and articulatory processing in working memory (see Fig. 1). We shall return to this interaction later in the introduction when making predictions for the current study.

1.2. Neuropsychology of verbal working memory

Neuropsychological studies have provided an important source of evidence in the development of the Baddeley–Hitch model, including dissociations in sup-

¹ For a similar argument from a developmental cognitive neuroscience perspective on the “preserved” abilities of individuals with Williams Syndrome, see Karmiloff-Smith (1998).

² The term *phonetic* refers to a more perceptual representation than does the term *phonological*. The determination of voice-onset time (VOT) to distinguish a /t/ from a /d/, for example, is more correctly referred to as a phonetic process, whereas the symbolic representation of the phonemes /t/ or /d/ is more correctly referred to as phonological. Phonetic representations are input-based, whereas phonological representations are abstract. We attempt to maintain this distinction here, while retaining the connection in the Baddeley–Hitch model between input-based representations and the “phonological” short-term store. (See Phillips et al., 2000; Phillips, 2001, for a discussion of the differences between phonetic and phonological representation.) For output-based representations, we use the term *articulatory*.

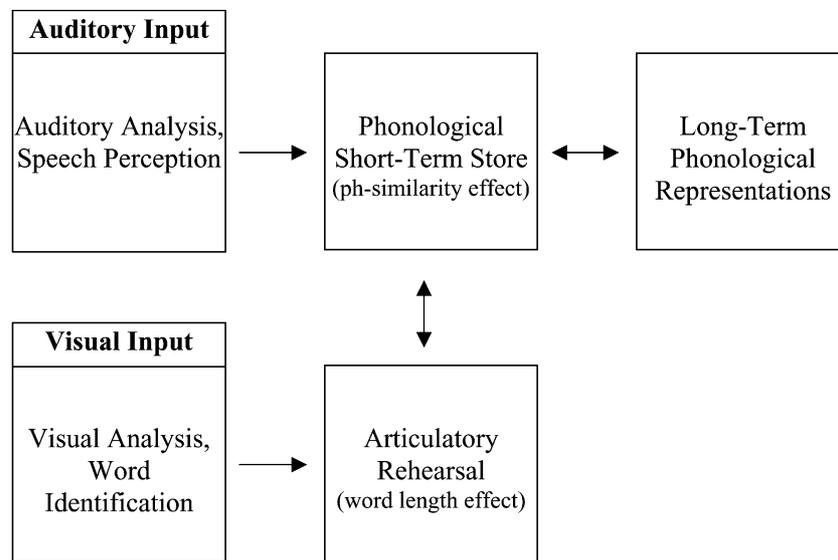


Fig. 1. The Baddeley–Hitch model. According to the model, the phonological short-term store is the locus of the phonological similarity effect, and receives spoken language automatically. The articulatory rehearsal mechanism is the locus of the word length effect and is required to recode written language for the phonological short-term store (adapted from Baddeley et al., 1998).

port of its subdivisions. The typical profile of the “short-term memory (STM) patient” includes a reduced word span despite normal speech perception and production.³ This pattern has been interpreted as a selective disruption of the phonological short-term store. Two of the most studied STM patients were KF (Warrington & Shallice, 1969) and JB (Warrington, Logue, & Pratt, 1971). KF suffered damage to the left inferior parietal/occipitotemporal region, whereas JB suffered damage to the left middle and superior temporal gyri spreading into the inferior parietal lobe. The area of overlap in these and other STM patients, the inferior parietal lobule (BA 40), has been argued to be critical for phonological short-term storage (Shallice & Vallar, 1990). The literature on the verbal working memory abilities of these cortical patients is extensive, and it is beyond the scope of this paper to review it here. The reader is referred to reviews by Shallice and Vallar (1990) and a more recent review by Vallar and Papagno (2002).

In contrast to the many cases of verbal working memory deficit following damage to the cerebral cortex, such impairments have not typically been reported following damage to the cerebellum. Studies of cerebellar patients that have incorporated the digit span into the neuropsychological battery typically have found scores in the normal range. For instance, Bürk et al. (1999) found that even the demented subset of their German spinocerebellar ataxia (SCA) 2 patients was only slightly lowered (4.8 ± 1) relative to the controls (6.1 ± 1), whereas their

non-demented SCA2 patients did not differ significantly from controls (5.9 ± 1.3). Other studies have similarly reported digit spans in the low-normal to normal range with no statistical differences between patients and controls (e.g., Bracke-Tolkmitt et al., 1989; Bürk et al., 2003; Fabbro et al., 2004; Fiez, Petersen, Cheney, & Raichle, 1992; Globas et al., 2003; Le Pira et al., 2002; Schmahmann & Sherman, 1998; Timmann et al., 2002). Those studies that have reported digit spans to be reduced (e.g., Akshoomoff, Courchesne, Press, & Iragui, 1992; Schelhaas et al., 2001), even when significantly reduced relative to controls (e.g., Maddox, Aparicio, Marchant, & Ivry, in press; Ravizza, McCormick, Justus, & Fiez, 2004; Ravizza, McCormick, Justus, Ivry, & Fiez, submitted; Witt, Nühsman, & Deuschl, 2002), typically report a reduction of only one or two items from the normal range. This stands in contrast to the more profound deficits of cortical STM patients (e.g., 2 or 3 items). Interestingly, more severe digit-span deficits are observed in individuals who suffered cerebellar damage during childhood (Schatz, Hale, & Myerson, 1998; Scott et al., 2001; Steinlin, Styger, & Boltshauser, 1999; Steinlin et al., 2003), emphasizing the difference between damage that disrupts the developmental process and damage acquired as an adult.

One case study does report verbal working memory data that revealed qualitative as well as quantitative changes. Silveri, Di Betta, Filippini, Leggio, and Molinari (1998) described an 18-year-old Italian patient who underwent surgical removal of the right cerebellar hemisphere. The patient was tested before surgery, 3 days after the surgery, and again 5 months later. Before and immediately after the surgery the patient had a reduced digit span of four items forwards and three items back-

³ Or at least a production deficit that cannot account for the reduction in span. Many of the patients summarized by Shallice and Vallar (1990) showed some degree of anomia and/or paraphasia.

wards. This study was unique in that the authors went beyond the simple digit span and collected data from verbal working memory tasks in which phonological similarity, word length, modality of presentation, and articulatory suppression were manipulated, and thus had the potential to observe some qualitative as well as quantitative changes in verbal working memory.

The patient showed a reduction in the phonological similarity effect that was dependant on the modality of presentation; there was an effect with auditory presentation but not with visual presentation. Interestingly, this patient's digit span improved to seven when he was tested 5 months later and the phonological similarity effect for visual presentation was significant. The patient also showed no significant effect of word length in either modality, even when tested 5 months later. This result is difficult to attribute to the patient's surgery because Silveri et al. also report two control subjects showing the same pattern. However, the interaction between phonological similarity and modality in particular suggests a sparing of the phonological short-term store and an impairment of a component of the articulatory rehearsal mechanism. This conclusion is not clear cut, however, as the patient still showed a significant effect of articulatory suppression, unlike other patients with a proposed selective rehearsal deficit (Vallar, Di Betta, & Silveri, 1997).

1.3. Neuroimaging of verbal working memory

In contrast to the mixed results from neuropsychology, the cerebellum is one of the most consistently activated regions in neuroimaging studies of verbal working memory, along with a network of cortical regions including the inferior frontal lobe (especially BA 44/45), the supplementary motor area (SMA, medial BA 6), premotor cortex (PMC, lateral BA 6), and the parietal lobe (BA 7/40) (Andreasen et al., 1995; Awh et al., 1996; Chein & Fiez, 2001; Davachi, Maril, & Wagner, 2001; Fiez et al., 1996; Grasby et al., 1994; Gruber, 2001; Jonides et al., 1998; Paulesu, Frith, & Frackowiak, 1993; Petrides, Alivisatos, Meyer, & Evans, 1993; Ravizza, Delgado, Chein, Becker, & Fiez, 2004; Salmon et al., 1996; Schumacher et al., 1996). For example, Paulesu et al. (1993, Experiment 1) showed their participants a series of six letters in each trial, followed by a probe presented 2s after the end of the sequence. Participants judged whether each probe was present in the preceding sequence. Activation during this task was compared to a second condition in which Korean characters were used, which the English-speaking participants could not code phonologically. This contrast (Roman letters–Korean characters) revealed significant differences in BA 44, the SMA, BA 40, BA 22/42 (superior temporal), the insula, BA 18 (occipital), and the cerebellum.

1.4. The articulatory rehearsal hypothesis

The majority of these neuroimaging studies, like the Silveri et al. (1998) neuropsychological study, hypothesize a cerebellar role in articulatory rehearsal. Paulesu et al. (1993) argued that the cerebellum, in conjunction with the inferior frontal lobe and supplementary motor area, is part of an articulatory rehearsal mechanism, whereas the inferior parietal lobe is the locus of the phonological short-term store. In support of a link to overt speech, Petrides et al. (1993) observed bilateral cerebellar activation when comparing a condition involving more speech output (generating the numbers 1–10 in a mixed order) to a condition involving more speech input (monitoring a series generated by the experimenter and providing the missing number). Rehearsal processes were further suggested by a study showing a correlation between the length of the items to be remembered and activation in the cerebellar vermis and hemispheres (Grasby et al., 1994; also see Chein & Fiez, 2001).

The articulatory rehearsal hypothesis is motivated in part by the long-standing connection between the cerebellum and speech output (e.g., Ackermann & Hertrich, 2000). However, overt articulation and the processes used in articulatory rehearsal do not necessarily overlap. A group of dysarthric patients studied by Baddeley and Wilson (1985) did not show any evidence of impairment to the articulatory rehearsal mechanism. Similarly, Bishop and Robson (1989) reported intact articulatory rehearsal in a group of teenagers who were developmentally dysarthric due to cerebral palsy. In contrast, Waters, Rochon, and Caplan (1992) reported a group of left-hemisphere patients with speech apraxia (a disorder of speech planning rather than implementation), who did show an abnormal pattern of rehearsal effects, as did a group of five Broca's aphasics studied by Goerlich, Daum, Hertrich, and Ackermann (1995). Although none of these studies focused on patients with a dysarthria related to cerebellar damage, they do suggest that one cannot simply equate the mechanisms used in covert rehearsal with those of overt speech.

Some of the previously mentioned neuroimaging studies also suggest that articulatory rehearsal may not provide a complete account of cerebellar involvement in verbal working memory. Awh et al. (1996) replicated the cerebellar involvement during verbal working memory tasks. However, a condition involving an articulatory rehearsal control failed to account for this activity; significant activation in the right cerebellar hemisphere was observed even when a rehearsal control condition was subtracted from their working memory (two-back) task. Assuming that the rehearsal condition in this study was sufficient to mimic the articulatory requirements of the working memory tasks, the result suggests that the

cerebellum is doing something in addition to or instead of articulatory rehearsal.

The results of Chein and Fiez (2001) are also problematic for the rehearsal hypothesis. They attempted to separate activations associated with encoding, maintenance, and retrieval. Whereas the dorsolateral and inferior frontal cortex, insula, SMA, and (in some conditions) the inferior parietal lobe remained active throughout the maintenance period, the cerebellum was primarily active during encoding and retrieval. Contrary to the rehearsal hypothesis, no increase in cerebellar activation was observed during maintenance. This suggests that although the cerebellum may play a role in the initial perceptual analysis and/or initial articulatory encoding of the stimuli, it may not be engaged during rehearsal per se.⁴

1.5. Alternative hypotheses

An alternative hypothesis is that the cerebellum contributes to the phonological short-term store, or to the phonetic analysis that precedes this representation. Although this possibility has not been considered within the verbal working memory literature, a variety of evidence from neuropsychology and neuroimaging in other areas of language is suggestive of cerebellar roles in speech perception and phonological processing. Ackermann, Gräber, Hertrich, and Daum (1997) showed that a subset of patients with cerebellar atrophy did not perceive a clear phoneme distinction between sounds constructed along a closure time (CLT) continuum between the words *Boten* and *Boden*. The deficit has only been found when the cue is predominantly temporal and is not based on aspiration or articulatory events that result in spectral differences, as is typically the case with voice onset time (VOT) (Ackermann et al., 1997; Ivry & Gopal, 1992). Further, Mathiak, Hertrich, Grodd, and Ackermann (2002) found that during a *Boten/Boden* discrimination task, the left inferior frontal gyrus (in the vicinity of BA 47) and the right cerebellar hemisphere were recruited to a larger degree when the stimuli were constructed using a CLT continuum, the purely temporal distinction, compared to a VOT continuum that also included distinctions based on aspiration (see also Burton, Small, & Blumstein, 2000). Other work in a variety of lexical retrieval paradigms (e.g., Desmond, Gabrieli, & Glover, 1998; Petersen, Fox, Posner, Mintun, & Raichle, 1988, 1989; Roskies, Fiez, Balota, Raichle, & Petersen, 2001) suggests that the cerebellum is involved in some combi-

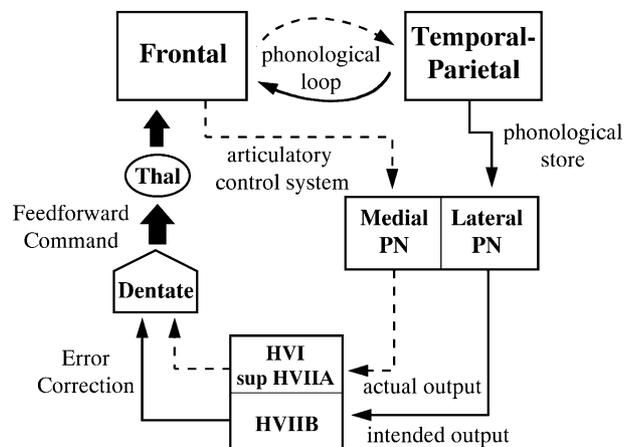


Fig. 2. Model of Desmond et al. (1997). According to this model, during each rehearsal cycle a frontal articulatory rehearsal mechanism sends input through the medial pontine nuclei (PN) to the superior cerebellum and a temporal-parietal phonological short-term store sends input through the lateral pontine nuclei to the inferior cerebellum. Discrepancies between the two are fed forward through the dentate nuclei and thalamus back to the frontal lobe. Copyright 1997 by the Society for Neuroscience.

nation of the semantic and phonological stages of lexical retrieval.⁵ Developmental work in reading and dyslexia, a disorder considered by many to stem from abnormal phonological processing, has also suggested a cerebellar component (e.g., Nicolson, Fawcett, & Dean, 2001; but see Ramus, Pidgeon, & Frith, 2003). Finally, perceptual tasks tapping grammatical morphology have also suggested that cerebellar patients may have difficulty perceiving and encoding morphological markers that are not acoustically salient (Justus, 2004; Justus, Hertrich, Ackermann, Bürk, & Ivry, 2004). Given these links to phonetics and phonology, we also consider the hypothesis that the cerebellum contributes to the phonological short-term store.

A third hypothesis, argued by Desmond, Gabrieli, Wagner, Ginier, and Glover (1997; Desmond, 2001), is that the cerebellum compares the contents of the articulatory rehearsal mechanism with the intended action represented by the phonological short-term store, and thus serves as an interface between the phonological short-term store and articulatory rehearsal (Fig. 2). In this model, regions within the superior cerebellum (lobules HVI and HVIIA) receive input from frontal areas involved in articulatory rehearsal via the medial pontine nuclei. The inferior cerebellum (lobule HVIIIB) receives input from parietal areas involved in the phonological short-term store via the lateral pontine nuclei. Discrep-

⁴ Chein and Fiez (2001) also question the hypothesis that the inferior parietal lobe serves as the locus of the phonological short-term store. See Fiez et al. (1996), Becker, MacAndrew, and Fiez (1999), Jonides et al. (1998), Chein, Ravizza, and Fiez (2003), and Ravizza, Delgado, et al. (2004) for discussion of this issue.

⁵ Interestingly, lexical retrieval paradigms seem to show the same discrepancy between neuroimaging findings that consistently indicate cerebellar involvement and largely preserved behavioral outcomes (although not necessarily identical cognitive processes) in cerebellar patients (e.g., Helmuth, Ivry, & Shimizu, 1997; Richter et al., 2004).

Table 1
Predictions for the current study

Hypothesized role for the cerebellum	Prediction: visual presentation	Prediction: auditory presentation
(1) Articulatory rehearsal, e.g., Paulesu et al. (1993)	(–) Reduced similarity effect	(+) <i>Preserved</i> similarity effect
(2) Phonological short-term store	(–) Reduced similarity effect	(–) Reduced similarity effect
(3) Interface between articulatory rehearsal and phonological short-term store, e.g., Desmond et al. (1997)	(–) Reduced similarity effect	(+) <i>Preserved</i> similarity effect ^a

^a Assuming that the inferior cerebellum is not itself part of the phonological STS.

ancies between the two are detected when these two pathways converge at the dentate nucleus and this information is fed forward to the frontal lobe via the thalamus. This model was based on a neuroimaging study in which the memory load was manipulated for conditions designed to engage working memory or rehearsal processes alone. Whereas the superior loci were affected by the load manipulation in both working memory and rehearsal conditions, the inferior loci were only affected by the load manipulation in the working memory condition, suggesting that phonological storage and not just rehearsal was essential for their participation (Desmond et al., 1997).

1.6. The present study

The relationship between the phonological similarity effect, modality of presentation, and articulatory suppression in verbal working memory studies in normal individuals offers a non-trivial prediction regarding selective damage to the articulatory rehearsal mechanism. In neurologically normal individuals, articulatory suppression is believed to engage the rehearsal mechanism selectively and not the phonological short-term store. Requiring a second articulatory task during a verbal working memory study diminishes the word length effect with both auditory and visual presentation, but diminishes the phonological similarity effect only when presentation is visual (Baddeley et al., 1984). Because of this, the Baddeley–Hitch model claims that spoken language gains access to the phonological short-term store automatically, whereas written language is dependent upon the articulatory rehearsal mechanism to be re-coded phonologically.

The articulatory rehearsal hypothesis predicts that the pattern associated with articulatory suppression should also be found with cerebellar patients: a reduced effect of phonological similarity for word lists presented visually but not aurally. This is the pattern observed in the previously mentioned cerebellar case study reported by Silveri et al. (1998).

In contrast, a single deficit to the phonological short-term store (Hypothesis 2), would predict a different pattern of results. The phonological similarity effect should be diminished with damage to the phonological short-term store with either presentation modality, given that it is the proposed locus of the effect.

Desmond's interface hypothesis (Hypothesis 3) also makes similar predictions to the rehearsal hypothesis. Despite the fact that the cerebellum receives input from the phonological short-term store in this model, we argue that a reduction of the phonological similarity effect is predicted only when presentation is visual, as in Hypothesis 1. Whereas the rehearsal mechanism in this model would be critically disrupted with damage to the cerebellum, the phonological short-term store would still be intact in its hypothesized temporal–parietal locus. The intact store would continue to input clearer phonological representations for phonologically dissimilar lists compared to phonologically similar lists into the rehearsal mechanism, which then would presumably degrade at an equal rate in the absence of effective rehearsal (thus preserving any initial difference between the two). If the model were altered to include a more direct role for the cerebellum in the phonological short-term store, rather than being downstream from it, then reductions in the auditory modality might be expected as well.

Table 1 lists these three hypotheses and associated predictions. Note that the hypotheses in Table 1 do not speak to the possibility of multiple deficits. In each case the predictions are based on the assumption that all other elements of the working memory system are intact. Thus failing to find a particular pattern in the data predicted by Table 1 argues against a *single deficit* in each of these components of working memory, rather than arguing that the component in question is *intact*.

Additionally, it should be noted that the current study was not designed to distinguish between Hypotheses 1 and 3, which make identical predictions and would have required additional study to tease them apart if the data were consistent with these predictions. To anticipate, the data were not consistent with either of these hypotheses.

2. Method

2.1. Participants

Ten patients with damage to the cerebellum were examined for this experiment: four with bilateral degeneration (B2, B3, B4, and B5), three with focal lesions in the left hemisphere (L2, L3, and L4), and three with focal

Table 2
Cerebellar patients

Patient	Hemisphere	Etiology (at age)	Age	Education	Handedness	Sex	Language (n = native)	NART	Verbal fluency		WAIS-III Digit Span			ICARS	
									Letter	Category	Forward	Back	Scaled	Total	Dysarthria
B2	Bilateral	Degeneration (c. 30-)	71	12	Right	M	English	100	25	47	4.5	2.5	6	45	4.75
B3	Bilateral	Degeneration (c. 61-)	62	20	Right	M	English	116	35	45	4	3.5	7	17.75	3.25
B4	Bilateral	Degeneration (c. 20s-)	62	17	Right	M	Spanish ⁿ , English (5-)	111	30	47	4.5	2	6	42.75	5.5
B5	Bilateral	SCA3 (c. 27-)	44	13	Right	F	English	111	16	34	5	3	7	—	—
L2 ^a	Left	Tumor (34)	56	11	Mixed	M	English	87	21	35	4	2.5	6	23.25	5
L3 ^a	Left	Stroke (66)	78	8	Right	M	English	—	18	33	~3	—	—	—	—
L4	Left	Stroke (48)	52	13	Right	M	English	117	51	48	8	4.5	13	10	1.5
R1	Right	Stroke (66)	75	18	Right	M	English	112	19	48	5.5	5	12	34	3
R2	Right	Tumor (42)	46	18	Left	M	English ⁿ , German (9-)	114	27	50	6.5	4	10	32.75	3.5
R3	Right	Stroke (55)	65	12	Right	M	English	111	61	58	7.5	3	11	4.25	1

Abbreviations. NART: National Adult Reading Test (mean 100, estimate of premorbid IQ); WAIS: Wechsler Adult Intelligence Scale, forward span: number of items able to hold and recall (not the score), backward span: number of items able to hold and recall backwards (not the score), WAIS scaled score representing forward and backward span, standardized to age group (mean 10); ICARS: International Cooperative Ataxia Rating Scale (Trouillas et al., 1997), overall estimate of ataxic impairment (maximum 100), dysarthria subscore (maximum 8).

^a Participated in only the auditory experiment due to poor vision.

lesions in the right hemisphere (R1, R2, and R3).⁶ Ten controls of similar age (mean 67), education (mean 13 years), and handedness (8 right handed) also participated in the experiment. Further details concerning the etiologies, demographics, and test scores of the patients are given in Table 2. The specific regions of cerebellar damage varied from patient to patient and are illustrated in Fig. 3.

Consistent with the previously mentioned neuropsychological studies, standardized data for 9 of the 10 cerebellar patients indicated that overall verbal working memory capacity (WAIS-III digit span) was in the low average range for some of the participants (B2, B3, B4, B5, and L2), whereas the scores of the other patients were normal (R1, R2, R3, and L4). No standardized data on the digit span are available for L3, who is now deceased. For this patient, an estimate of forward digit span is given based on performance in the current study.

One might object that, because there was no compelling deficit on the digit span, no further neuropsychological study of the verbal working memory of these patients was motivated. The group detriment in verbal working memory capacity is subtle; only when combined in larger groups have we demonstrated a significant reduction in digit span scores relative to controls, with no effect on WAIS spatial span (Maddox et al., in press; Ravizza, McCormick, et al., 2004). As described earlier, the relatively preserved digit span of these patients, along with the evidence from neuroimaging which consistently documented cerebellar activation during similar tasks, suggested to us that qualitative changes in verbal working memory performance might be observed in these patients even if overall capacity were not significantly reduced.

2.2. Experimental design

The stimuli were 60 monosyllabic English words, representing six vowels and 10 initial consonants (Table 3). In the auditory condition, the experimenter read the word lists. In the visual condition, the words were presented on the computer screen. In both conditions, the words were presented at a rate of 1 word per 1.5 s. The visual stimuli were printed in the middle of the screen, with the words spanning approximately 5° of visual angle. After 5 s, the participant was cued by the computer to recall the words orally to the experimenter.

Word lists were composed of five or six items depending on each individual's overall ability, as determined by a practice session. We were concerned that testing all participants with the same list length would result in ceiling effects for some participants, thus diminishing the observed size of the phonological similarity effect. Thus, we used five-item lists for all of the participants unless they performed perfectly on multiple five-item lists dur-

⁶ Patient labels correspond to those used by Justus (2004).

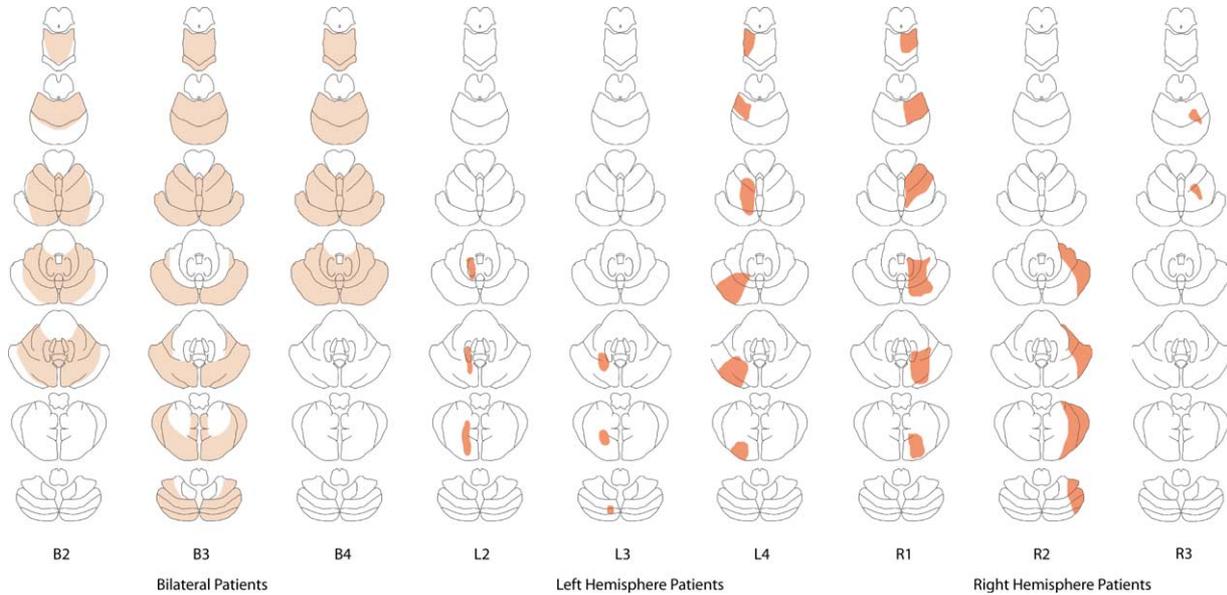


Fig. 3. Cerebellar lesions. For each patient, a column of seven horizontal slices through the pons and cerebellum are shown, with the most superior slice at the top. Within each slice, rostral is toward the top and caudal toward the bottom; left is left and right is right. Dark gray indicates a tissue lesion, whereas medium gray indicates tissue degeneration. No scan was available for Patient B5, who is a genetically confirmed case of SCA3 ataxia.

Table 3
Experimental stimuli for generating phonologically similar and dissimilar lists

Initial consonant	Vowel					
	/i/	/e/	/E/	/ae/	/ʌ/	/I/
/b/	bead	bathe	bell	back	bus	bin
/p/	peace	pace	peg	pan	pun	pick
/d/	deal	date	deaf	dad	done	dip
/t/	tease	tail	ten	tab	tug	tin
/k/	keen	cage	keg	cat	cut	kiss
/s/	seek	safe	set	sad	sum	sip
/f/	feet	fame	fed	fad	fudge	fit
/l/	leaf	lake	ledge	lag	luck	lid
/m/	meet	maze	men	mass	mud	mill
/n/	need	name	neck	nap	nut	knit

ing the practice session. This occurred in four cases (Patient B3, Patient B5, and two controls). These four individuals were tested with six-item lists.

Half of the lists were constructed using words from the same vowel category (e.g., *bead, peace, leaf, tease, deal*) to create a *phonologically similar list*. The other half were constructed using only one word per vowel category (e.g., *bead, pace, ledge, tab, dip*) to create a *phonologically dissimilar list*.⁷ Note that any particular word occurred equally often in both the phonologically simi-

lar and dissimilar conditions; thus both conditions were inherently balanced for word frequency, abstractness, and the like. Each block consisted of 12 lists, six phonologically similar and six phonologically dissimilar, and the participants tested with both visual and auditory conditions alternated between the two modalities, doing two blocks of each. The modality order was counterbalanced.

Because the stimuli were real words, as opposed to letters or pseudowords, one might object that participants could have used a semantic strategy to remember the lists. However, this would not undermine the utility of the difference scores representing the phonological similarity effect. Any additional boost in performance resulting from semantic coding would have increased recall in both the phonologically similar and dissimilar lists (and in both the visual and auditory conditions as well), given that every word was equally likely to occur in all conditions. Thus the comparison of performance in different conditions should not be affected by a semantic effect. Further, a semantic strategy was specifically discouraged by the experimenter, who informed the participants that each word would appear in the experiment multiple times and that the best strategy was to mentally rehearse each list.

The use of real words was motivated, on the other hand, for three reasons. First, the dysarthria of some of the patients would have made the coding of errors in the production of letter names or pseudowords extremely unreliable. Second, we would have had the additional concern that participants were not *perceiving* the stimuli correctly, particularly for the aural condition. Finally, unlike the use of letters, our real-word stimulus set

⁷ The stimuli in Table 3 also lend themselves to combination by initial consonant, rather than by vowel. We chose a vowel manipulation for this study to be consistent with the majority of previous manipulations of phonological similarity, and because we suspected that explicit strategies might aid in recalling lists that begin with the same consonant. Only one patient (B3) and one control had any awareness of the (vowel-based) phonological similarity manipulation by the end of the experiment.

allowed for the same words to be used in both phonologically similar and dissimilar lists. For instance, *bead* was a similar item if combined with *peace*, *leaf*, *tease*, and *deal*, and was a dissimilar item if combined with *pace*, *ledge*, *tab*, and *dip*. The pronunciations of the 26 letters do not allow this kind of manipulation, which raises the possibility of any number of confounds between phonologically similar and dissimilar items (e.g., orthographic similarity).

In summary, there were three variables in the experiment—(1) phonological similarity: whether the list words were combined such that all contained the same or different vowels, (2) modality of presentation: auditory or visual, and (3) group: cerebellar patient (bilateral, left, or right) or healthy control.

3. Results

3.1. Auditory condition

Given that there were two patients who completed only the auditory condition, separate analyses of variance were conducted for the auditory and visual experi-

ments, each with the variables of phonological similarity and group, before combining the data into a larger analysis, which included the variables of phonological similarity, modality, and group.

Fig. 4 presents the data for the auditory condition only for both the patients individually and the four groups. The data are presented as the probability of recalling a word when presented in a phonologically dissimilar context (black bars) and when presented in a phonologically similar context (gray bars). Although there was a trend for worse performance in general on the part of the patients, this difference was not significant ($F(1, 18) = 2.2, p = .16$). This was as expected, because we hypothesized a qualitative difference (effect size) rather than a quantitative difference (overall ability) in verbal working memory. The critical information comes from the difference in performance between the two conditions for each participant.

The control participants, shown at the right of each plot, showed a significant effect of phonological similarity ($t(9) = 4.7, p = .001$). The patients demonstrated a good deal of individual variability in the size of the effect. Patient L4, who had the strongest digit span of the group, stood out with the largest effect size. Addi-

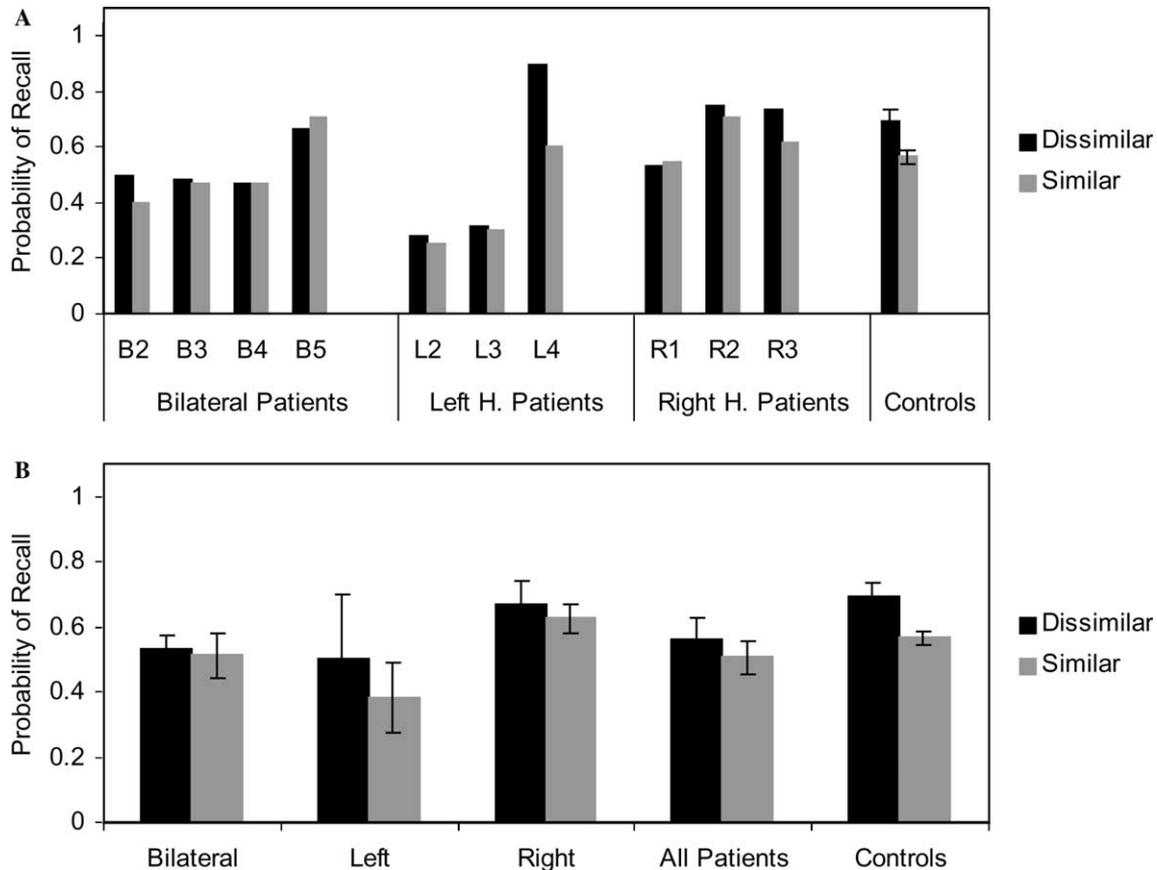


Fig. 4. Phonological similarity effects with auditory presentation. The probability of recalling a word is shown for both phonologically dissimilar contexts (black) and phonologically similar contexts (gray), for the individual patients (A) and the groups (B). These data are for the trials in which words were presented aurally.

tionally, patients B2 and R3 showed effects in the same range as the controls. However, the other seven patients demonstrated relatively flat effects, suggesting that phonological dissimilarity did not aid them in their performance of the task. As shown in the lower plot, the patients as a single group showed a trend in the same direction as the controls that was not significant ($t(9) = 1.8, p = .10$). Comparisons of the patients divided into groups based on laterality also did not show a significant effect of phonological similarity for any of the three groups (bilateral, left, and right, all $p > .30$). This reduction in the effect for the patients relative to controls would have been strongly supported by an interaction between phonological similarity and group, but this did not reach statistical significance ($F(1, 18) = 3.0, p = .10$).

3.2. Visual condition

Fig. 5 presents an analogous plot for the visual condition. Note that patients L2 and L3 could not participate in this condition. Unlike the auditory condition, the patients performed more poorly in general on this task relative to the controls ($F(1, 16) = 6.0, p = .03$). But again, the design

of the study emphasizes the difference in the size of the phonological similarity effect for each participant.

The control participants showed a significant effect of phonological similarity ($t(9) = 3.9, p = .004$), but as in the auditory condition, the patients were more variable. Patient L4 again stood out as having the largest effect of phonological similarity. The three right hemisphere patients demonstrated relatively weak effects in the predicted direction, whereas patient B3 showed a reverse effect. The remaining three bilateral patients showed relatively flat effects. As shown in the lower plot, the patients as a single group showed a weak trend in the same direction as the controls that was not significant ($t(7) = 1.1, p = .32$). Comparisons of the patients divided into right hemisphere and bilateral groups also did not show a significant effect of phonological similarity for either (right: $t(2) = 3.0, p = .10$; bilateral: $t(3) = -1.1, p = .34$). This reduction in the effect for the patient group as a whole was supported by a significant interaction between phonological similarity and group ($F(1, 16) = 5.4, p = .03$). Paired comparisons indicated that the interaction was only significant for the bilateral patients compared to the controls ($F(1, 12) = 7.8, p = .02$).

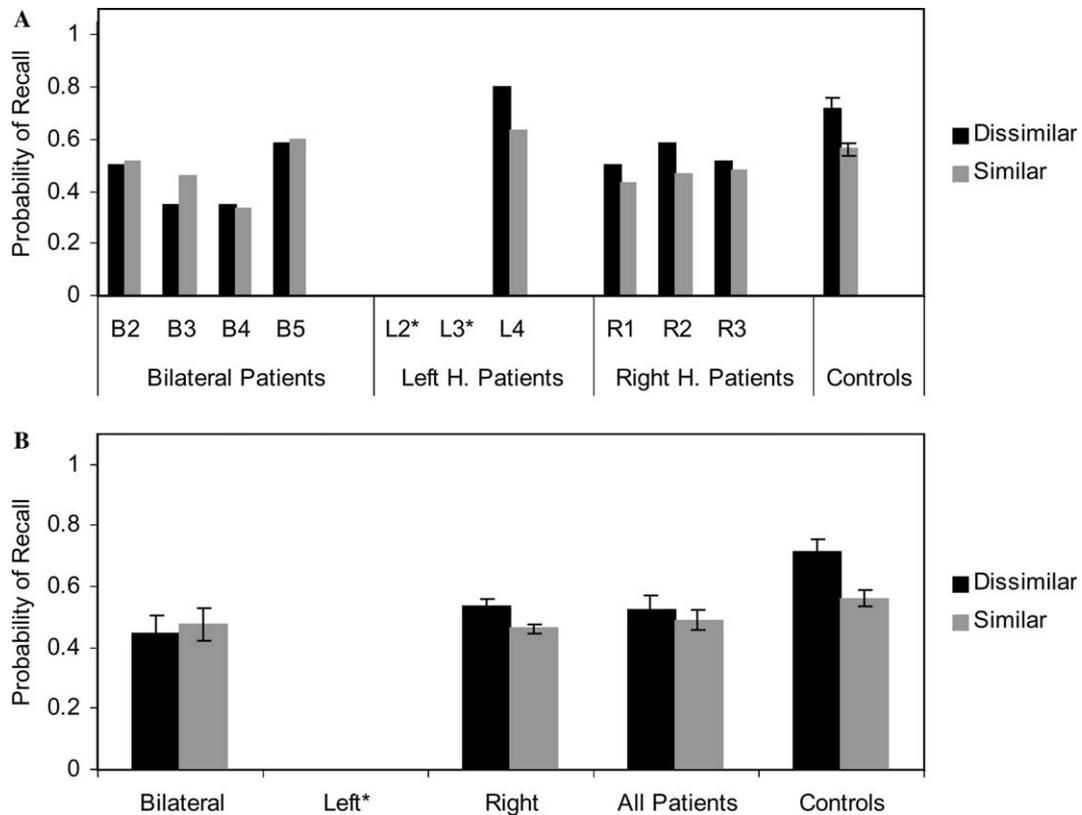


Fig. 5. Phonological similarity effects with visual presentation. The probability of recalling a word is shown for both phonologically dissimilar contexts (black) and phonologically similar contexts (gray), for the individual patients (A) and the groups (B). These data are for the trials in which words were presented visually. (*Only one left-hemisphere patient participated in the visual portion of the study, thus no left-hemisphere group data are shown in the lower plot.)

3.3. Combined auditory and visual analysis

To compare the reduction of the phonological similarity effect across the two modalities in a more direct way, a third analysis was conducted on the combined data for the eight patients who participated in both auditory and visual conditions. First, there was a tendency for the patients to do more poorly in the visual condition relative to the auditory condition in general ($F(1,7)=9.8, p=.02$), whereas the controls did not differ between the modalities ($F(1,9)=.06, p=.82$). This difference was supported by a marginally significant interaction between modality and group ($F(1,16)=3.9, p=.07$).

Consistent with the individual modality analyses, the overall effect of phonological similarity for both modalities combined ($F(1,16)=18.8, p=.001$) was significant for the control participants ($F(1,9)=21.7, p=.001$), but not for the patients ($F(1,7)=2.4, p=.16$). The interaction between phonological similarity and group was significant ($F(1,16)=4.5, p=.05$). Paired comparisons indicated that the interaction was only significant for the bilateral patients compared to the controls ($F(1,12)=8.6, p=.01$).

The separate analyses of the auditory and visual condition suggested that the group reduction in the phono-

logical similarity effect was more consistent in the visual condition. However, in the combined analysis there was neither an interaction between phonological similarity and modality ($F(1,16)=.02, p=.89$; patients only: $F(1,7)=.95, p=.36$; controls only $F(1,9)=.67, p=.43$) nor a three-way interaction between similarity, modality, and group: $F(1,16)=1.6, p=.23$. This suggests that the difference between the patients and controls in the size of the phonological similarity effect was not systematically affected by the modality of presentation.

To help illustrate the phonological similarity effect as a function of modality more clearly, Fig. 6 shows the same data from the auditory condition (black bars) and the visual condition (gray bars) as difference scores between the probability of recalling a word within a phonologically dissimilar list and the probability of recalling a word within a phonologically similar list. A value of zero means that the participant was equally successful in recalling words in the two conditions, and thus had no effect of phonological similarity. Positive values mean that phonologically dissimilar words were recalled more successfully than phonologically similar words, the typical phonological similarity effect, whereas negative values mean the reverse. As can be seen in the lower plot,

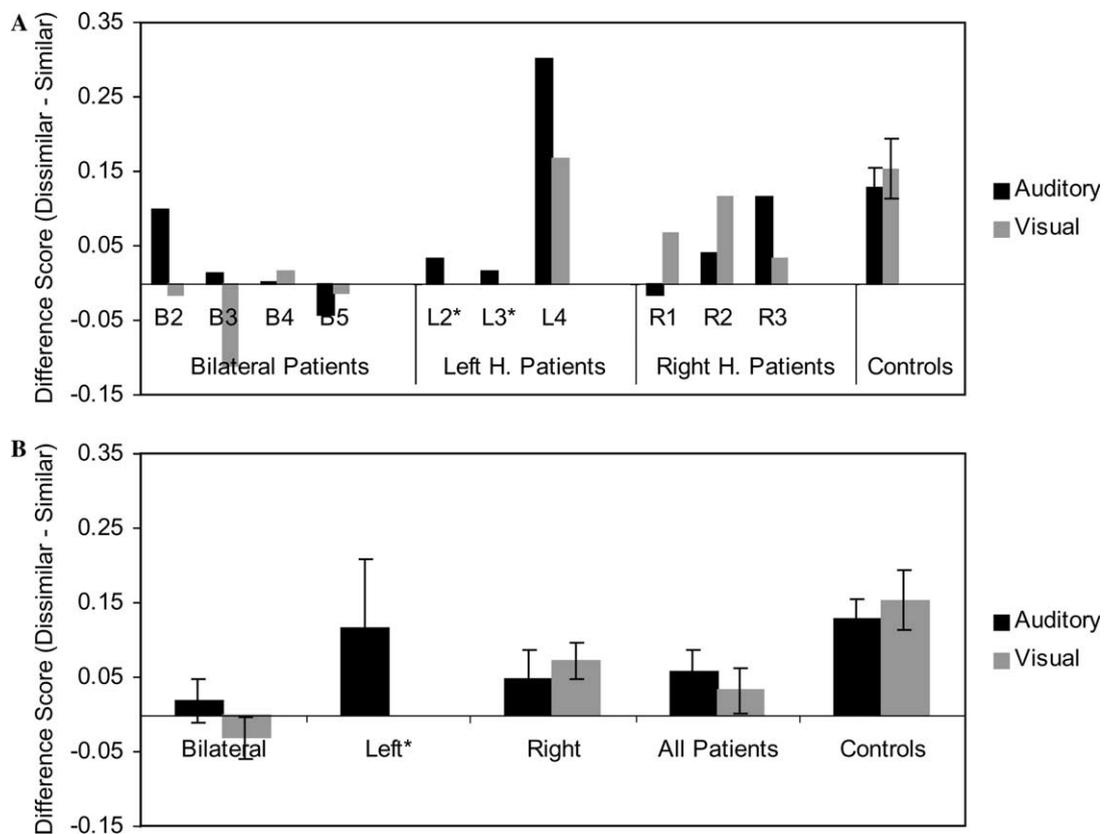


Fig. 6. Difference scores representing phonological similarity effects in both modalities. The data from Figs. 4 and 5 have been redrawn to show the difference between the recall for words in phonologically similar contexts and similar contexts, for both auditory presentation (gray) and visual presentation (white). (*Only one left-hemisphere patient participated in the visual portion of the study, thus left-hemisphere group data are shown only for the auditory condition in the lower plot.)

the mean phonological similarity effect for the patient group is smaller for that of the controls in both modalities.

4. Discussion

Ten cerebellar patients were compared to control subjects on a verbal working memory task in which the phonological similarity of the words to be remembered and their modality of presentation were manipulated. With the exception of one left-hemisphere patient, cerebellar patients demonstrated a reduction of the phonological similarity effect relative to controls in one or both of the modalities. Although separate analyses of each modality suggested that the group reduction of the effect may have been more consistent in the visual modality, examination of the individual scores and group means clearly suggests that a reduction occurred in the auditory condition as well.

Although the group means are also suggestive of a laterality effect, with the right cerebellar patients showing smaller similarity effects than did the left cerebellar patients, this should be taken with caution. Two of the left hemisphere patients (L2 and L3) could participate only in the auditory portion of the experiment (and both showed very flat similarity effects in this condition), whereas the third patient (L4) showed particularly large similarity effects.

A first point of discussion is that these experiments demonstrate a *qualitative* change in the verbal working memory of patients with damage to the cerebellum. The results suggest a way in which an apparent discrepancy might be resolved between the neuroimaging literature, which has shown consistent involvement of the cerebellum in verbal working memory, and the neuropsychological literature, which has typically demonstrated normal or near-normal digit span scores in cerebellar patients. It may be the case that the cerebellum does contribute to verbal working memory as the neuroimaging data suggest, but that upon cerebellar damage, other neural systems may be able to compensate for the damage by performing the task in a qualitatively different way.

The manipulations of phonological similarity and modality of presentation were designed as a critical test of the most frequently hypothesized role for the cerebellum in verbal working memory, namely that the cerebellum plays a role within the articulatory rehearsal component and not phonological short-term storage (Hypothesis 1 in Table 1). The Baddeley–Hitch model predicts that selective damage to the articulatory rehearsal mechanism should result in a reduced phonological similarity effect only when the modality of presentation is visual. The phonological similarity effect should be preserved with auditory presentation; this is

because the Baddeley–Hitch model attributes the phonological similarity effect entirely to the phonological short-term store, which receives speech independently of articulatory rehearsal. Our results do not provide clear support for the articulatory rehearsal hypothesis, as a reduction of the phonological similarity effect was observed in some patients for both auditory (Fig. 4) and visual (Fig. 5) modalities of presentation. Note that this does not mean that we are arguing that the articulatory rehearsal mechanism is necessarily preserved in cerebellar patients. Rather, a single deficit to articulatory rehearsal does not seem to explain the cerebellar contribution to verbal working memory completely.⁸

Next consider the hypothesis of Desmond et al. (1997) that the cerebellum serves as the interface between the articulatory rehearsal mechanism and the phonological short-term store (Hypothesis 3). Assuming that the inferior cerebellum is *receiving* phonological input from the inferior parietal lobe without playing an integral role in analysis or storage, our results are also inconsistent with this account. As with the pure articulation hypothesis, the diminished effect of phonological similarity with auditory presentation would not be expected. However, one point of interest with regard to the Desmond hypothesis relates to the data of patient R3, a right hemisphere patient whose cerebellar damage is the most selective to the superior portions of the hemisphere and patient B2, a bilateral patient with damage also concentrated in the superior portions of the cerebellum (as well as the vermis). Patients R3 and B2 did seem to fit the predictions of an articulatory deficit: they showed a reduction of the phonological similarity effect primarily with visual presentation. With auditory presentation, their effect sizes were similar to the control average. The other patient with damage concentrated in the superior regions of the cerebellum, patient B4, does not fit this pattern; he showed no effect of phonological similarity in either modality.

Finally, consider the hypothesis that the cerebellum is part of the phonological short-term store (Hypothesis 2). When considered in isolation, the current results are the most consistent with this hypothesis, explaining the reduction of the phonological similarity effect in both modalities. The phonological short-term store hypothesis is also consistent with another study on a separate group of eight cerebellar patients who demonstrated pre-

⁸ It should be noted that given our design, the strongest support for the articulatory rehearsal hypothesis would have been provided by a three-way interaction between phonological similarity, modality, and group. Although this interaction did not approach significance ($p = .23$), the two-way interaction was in fact stronger for the visual modality ($p = .03$) than for the auditory modality ($p = .10$). Thus, caution should be used in interpreting this null result. Nevertheless, with the exception of patients R3 and B2, it is difficult to reconcile the individual data with the predictions of the articulatory rehearsal hypothesis.

served word length and articulatory suppression effects (Ravizza et al., submitted, Experiment 4). Such an idea may seem at odds with the connection of the cerebellum with speech dysarthria. However, as mentioned previously, work with cortical patients suggests that speech *dyspraxia* is more likely to be related to articulatory rehearsal problems than is speech dysarthria (Baddeley & Wilson, 1985; Bishop & Robson, 1989; Goerlich et al., 1995; Waters et al., 1992). Further, there is a growing consensus that the cerebellum contributes to components of language other than overt and covert articulation (for reviews see Justus & Ivry, 2001; Mariën, Engelborghs, Fabbro, & De Deyn, 2001), and it is not implausible that its contribution to verbal working memory could relate to phonological short-term storage instead of or in addition to articulatory rehearsal. The current studies add to the case for a non-articulatory role for the cerebellum, and, if one is partial to the Baddeley–Hitch model, suggest consideration of how the cerebellum may be a component of both the phonetic and articulatory sides of speech.

4.1. Beyond the Baddeley–Hitch model

All of the discussion thus far has assumed that the algorithmic-level description given by the Baddeley–Hitch model is correct. Although the cognitive neuroscience literature has shown a preference for interpreting studies within this model, it is certainly not the only possibility (e.g., Miyake & Shah, 1999).⁹ In evaluating the Baddeley–Hitch model, it is important to examine three critical and interrelated assumptions. First, the model posits a clear distinction between phonetic and articulatory representation. Second, the model assumes that the phonological similarity effect and the word length effect are the results of capacity limits of the phonological short-term store and the articulatory rehearsal mechanism, respectively. Third, the model argues that spoken language gains initial, automatic representation in the phonological short-term store whereas written language requires articulatory rehearsal to gain access to phonological representations. We discuss each of these in turn.

As mentioned previously, a central position of the Baddeley–Hitch model is that phonetic and articulatory representations are separated, both at the algorithmic level of description and in terms of neural implementation. Other theories have suggested that speech perception inherently involves mapping the speech signal onto the articulatory gestures used by the speaker (i.e., motor theories of speech perception, e.g., Liberman & Mattingly, 1985). These theories would suggest that the divi-

sion between phonetic, phonological, and articulatory processing is less clear.

The second critical assumption of the Baddeley–Hitch model is that the phonological similarity and word length effects stem from the operations of the phonological short-term store and articulatory rehearsal mechanism, respectively. Even if one acknowledges the separation of the two components, it could be the case that the similarity manipulation affects rehearsal (as phonologically similar words are also similarly articulated) or that the length manipulation affects phonological short-term storage (as there is more phonological information to be represented).

Finally, the interpretation of these experiments also relies on claims concerning how spoken and written language gain access to the verbal working memory system. It could be the case that the analysis of spoken language does require intact articulatory representations, or that written language does not, contrary to the claims of the Baddeley–Hitch model. Either case would change the pattern of predictions made concerning the modality effects that are at the core of our predictions in these studies.

These two final claims of the model—the locus of the two effects and their relationship with presentation modality—were critical to the initial arguments concerning the separation of the phonological short-term store and articulatory rehearsal mechanisms (e.g., Baddeley et al., 1984). Thus, questioning either of them relates back to the argument of phonetic–articulatory separation in the model. Perhaps rather than contributing independently to phonetic and articulatory representations, the cerebellum (and other areas) contributes to verbal working memory tasks in ways that do not allow for a clear distinction to be made between the two.

4.2. Conclusion

Although cerebellar patients do not consistently present with a profound deficit in verbal working memory as measured by the digit span, neuropsychological tests designed to tap qualitative differences suggest that even in patients whose spans are largely preserved, the verbal working memory system may be altered. Our data suggesting a reduction in the phonological similarity effect for words presented in both the visual and auditory modalities are also of relevance to the functional role often attributed to the cerebellum in neuroimaging studies of verbal working memory; these data suggest that the assignment of the cerebellum to the articulatory side of the Baddeley–Hitch model may be premature, and complement other sources of data suggesting that the cerebellum may play numerous roles in language, including ones that do not relate to articulation.

⁹ See Chein et al. (2003) for an interpretation of the neuroimaging working memory literature from the perspective of Cowan's Embedded-Process Model (1995).

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