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IMPACT OF CEREBELLAR LESIONS ON READING AND PHONOLOGICAL PROCESSING

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ABSTRACT

The relationship between cerebellar function and reading abilities is unclear. One theory of developmental dyslexia implicates the cerebellum in this reading disorder. Neuroimaging studies in normal readers consistently show cerebellar activation in tasks that involve reading. However, neuropsychological evidence for a relationship between cerebellar function and skilled reading is sparse. To further examine the role of the cerebellum in reading, we assessed reading skills and phonological processing in a group of patients with focal damage to the cerebellum. The patients' accuracy in naming single words and nonwords and their reading fluency and comprehension did not differ from that of age- and education-matched healthy controls. The patients' performance on phonological awareness and phonological memory tasks was also within the range of the control group though their performance was highly variable. In contrast, cerebellar damage did significantly compromise performance in two other tasks associated with phonological processing. In a visual rhyme judgment task, a subset of the patient group was impaired on items with a mismatch between orthographic and phonological information. On a verbal working memory task, the cerebellar compared to the control group recalled fewer items from a list of nonwords, but not from lists of familiar items. Based on the patients' pattern of behavioral impairments, we propose that cerebellar damage affects an articulatory monitoring process. Our findings indicate that intact cerebellar function is not necessary for skilled reading; however, we cannot exclude the potential contribution of the cerebellum to reading acquisition.

INTRODUCTION

Reading is a cognitive skill that involves segmentation, association, and integration of information both within and between different levels of representation (visual, phonological, semantic, and linguistic). Despite the highly complex nature of these skills, children typically learn to read within a year of explicit instruction (Seymour *et al.*, 2003), and for many adults reading is an effortless task. This is not the case for 5-10% of the population who suffer from a specific reading disorder (Shaywitz, 1998). First documented more than 100 years ago, developmental dyslexia is characterized by slow and erroneous reading, spelling mistakes, and phonological impairments, some of which persist into adulthood (Pennington *et al.*, 1990; Wilson & Lesaux, 2001).

Although the predominant explanation for developmental dyslexia is a deficit in phonological processes (Ramus, 2003; Snowling, 2000). some research has suggested that broader perceptual or motor deficits may be at the core of this reading disorder (Nicolson & Fawcett, 1990; Stein & Walsh, 1997; Tallal, 1980). One theory of developmental dyslexia proposed that abnormal processing in the cerebellum could cause reading difficulties as well as a range of mild perceptual and motor impairments associated with dyslexia (Nicolson & Fawcett, 1990). An updated account of this "cerebellar deficit hypothesis" (Nicolson *et al.*, 2001) claimed that 80% of dyslexic children had motor and non-motor impairments similar to those of patients with cerebellar damage. For instance, the dyslexic children had poor balance and muscle tone (Fawcett & Nicolson, 1999), as well as a difficulty estimating differences in the duration of consecutive tones (Nicolson *et al.*, 1995).

The cerebellar deficit hypothesis explains the causal relationship between cerebellar function and reading abilities by considering two motor functions to which the cerebellum is thought to contribute: the automation of skills and the production of inner speech. The former function relates to the long-standing theory that the cerebellum associates, through trial-and-error, a sequence of movements with a specific behavioral context; thus, over time motor execution of learned actions becomes rapid and automatic (also see Laycock *et al*. this volume) (Albus, 1971; Marr, 1969). The latter function relates to a recent idea that the cerebellum may contribute to cognitive processes that rely on internal speech (Ackermann *et al.*, 2004). For instance, verbal working memory is a cognitive process that relies on an articulatory rehearsal mechanism to maintain verbal items in a memory buffer (Baddeley, 2003). Poor verbal working memory is a well-known characteristic of developmental dyslexia (Pennington et al., 1990; Wilson & Lesaux, 2001). The cerebellar deficit hypothesis suggests that impairments in these functions may lead to difficulties automating word recognition processes and to impoverished phonological representations.

While the cerebellar-deficit account of dyslexia provides a logical framework for the involvement of the cerebellum in reading, support for this hypothesis has been mixed. Some researchers have argued against the cerebellar deficit hypothesis of dyslexia, proposing that the cerebellum receives input from and projects to perisylvian cortical regions that show anatomical abnormalities; thus, deficient cerebellar function may just as well reflect disordered processing in the cortex (Zeffiro & Eden, 2001). Others have suggested that abnormal development of the cerebellum is common to several neurodevelopmental disorders and therefore may be a correlate and not a cause of specific reading disorders (Ivry & Justus, 2001). Moreover, only a subset of the findings reported by Nicolson and colleagues (Nicolson et al., 2001) have been observed by other research groups that examined motor and perceptual deficits in dyslexic individuals (Ramus *et al.*, 2003).

If the cerebellum contributes to reading, then it should be possible to find evidence in support of the cerebellar deficit account by turning to studies of normal readers and the impact of acquired cerebellar damage on reading abilities. Initially, functional imaging studies of normal readers and neuropsychological studies focused on cerebellar involvement in cognitive functions such as language and memory (Desmond & Fiez, 1998; Ivry & Fiez, 2000). However, these studies also incidentally examined the role of the cerebellum in reading because they used written words as stimuli. One of the first studies to report cerebellar activity during higher-level language processing found increased blood flow to the right lateral cerebellum that was specific to the generation of verbs for presented nouns (Petersen *et al.*, 1989). More medial and bilateral cerebellar regions, on the other hand, were active during a range of tasks that involved reading. These findings were consistent with a neuropsychological report of a patient with right cerebellar damage who was impaired on a similar verb generation task but did not experience difficulties in reading (Fiez *et al.*, 1992). Although this case study suggested that the cerebellum was not involved in skilled reading, later neuroimaging studies consistently observed bilateral and paravermal cerebellar activity in adults during tasks that involved reading (Mechelli *et al.*, 2003; Turkeltaub *et al.*, 2002).

One way to reconcile these seemingly contradictory findings of cerebellar involvement in reading is to acknowledge that the cerebellum is a large brain structure that contains about half of the number of neurons in the brain (Zagon *et al.*, 1977). Therefore some cerebellar regions may be involved in reading while others are not. Moreover, different lobules of the cerebellum may contribute to different aspects of reading as suggested by findings that reading aloud engages different cerebellar regions depending on the characteristics of the stimuli (Fiez *et al.*, 1999). Specifically, bilateral medial and paramedial cerebellar regions were similarly active for reading both words (varying with frequency and consistency) and nonwords whereas the right lateral cerebellum was active more for nonwords than words.

Neuropsychological studies provide another method to examine the relationship between cerebellar function and reading skills. To our knowledge, only one study has been designed to directly test this relationship and it was conducted with a group of ten Italian patients with lesions to the vermis and the paravermis regions (Moretti *et al.*, 2002). This study found a significant increase in the number of errors that patients made when reading words, nonwords, sentences, and a passage relative to the errors made by the control group. The patients' elevated number of errors was most pronounced in the sentence and passage reading conditions. Across all of the reading conditions, the most frequent types of errors in the patient group were anticipations (e.g. "tortrino" for "tortino") and regularizations (e.g. "catrame" for "catrumo"). These acquired reading errors are different from those typically described in the developmental dyslexia literature, in which reading words in context improves accuracy, and regularization errors are less prevalent (Ellis *et al.*, 1996; Nation & Snowling, 1998).

In summary, one theory of developmental dyslexia implicates the cerebellum in this reading disorder despite mixed findings in the literature (Nicolson et al., 2001). To date, only one neuropsychological study has investigated the relationship between cerebellar damage and reading abilities (Moretti et al., 2002). One limitation of that study was that the patients' lesions were confined to vermial/paravermial regions. Functional imaging studies of reading typically observe activation in several cerebellar lobules. Therefore, to fully understand the relationship between cerebellar function and reading, it is important to examine reading skills in patients with damage to cerebellar regions other than the vermis. In the present study we assessed a range of reading skills in patients with lesions to the lateral cerebellar hemispheres relative to an age- and education-matched healthy control group. We also evaluated phonological abilities known to be impaired in developmental dyslexia, such as phonological awareness and verbal working memory. A finding that damage to the cerebellum in adults without a history of reading disorders results in impaired reading (particularly of unfamiliar words) and poor phonological abilities would provide strong support for the cerebellar deficit hypothesis of dyslexia. Null findings, on the other hand, would suggest that skilled reading does not depend on the cerebellum, although its involvement in the acquisition of reading skill could not be excluded.

METHODS

Participants

Six patients with focal damage to the cerebellum, and six healthy controls participated in this study. The patient and the control groups were carefully matched on age (respectively, 63.5 and 59.7 years; $t(10) = -0.5$, $p > 0.5$) and education (respectively, 12.2 and 12.5 years, $t(10) = 0.6$, $p > 0.5$). All of the participants scored in the normal range (>23 points) on the Mini-Mental State Exam (Folstein *et al.*, 1975), which assesses general cognitive competence (patients average score 27.6 and range 26-30, controls average score 29.2; range 26-30). A speech pathologist present at the time of testing indicated that the patients did not suffer from speech deficits, as assessed by the Frenchay Dysarthria Battery (Enderby, 1983). The control subjects did not report any history of neurological abnormalities or current cognitive difficulties. The patients did not report any reading difficulties prior to the cerebellar damage. The neurological damage resulted from an ischemic event to the left (n=3) or right (n=3) cerebellar hemisphere that occurred at least 3 years before this study. Laterality of the cerebellar damage as well as the lobular localization and extent of this damage was determined from the medical MRI or CT scans of each patient (Figure 1, Table 1). The patients described in this study are a subset of the patients who participated in a previous study, therefore additional details on the lesion analysis method are described in Ravizza *et al.* (2006). All of the participants gave their informed consent to participate in this study and were compensated for their time.

-- Insert Figure 1 and Table 1 approximately here --

Reading, phonology and working memory tests

We administered a large battery of standardized and custom-made tests to assess reading skills, phonological processing, and working memory abilities in all of the participants. Reading skills were assessed with the standardized Woodcock Reading Mastery Tests – Revised (WRMT-R, form H, Woodcock, 1998), which provides a comprehensive assessment of single word and nonword reading (word identification and word attack subtests, respectively) and comprehension of words (i.e. generation of synonyms, antonyms and analogies) and passages. Reading fluency was measured using a college-level passage from the Nelson-Denny Comprehension test (form E, passage five, Brown *et al.*, 1981). Participants were asked to accurately read the passage aloud at their normal reading pace. Once they finished reading, the passage was removed and the participants had to answer a simple comprehension question from memory. Fluency was defined as the reading rate in words per minute, irrespective of the number of reading errors but contingent upon a correct response to the comprehension question. All of the participants answered the comprehension question correctly and the groups did not differ in their reading accuracy (data not shown).

Phonological processing was assessed with two tests of phonological awareness and a standardized test of phonological memory. One measure of phonological awareness was rhyme judgment. In this custom–made test, 24 pairs of words were presented in upper case, each pair on a separate note card. The word pairs varied in their orthographic and phonological similarity, which resulted in four categories of stimuli: orthographic and phonologically similar (SAIL-PAIL, 9 pairs), orthographic and phonologically dissimilar (RUN-FIND, 6 pairs), orthographically dissimilar but phonologically similar (THIGH-FLY, 4 pairs), and orthographically similar but phonologically dissimilar (FEAR-BEAR, 5 pairs). Participants were asked to say ‘yes’ if the words rhymed and ‘no’ if the words did not rhyme. Ample time was given to respond. The second measure of phonological awareness was a Spoonerism test, adapted from Brunswick *et al.* (1999). In this test, participants listened to 12 pairs of unrelated words (e.g. basket-lemon). After hearing each pair, they were asked to swap the initial sounds in each word and say aloud the resulting nonword (e.g. lasket-bemon). Details on the stimuli and the administration procedure are described in Brunswick *et al.* (1999). The Spoonerism test requires manipulation at the phonemic level, as well as maintenance of items in working memory. Therefore, this test is considered a more difficult task than rhyme judgment and a better measure of phonological awareness in adults (Walton & Brooks, 1995). Finally, phonological memory was assessed with the nonword repetition subtest from the standardized Comprehensive Test of Phonological Processing (CTOPP, Wagner *et al.*, 1999). In this test, participants listened to one nonword at a time and then repeated it aloud. The test items gradually increased in length from one to seven syllables. Prior to the commencement of each phonological processing test, detailed instructions and a number of practice items were given. All of the participants understood the instructions and were able to complete the practice items, except for two patients and one control subject who could not do the practice items for the Spoonersim test. Their data on this test are not included in the group averages reported in the Results section.

Working memory span was measured for both verbal and visuo-spatial items using, respectively, the digit span and the visual memory span subtests from the standardized Wechsler Memory Scale-Revised test battery (WMS-R, Wechsler, 1987). Administration followed standard testing procedures, in which a list of digits were spoken or a series of blocks were tapped in a spatial pattern at a rate of one per second. Participants were then required to immediately recall the digits (or tap the blocks) in forward or backward (reverse) order. We further assessed verbal working memory with two custom-made tests whose stimuli were either an open set of one-syllable words (word span) or pronounceable nonwords (nonword span). The word stimuli were not related semantically, and each item began with a different phoneme to avoid phonological confusions. The nonwords were generated from the items used in the word span test by switching initial consonants (or consonant clusters) between items. The administration procedure of the custom-made span tests followed the forward recall protocol of the standardized digit span subtest. Each set size had two trials, beginning with a set size of two items and gradually increasing in length until the participant failed on both trials of a set size.

To determine significant differences in performance between the cerebellar patient group and the control group, we applied a set of t-tests between independent samples. Since we had no a-priori hypothesis about group differences on reading measures, we used two-tailed t-tests to determine the significance of group effects. Based on previous findings, we hypothesized that cerebellar patients would have lower verbal working memory spans, however we choose a conservative approach and examined group differences in verbal working memory using two-tailed t-tests between independent samples. We had several measures of verbal working memory, in which we manipulated the type of stimuli (digits, words, nonwords) and recall paradigm (forward vs. backward). To assess the effect of these variables on verbal working memory performance, we conducted a series of repeated measures analyses of variance.

RESULTS

Table 2 summarizes the performance of the cerebellar patient group and the control group on the reading and the phonological processing tests. The patients' basic reading skills and reading comprehension abilities did not differ from those of the control group. On the various subtests, the mean WRMT-R standard score in both groups was less than one standard deviation from the mean of the general population (mean = 100, SD = 15). These mean scores are expected from the groups' self-reports of a high school education. Cerebellar damage can cause dysfluent speech (Duffy, 1995) and thus impact reading fluency. To assess fluency, participants read aloud a college-level passage for comprehension. The mean reading rate of the cerebellar patient group did not differ from that of the control group. Furthermore, the two groups did not differ in their reading accuracy or basic comprehension of the passage, thus indicating that there was no speed-accuracy tradeoff.

-- Insert Table 2 approximately here --

Cerebellar damage had a differential influence on performance in the phonological processing tasks (Table 2). Accuracy on the rhyme judgment task was significantly worse in the patient group relative to the control group ($t(7.01) = 2.6$, $p < 0.05$). An error analysis showed that mistakes in both groups were limited to the word pairs that contained a mismatch between orthography and phonology (i.e. FEAR-BEAR and THIGH-FLY). Half of the patients made an erroneous response to almost all of the stimuli (mean of 4.6 items out of five) that were orthographically similar but did not rhyme (ortho+phono-, Figure 2). Only one control subject (C2) judged incorrectly three of the five items in this category. Interestingly, the patients (P1, P2, P4) with severe difficulties on the rhyme judgment task had cerebellar lesions that were located in the anterior and superior lobules (including medial damage) whereas patients with performance in the normal range had damage that was limited to the inferior cerebellar lobules. There was no evidence that hemispheric lateralization of the lesions was related to the patients' performance on the rhyme judgment task.

-- Insert Figure 2 approximately here --

In contrast to the significant group difference found on the rhyme judgment task, the patient and control groups did not differ in their performance on the Spoonerism task. This finding is surprising because Spoonerism is considered to be a more sensitive measure of phonological awareness in this age group (Walton & Brooks, 1995). In both groups, there was a large variance in the accuracy scores (patient accuracy range: 0 – 100 % correct, control accuracy range: 0 – 92 % correct) though it was larger in the patient group. Unfortunately, the high degree of variability makes it difficult to determine the effect of cerebellar damage on the performance in this task.

Phonological memory, as measured by the CTOPP nonword repetition subtest, did not differ between the patient and control groups. On average, participants in both groups could accurately repeat nonwords that were 4-syllables long but could not repeat longer nonwords. The patients' variance on this task, however, was more than twice that of the control group (patient SD 18.1, control SD 7.4). In general, the patients showed a tendency towards larger variability in their performance on the Spoonerism and nonword repetition tasks. This variability may reflect the presence of different subtypes of patients in the group we assessed, although we did not find a clear association between performance on these tasks and the anatomical location of the cerebellar lesions.

Table 3 summarizes the performance of the cerebellar patient group and the control group on the verbal and spatial working memory tests. The dependent measure on these tests is working memory span, which is the largest number of items that can be immediately recalled in the order of presentation (forward) or in the reverse order of presentation (backward). Memory span for verbal items showed the characteristic pattern of significantly larger spans for familiar verbal items relative to unfamiliar items (digits > words > nonwords; $F(2,20) = 62.2$, $p < 0.001$). This pattern was similar across both groups, though there was a trend for a group difference ($F(1,10)=3.8$, $p=0.08$) that resulted from the patients' significantly smaller spans for unfamiliar verbal items compared to the control group (nonword-forward, $t(10)=2.24$, $p < 0.05$). Digit span in both groups, as assessed by the WMS-R subtest, also showed the typical pattern of significantly larger spans for the forward condition compared to the backward condition ($F(1,10)=72.0$, $P<0.001$). Although there was no significant group difference, there was a trend towards a smaller mean span in the patient group for the more difficult digit-backward condition ($t(10)=1.94$, $p = 0.08$). Memory span for the spatial order of nonverbal items, on the other hand, did not differ between the two groups for either the forward or backward recall conditions. To summarize, patients did not differ from controls in their ability to recall familiar verbal items (digits and words) in order of presentation, but their performance deteriorated when the verbal items were unfamiliar (non-words) or the order of recall was reversed. In contrast to the patients' mild verbal working memory deficit, spatial working memory was not affected by overall cerebellar damage or hemispheric lateralization of the lesion.

-- Insert Table 3 approximately here --

DISCUSSION

Neuroimaging studies typically observe cerebellar activation during tasks that require reading (Mechelli et al., 2003; Turkeltaub et al., 2002). Motor and non-motor symptoms associated with cerebellar damage have been observed in children with developmental reading disorders (Nicolson et al., 2001). These disparate findings suggest that the cerebellum may be involved in some aspects of reading. Indeed, patients with cerebellar damage to vermial/paravermial regions have reading impairments (Moretti et al., 2002), but the spectrum of these impairments is not similar to that seen in developmental dyslexia. To further investigate cerebellar contributions to reading, we examined the performance of patients with lateral cerebellar lesions relative to age- and education-matched healthy controls on a range of reading and phonological tasks. We found that in adults who reported normal reading abilities prior to an ischemic event, cerebellar damage did not affect reading abilities such as naming familiar and unfamiliar words, reading fluency, and comprehension at both the word and the passage level. Phonological awareness, as assessed by a Spoonersim task, and phonological memory (i.e. nonword repetition) were also intact in the cerebellar patient group although the high degree of variability observed in both the patient and control groups complicates the interpretation of these null effects. Performance on a rhyme judgment task was compromised, particularly for patients with anterior/superior cerebellar lesions, and most noticeably for items in which there was a mismatch between orthographic and phonological information.

Rhyme judgment and Spoonerism tasks are commonly used to assess phonological awareness in different age groups (Treiman & Zukowski, 1991). The rhyme judgment task is typically used to assess young children's awareness of onset-rime structure of words (e.g. N-AP vs. CL-AP) (Lenel & Cantor, 1981). The ability to identify phonological similarity at the level of the rime unit is one factor that predicts the development of reading abilities in children (Bradley & Bryant, 1983; Bryant *et al.*, 1990; Gathercole *et al.*, 1991). Spoonerism, on the other hand, requires both segmentation and manipulation at the phonemic level. This is a sensitive measure of phonological awareness in adults, particularly those with a history of reading disorders (Brunswick et al., 1999). It is therefore surprising that the cerebellar patients were impaired on the easier rhyme judgment but not on the more challenging Spoonerism task, though their highly variable performance on the latter task permits only limited speculation regarding performance differences.

For preschool children, the rhyme judgment task is administered using an auditory presentation of word pairs. In our study, the word pairs were written (visual) and presented as a pair until the subject made a judgment. In contrast, the word pairs in the Spoonerism task were spoken (auditory) sequentially and then subjects produced a response without a time limit. It is possible that presentation modality is an important fact in the performance of a rhyme judgment. Rhyme judgment becomes difficult when a word's spelling induces conflict between regular and exceptional pronunciations of a rime unit (e.g. /int/ as in MINT versus PINT) (Johnston & McDermott, 1986). The ability to resolve this conflict may invoke an articulatory process supported by the cerebellum, which we speculate upon in the following sections.

Further support for the view that rhyme judgment, possibly more so with visual presentation, can require an additional process to resolve conflict between orthographic and phonological information comes from findings in both normal and impaired readers. In normal readers, visual rhyme judgment is slower and more error prone than auditory rhyme judgment for items with a mismatch between orthographic and phonological information (McPherson *et al.*, 1997). Dyslexic adolescents are extremely impaired on a visual relative to an auditory rhyme judgment, particularly for items that share orthography but not phonology (McPherson et al., 1997). The similarity between dyslexics' and cerebellar patients' item-specific impairments on visual rhyme judgment supports the involvement of the cerebellum in an aspect of phonological processing. However, a comparison across these populations is limited because our study did not assess rhyme judgment with an auditory presentation.

Another main finding of our study was the patients' specific difficulty in recalling a list of nonwords relative to their intact recall of familiar items (i.e. digits and words). Although previous case studies investigating the impact of cerebellar lesions on verbal working memory have reported mixed findings (Fiez et al., 1992; Silveri *et al.*, 1998), a recent study with a large sample of cerebellar patients found mild but significant impairments on standard digit span tasks and a significant group effect for the written recall of visually presented lists of words and nonwords (Ravizza et al., 2006). According to a predominant theory of verbal working memory, this cognitive construct has two components: (1) a temporary buffer that stores verbal information in a phonological code and (2) a maintenance mechanism that relies on subvocal rehearsal to refresh a decaying memory trace (Baddeley, 1986). Subvocal rehearsal is thought to involve prefrontal cortical regions that support articulatory planning (e.g. inferior frontal and premotor cortex) and subcortical regions such as the cerebellum (Baddeley, 2003). Although the role of the cerebellum in verbal working memory remains unclear, we proposed that existing neuroimaging and neuropsychological findings support an articulatory monitoring function of the cerebellum (Ben-Yehudah *et al.*, 2007), which we discuss in more detail in the following sections. Thus, our finding that recall of nonwords, but not digits or real words, was significantly worse in the patient compared to the control group suggests that unfamiliar items may benefit more than familiar items from such an articulatory monitoring process. Consistent with this idea are neuroimaging findings of increased prefrontal and cerebellar activation for nonwords relative to words during verbal working memory tasks (Fiez *et al.*, 1996) (though see Chein & Fiez, 2001) and rhyme judgments (Burton *et al.*, 2005; Xu *et al.*, 2001). Future studies are needed to determine whether tasks that use nonwords as stimuli are more sensitive to the cognitive consequences of cerebellar damage.

To summarize, cerebellar damage in adults did not affect reading skills, but it did impair visual rhyme judgment and immediate recall of nonwords. These neuropsychological findings suggest that rhyme judgment and verbal working memory may share a common process that is supported by the cerebellum. In the following sections we present evidence for a common articulatory process and speculate about its role in the acquisition of skilled reading.

A common articulatory process?

In considering the potential for a common process that underlies the patients' impaired performance on rhyme judgment and some verbal working memory tasks, we were struck by the similarity between concurrent articulation effects on these tasks and that of cerebellar damage. In a concurrent articulation paradigm, the participant continuously speaks irrelevant information (e.g. "the, the, the …") while performing a primary task, such as deciding whether two words rhyme or remembering a list of items. When performance on a primary task has been disrupted by concurrent articulation, this disruption is attributed to the engagement of the articulatory system by both the primary and secondary tasks. To explore the hypothesis that damage to the cerebellum could result in the concurrent articulation effect--and therefore disruption of the articulatory process--we first turn to the rich literature on concurrent articulation and its influence on rhyme judgment and verbal working memory.

A large number of behavioral studies have established that concurrent articulation interferes with rhyme judgments on visually presented pairs of words or nonwords (Barron & Baron, 1977; Besner *et al.*, 1981; Johnston & McDermott, 1986; Kleiman, 1975; Wilding & White, 1985). Since rhyme judgment requires a comparison of phonological representations, early studies suggested that concurrent articulation interferes with the generation (or retrieval) of phonology for a given visual form (Barron & Baron, 1977; Kleiman, 1975). However, later studies showed that concurrent articulation does not disrupt tasks that explicitly require the generation of phonology, such as homophony judgment (e.g. do AIL-ALE have the same sound?) or phonological lexical decision (e.g. does FORREN sound like a real word?) (Baddeley *et al.*, 1981; Besner et al., 1981). Based on these findings, Besner and colleagues (1981) proposed that concurrent articulation impairs a phonological segmentation process that occurs after the retrieval of whole-word phonology. This hypothesis accounts for the cerebellar patients' normal reading abilities because reading requires generation of phonology and not a post-lexical segmentation process. However, this hypothesis does not explain the patients' item-specific impairments on the rhyme judgment task.

Verbal working memory studies attribute the detrimental effect of concurrent articulation on recall to the limited resources of the articulatory system (Baddeley *et al.*, 1984; Baddeley *et al.*, 1975). Specifically, Baddeley (1986) proposed that concurrent articulation interferes with verbal working memory because it engages articulatory mechanisms that also support subvocal rehearsal, an inner speech process that maintains verbal items in a short-term store. This hypothesis attributes the cerebellar patients' mild verbal working memory deficits to impaired subvocal rehearsal. Recent findings that patients with cerebellar damage continue to use rehearsal to maintain items in working memory challenge this hypothesis (Ravizza et al., 2006). Furthermore, this hypothesis fails to easily account for our finding that the patients' recall of unfamiliar items was disproportionately impaired relative to their ability to recall familiar items; however, it is possible that access to long-term lexical representations reduces the burden on subvocal rehearsal for familiar items as compared to nonwords (Gathercole *et al.*, 2001).

In summary, the effect of concurrent articulation on rhyme judgment and verbal working memory has been attributed to different sources of interference. Rhyme judgment studies suggest that concurrent articulation disrupts a post-lexical segmentation process whereas verbal working memory studies attribute this interference to joint reliance on articulatory mechanisms. In our study, the patients' item-specific impairments on these tasks pose a problem for both hypotheses. Though we agree with the view that concurrent articulation interferes with an articulatory process, we believe that it is possible to refine this general hypothesis by examining the role of the cerebellum in monitoring errors in motor and non-motor tasks.

Articulatory monitoring

We propose that verbal working memory and rhyme judgment are both impaired in our patient group because these tasks rely on a common articulatory process supported by the cerebellum. To account for the patients' poor performance on specific items, we now turn to a motor theory of cerebellar function that has evolved into the idea that the cerebellum monitors errors in performance. One predominant theory of the cerebellum is that it is involved in motor learning through a trial-and-error process that detects and corrects errors in motor commands (Ramnani, 2006). Motor learning theories in the early 1970s attributed the automatic execution of an action to experience-dependent learning in cerebellar circuits (Albus, 1971; Marr, 1969). In essence, a sequence of movements becomes associated over time with a specific behavioral context. Experience-dependent learning occurs by modifying the synaptic strength between Purkinje and granule cells in the cerebellum. These synaptic changes are guided by error signals that are conveyed by climbing fibers from the inferior olive (De Zeeuw & Yeo, 2005; Ito, 1993). A recent computational implementation of experience-dependent learning is based on the idea that the cerebellum consists of "internal models" that simulate motor commands and their predicted sensory consequences (e.g. visual, tactile) (Wolpert *et al*., 1998). In this model, an error signal results from a mismatch between the predicted and the actual sensory consequence of an action. These error signals continuously refine the internal model and can potentially inform the motor system about an execution error before it occurs.

Monitoring is essential to a wide range of motor tasks, including speech production (Guenther, 2006). Recently, the cerebellum has been implicated in cognitive functions that rely on inner speech (Ackermann et al., 2004), possibly because of its role in monitoring articulatory plans for errors (Ben-Yehudah et al., 2007). Rhyme judgment and verbal working memory may both rely on inner speech. Subvocal rehearsal used to maintain items in verbal working memory is akin to an inner speech process (Baddeley, 2003). Rhyme judgment may also engage an inner speech process to silently reiterate word pairs. During inner speech, the cerebellum may simulate the sensory consequences of this subvocal articulation and compare these consequences to input from phonological representations (Desmond *et al*., 1997). Cerebellar damage that prevents this simulation interferes with articulatory monitoring. Verbal items susceptible to pronunciation errors will be affected more by impaired articulatory monitoring. Indeed, the patients' errors in rhyme judgment and serial recall were limited to items that had either inconsistent or unfamiliar pronunciations.

Specifically, the patients' ability to judge whether two words rhymed was impaired on items that had a mismatch between orthography and phonology. Rhyme judgment was particularly difficult on items in which one word had a consistent spelling-sound correspondence (e.g. FEAR) and the other word had an inconsistent correspondence (e.g. BEAR). Findings from word identification studies suggest that once a word is encountered activation spreads to orthographic neighbors that share the rime unit but not necessarily the pronunciation (e.g. HEAR) (Grainger *et al.*, 2005). Activation of several phonological forms for the same rime unit results in conflict, which impairs speed and accuracy of judgments (Johnston & McDermott, 1986). Behavioral and computational findings suggest that the amount of conflict is a function of both the number and the frequency of a word's orthographic neighbors (Jared, 2002). One way to reduce conflict during rhyme judgments of this type is to articulate the word pair several times. This articulation (overt or covert) may provide input to a monitoring mechanism that detects errors in pronunciation, thus amplifying the correct (or suppressing the incorrect) pronunciation. In the case of cerebellar damage, we propose that articulatory monitoring is impaired and the consistent pronunciation overrides the inconsistent one resulting in a mistaken judgment. Our study shows that damage to the anterior/superior cerebellar lobules has a detrimental effect on rhyme judgments of items with orthographic-phonological mismatches, suggesting that this cerebellar region is involved in articulatory monitoring.

We found that verbal working memory for familiar items (e.g. words and digits) was not impaired in our cerebellar patient group (though see Ravizza et al., 2006). However, the patients' memory span for nonwords was significantly reduced compared to the control group. Nonwords are more prone to articulation errors because they do not have pre-existing lexical knowledge to support their decaying memory trace and consequently their accurate recall (Gathercole *et al.*, 1999; Gathercole et al., 2001). Serial recall of nonwords, therefore, would benefit more from articulatory monitoring. Evidence supporting this claim comes from a study by Besner and Davelaar (1983), in which serial recall of pseudohomophones (e.g. PHOOD) was less impaired by concurrent articulation compared to serial recall of nonwords (e.g. BEUED).

Taken together, an articulatory monitoring hypothesis can account for the patients' item-specific deficits in the visual rhyme judgment and serial recall tasks. Furthermore, this hypothesis predicts that skilled readers would not rely on articulatory monitoring as much as beginning readers because they make few pronunciation errors. Our finding that skilled readers who suffered from cerebellar damage did not show reading impairments is consistent with this prediction. Although an intact cerebellum may not be necessary to maintain an adequate level of skilled reading in adults, we cannot exclude the possibility that the cerebellum may contribute to the acquisition of reading.

One model of speech production proposes that the cerebellum functions as a feedforward control system that monitors errors in articulatory plans by receiving input from inferior frontal representations of speech sounds and then projecting back to the motor cortex (Guenther, 2006). Drawing from this model to reading, we speculate that such a feedforward control system may bootstrap reading in its early stages. For instance, a beginning reader has to associate arbitrary symbols with sounds and then blend these sounds into a meaningful phonological unit. Blending errors result in inaccurate articulatory plans that could benefit from adjustments by a monitoring process. Indeed, a comparison of two teaching strategies in preschool children suggests that a focus on blending by not pausing between successive sounds improves word identification more than an emphasis on phonetic segmentation by inducing artificial pauses between sounds (Weisberg & Savard, 1993). An articulatory monitoring process may require a certain degree of blending before it can boost reading; therefore, this process could apply to the former but not the latter teaching strategy. As readers become more proficient at blending speech sounds and directly mapping visual forms to their corresponding phonological representation, the role of articulatory monitoring may diminish so that skilled reading is unaffected by cerebellar damage. Future studies that examine reading acquisition in children with acquired cerebellar damage may help to refine this hypothesis and inform our understanding of the cerebellum's role in reading.

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Figure legends

Figure 1. Location of focal unilateral damage to the cerebellum in the 6 patients (denoted by the grey regions), shown on a cerebellar template. Patients are grouped by hemispheric lateralization of their lesion (P1-P3 left cerebellar lesions, P4-P6 right cerebellar lesions). (Modified with permission from Ravizza et al., 2006.)

Figure 2. The type and prevalence of errors in the rhyme judgment task is shown for each participant in the patient and the control groups. Filled bars indicate errors on items that shared orthography but not phonology (e.g. FEAR-BEAR, ortho+Phono-). Hatched bars indicate errors on items that did not share orthography but did rhyme (e.g. THIGH-FLY, ortho-Phono+).

Table 1 Characteristics of the cerebellar damage of each patient.

Patient	*Laterality*	*% Lesion total*	*% Lesion lobules I-V*	*% Lesion lobules VI-VII*	*% Lesion lobules VIII-X*
P1	Left	25.54	70.05	21.63	0.0
P2	Left	24.43	64.46	32.30	0.0
P3	Left	18.90	0.0	6.08	60.61
P4	Right	7.15	7.98	6.69	0.0
P5	Right	13.69	0.0	0.0	28.27
P6*	Right	-	-	-	43.14

*Only partial image available for analysis.

Table 2 Cerebellar patients' and control group's mean scores (and standard deviation) on the reading and phonological processing tests. P-values for significant group differences are noted for a two-tailed *t*-test between independent samples.

	Control	*Patient*	*P-value*
1. Basic reading skills*			
Word identification	106.0 (12.9)	98.2 (10.8)	n.s.
Word attack	110.7 (13.0)	99.0 (10.1)	n.s.
2. Comprehension*			
Words	105.8 (12.1)	98.0 (14.0)	n.s.
Passage	102.5 (7.5)	98.8 (20.3)	n.s.
3. Reading fluency^	109.9 (29.5)	113.3 (29.5)	n.s.
4. Phonological processing°			
Rhyme judgment	96.7 (4.7)	84.9 (10.2)	**.037**
Spoonerism	75.0 (21.2)	56.3 (41.6)	n.s.
Nonword repetition	62.0 (7.4)	54.6 (18.1)	n.s.

*Standard scores on WRMT-R subtests (population mean = 100, SD = 15); ^Reading rate in words per minute; °Accuracy on phonological processing tests in percent correct.

Table 3 Cerebellar patients' and control group's mean span (and standard deviation) on the working memory tests. P-values for significant group differences are noted for a two-tailed *t*-test between independent samples.

	Control	*Patient*	*P-value*
1. Verbal span*			
Digit - forward	6.7 (0.8)	6.2 (1.0)	n.s.
Digit - backward	5.0 (1.3)	3.8 (0.8)	**0.081**
Word - forward	4.5 (0.8)	4.2 (0.4)	n.s.
Nonword - forward	3.8 (1.0)	2.7 (0.8)	**0.049**
2. Spatial span^			
Spatial - forward	6.0 (1.3)	5.2 (0.8)	n.s.
Spatial - backward	4.8 (0.8)	4.3 (0.8)	n.s.

*Maximum number of verbal items accurately recalled in the correct order;
^ Maximum number of blocks tapped in the correct order.

Figure 1. Ben-Yehudah and Fiez

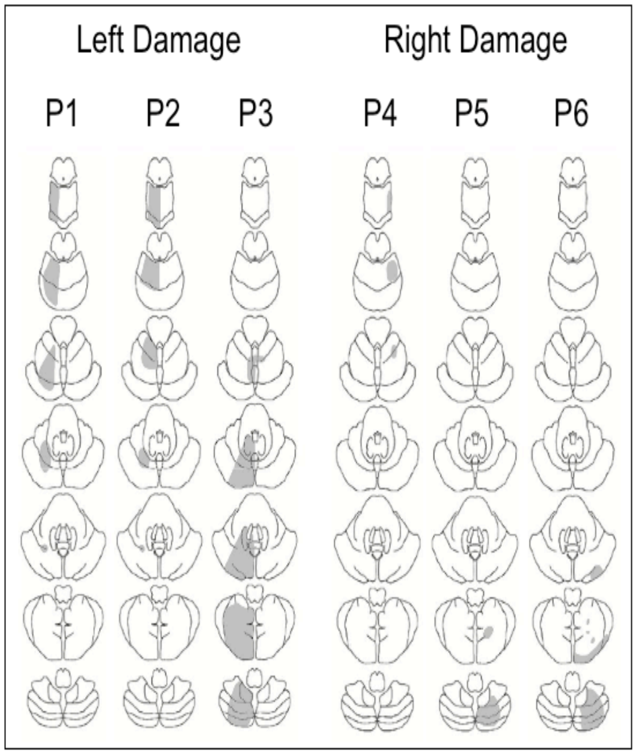

Figure 2. Ben-Yehudah and Fiez