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Cerebellar contribution to linguistic processing efficiency revealed by focal damage

JEFFREY SCHATZ, SANDRA HALE, AND JOEL MYERSON
Department of Psychology, Washington University, St. Louis, MO

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Abstract

The cerebellum's role in cognitive skills was examined in a child (L.C.) with focal injury to the left cerebellum. Initial symptoms included aphasia and dysarthria. At 3 and 9 months post-injury, clinical neuropsychological tests revealed persistent psychomotor slowing as well as deficits in executive functions. Further cognitive testing at 13 and 16 months post-injury demonstrated that L.C. processed information from both the linguistic and nonlinguistic domains more slowly than age-, grade- and sex-matched controls. Notably, her linguistic processing was more than twice as slow as that of her peers, whereas her nonlinguistic processing was only approximately 20% slower. Within each domain the degree of cognitive slowing was approximately the same across diverse tasks. These results are consistent with the hypothesis of a cerebellar contribution to cognitive processing, particularly the processing of linguistic information. (*JINS*, 1998, *4*, 491–501.)

Keywords: Cerebellum, Linguistic processing, Processing efficiency

INTRODUCTION

Recent findings suggest that the cerebellum, in addition to its traditionally ascribed role in motor behavior, may also play a role in higher level cognitive activity. Though the precise involvement of the cerebellum in higher level mental activity remains controversial, numerous studies have suggested a role for the cerebellum beyond motor behavior. Based on neuroanatomical evidence, Leiner et al. (1989, 1991) hypothesized that the cerebellum may be particularly important for language functions. These researchers pointed out that humans have an enlarged lateral portion of the cerebellum, including a newly evolved structure termed the neodentate. The neodentate primarily projects (via the thalamus) to the frontal lobe, especially prefrontal areas and Broca's area. In addition, expanded connections from the prefrontal cortex reach the neodentate in humans via several pathways. This reciprocal connectivity forms a neural loop that is hypothesized to facilitate cognitive, especially linguistic, functions in the same way that the cerebellum enhances motor functions (for a brief review, see Leiner et al., 1993).

The results of neuroimaging studies indicate that regions of the cerebellum are active during reading and the generation of word associations (Fiez et al., 1992; Petersen et al., 1989), during silent counting (Decety et al., 1990), and during the maintenance of verbal information in working memory (Fiez et al., 1996; Paulesu et al., 1993). In addition, cerebellar damage has been reported to result in disturbed grammar and decreased verbal fluency (e.g., Akshoomoff et al., 1992; Appollonio et al., 1993; Daum et al., 1993; Fiez et al., 1992; Grafman et al., 1992; Silveri et al., 1994). Finally, children with dyslexia have been reported to show behavioral deficits similar to individuals with cerebellar dysfunction, suggesting a correlation between cerebellar functioning and reading disorders (Nicolson et al., 1995).

The evidence for cerebellar involvement in cognitive functions is not confined to linguistic abilities. Neuroimaging studies of normal adults have shown enhanced activity in regions of the cerebellum during the acquisition and discrimination of sensory information (Gao et al., 1996) and while solving pegboard or the Tower of London puzzles (Baker et al., 1996; Kim et al., 1994). Moreover, studies of individuals with infarcts, tumors, or degenerative conditions affecting the cerebellum have revealed a number of nonlinguistic cognitive deficits, including problems with nonmotor learning and error detection, planning, velocity and time judgments, and rapid attentional shifts (e.g., Akshoo-

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Reprint requests to: Jeffrey C. Schatz, Department of Psychiatry, University of California at San Francisco, 401 Parnassus Avenue, Box CPT, San Francisco, CA 94143-0984. E-mail: jschatz@itsa.ucsf.edu

moff & Courchesne, 1992; Botez, 1992; Courchesne et al., 1994; Fiez et al., 1992; Grafman et al., 1992; Ivry & Diener, 1991).

Although the studies listed above support cerebellar involvement in both linguistic and nonlinguistic cognitive skills, the exact nature of the cerebellum's role has yet to be determined. It is widely believed that the unique circuitry of the cerebellar cortex serves to enhance the acquisition of motor skills and the production of skilled behavior. With respect to cognitive skills, several researchers recently have hypothesized that the cerebellum's unique architecture and connectivity may enable it to play a similar role in enhancing the general efficiency of higher cognitive functions (Ito, 1993; Leiner et al., 1989, 1991).

The mechanisms by which the cerebellum could enhance the efficiency of cognitive functions are only speculative at this time. The cerebellum appears to be involved in the formation of linguistic and nonlinguistic associations (Canavan et al., 1994; Raichle et al., 1994). The cerebellum appears to contribute to certain higher level cognitive operations when the task is more novel; once the task becomes more automatized (e.g., with practice), cerebellar contributions to cognitive tasks may decrease (Raichle et al., 1994). Based on such findings, several researchers have proposed that the cerebellum's role in higher level cognitive tasks involves facilitating learning through error detection and/or improving the formation of stimulus–response associations (Fiez et al., 1992; Petersen et al., 1989; Raichle et al., 1994). Thus, according to this formulation, the cerebellum's role in efficient information processing is more likely to involve a role in efficient acquisition and performance of more novel tasks, rather than contributing to fast "on-line" processing of familiar tasks. Whether this contribution would be specific to certain domains of cognition (as proposed by Leiner and colleagues) or is more general across a variety of cognitive operations, however, is not clear.

In order to measure such general contributions to information processing, researchers studying cognitive development have recently developed a nontraditional approach to the assessment of cognitive functioning (for a recent review, see Cerella & Hale, 1994). They have found that, when children and a reference group (e.g., young adults) are tested on a variety of cognitive tasks, there is typically a precise linear relationship between the children's response latencies and those of the reference group (Hale, 1990; Hale et al., 1993). The regression slope, which measures processing time relative to the reference group, has been shown to decrease systematically as children get older and their information processing becomes generally more efficient (Hale, 1990; Kail, 1991). While the slope of the regression provides a measure of processing efficiency, the proportion of variance accounted for by the regression line, which typically exceeds .90 in experiments with healthy children (Hale, 1990; Hale et al., 1993), provides a measure of the extent to which inefficient processing is due to a general factor.

This regression-based approach would appear to be potentially useful in evaluating the cerebellum's contribution to general processing efficiency, and in the present study we apply it to the case of a child (L.C.) who sustained an acute, focal injury to her left cerebellar hemisphere. After characterizing her cognitive performance on more traditional neuropsychological and cognitive measures, two batteries of speeded information-processing tasks were used to compare the efficiency of L.C.'s linguistic and nonlinguistic processing to that of her peers.

METHODS

Research Participants

At the time she suffered an acute onset of gait disturbance and headache, L.C. was an otherwise healthy, 7-year-old, right-handed girl in the first grade with no previous difficulties in her birth or development. Upon arrival at the hospital, a posterior fossa bleed was discovered which required emergency evacuation. Magnetic resonance imaging (MRI) revealed a small to moderate size left cerebellar arteriovenous malformation that derived feeders from the left superior cerebellar artery and the left posterior inferior cerebellar artery. This malformation was the source of the bleeding, and the condition was treated with embolization, blocking the flow of blood to the malformed area. Subsequent MRI scans showed significant injury in the left cerebellar hemisphere and a small area of signal abnormality in the middle cerebellar peduncle, with no other visible injury to cortical or subcortical regions (see Figure 1).

L.C.'s initial neurological symptoms included aphasia, dysarthria, both upper limb and gait ataxia, left neglect, and left greater than right side weakness in her extremities. Ten weeks post-injury, L.C. continued to show dysarthria, ataxia, and left side weakness; mild language and memory difficulties were also apparent. She was able to return to her regular second grade school placement, but whereas she had been receiving A's and B's, on her return she received B's and C's. In addition, her teachers now noted mild difficulties in sequencing ability and knowledge of phonetics, as well as difficulties learning in addition and subtraction tables. No concerns were expressed by L.C.'s mother regarding her social, emotional, or behavioral functioning post-injury. L.C. was tested with clinical neuropsychological measures at 3 months and 9 months post-injury and with experimental cognitive measures at 13 and 16 months post-injury. Prior to all testing sessions, assent was obtained from L.C., and informed consent was obtained from her mother.

In addition to L.C., 15 age-, grade-, and sex-matched children were tested. A total of 10 children (Group 1) were tested on the measures of executive functioning and speeded information processing completed by L.C. in her third session. Three months later (the same intertesting interval as that for L.C.), 5 of these children were tested on the same speeded tasks completed by L.C. in her fourth session. An additional 5 children were tested only on the information-processing tasks, first on those used in L.C.'s third session and then, three months later, on those used in L.C.'s fourth

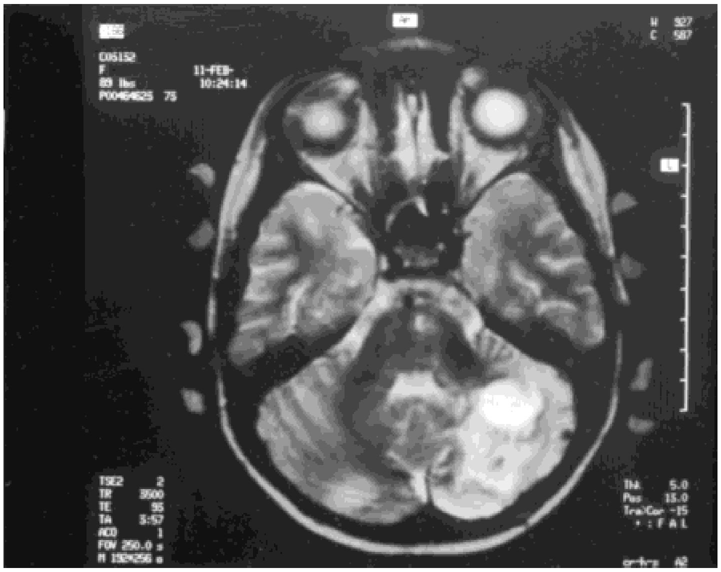

Fig. 1. Magnetic resonance imaging scan (horizontal section) of L.C. showing left cerebellar injury.

session, bringing the number of fourth session controls (Group 2) to 10. Age, education, and cognitive and reading ability scores for L.C. and the two comparison groups are given in Table 1.

TESTS AND RESULTS

Clinical Neuropsychological Examination: Sessions 1 and 2

Clinical neuropsychological evaluations of L.C. conducted at 3 months and 9 months post-injury (Sessions 1 and 2) revealed general intellectual and academic skills that were within the average range for her age. Behaviorally, L.C. was cooperative and friendly throughout testing, although she appeared to be mildly slow to respond to questions. L.C.'s Full Scale IQ on the Wechsler Intelligence Scale for Children (WISC–III; Wechsler, 1991) was 94 on the first testing and 92 on the second testing. Notably, L.C. demonstrated persistent difficulties with psychomotor speed as evidenced by low average to deficient scores in both sessions on the Symbol Search and Coding subtests of the WISC–III. L.C.'s scores on the Boston Naming Test (Kaplan et al., 1983), the Verbal Fluency Test (Halperin et al., 1989), and the Children's Auditory Verbal Learning Test (Talley, 1990) were all generally in the low average to average range. L.C. also performed within the normal range on all aspects of the Wisconsin Card Sorting Test (Heaton et al., 1993) except for an abnormally high number of perseverative errors. Based on the observation of psychomotor slowing and possible executive deficits in these first two testing sessions, it was decided to examine these areas in more detail using experimental cognitive tasks as well as further neuropsychological testing in a third session.

Tests of Executive Skills and Processing Speed: Session 3

The Tower of Hanoi test (Klahr & Robinson, 1981) and tests of verbal fluency (Halperin et al., 1989) and design fluency

Table 1. Age, grade, cognitive ability scores and reading level for L.C. and comparison groups

		Group 1		Group 2	
Variable	L.C.	*M*	*SD*	*M*	*SD*
Age in years	8.2	7.9	0.35	8.0	0.42
Grade	2.50	2.40	0.36	2.61	0.29
WISC–III Vocabulary	9	11.9	2.23	11.6	1.71
WISC–III Block Design	10	12.2	3.16	12.3	2.83
WRAT–3 Reading raw score	27	not given		30.1	3.41

Note. WISC–III = Wechsler Intelligence Test for Children, 3rd edition (values shown are age-corrected standard scores); WRAT–3 = Wide Range Achievement Test, 3rd edition.

(Jones-Gotman & Milner, 1977) were administered to assess executive skills. Working memory span tasks (Hale et al., 1996) were also used in order to test for sensitivity to interference. Finally, a battery of five speeded information-processing tasks was administered to test whether L.C. was suffering from generalized cognitive slowing: that is, whether different cognitive processes were slowed to approximately the same degree.

The Tower of Hanoi is a problem-solving task in which the participant moves three disks of different sizes on three pegs in order to match the configuration of the experimenter's identical three disks (Klahr & Robinson, 1981). The participant is allowed three attempts to solve each problem. There are two rules: the participant can only move one disk at a time and cannot place a larger disk on top of a smaller disk. L.C. was able to solve all of the problems except one, a seven-move problem. However, she had difficulty with planning as evidenced by an impulsive approach and difficulties maintaining a cognitive set. These difficulties can be seen in her small amount of planning time before initiating moves and the fact that she broke the rules more than any member of the comparison group.

Verbal fluency was assessed by the number of animal names produced in 1 min plus the number of food items produced in 1 min (Halperin et al., 1989). L.C.'s score was below the mean, but well within the range of scores for the comparison group. As described in Jones-Gotman and Milner (1977), design fluency was assessed by the number of unique designs produced in 5 min and the number of unique designs containing four lines produced in 4 min. L.C. demonstrated deficits relative to the comparison group on the design fluency tasks, producing fewer unique designs on both tasks than any member of the comparison group. However, L.C.'s rates of perseverative responses on the fluency tests were similar to those of the comparison group.

The susceptibility of working memory to interference was assessed using digit and location spans developed by Hale et al. (1996). Memory spans on these tasks were measured in the absence of secondary tasks and with secondary tasks from the same domain as the primary task (e.g., digit span while naming the colors of the digits) or from a different domain (e.g., digit span while pointing to matching color patches). Although L.C.'s working memory performance was generally below controls, she did not show greater sensitivity to interference from either type of secondary task. The results of performance on the tasks of executive functions are shown in Table 2.

Table 2. Performance on measures of executive skills administered in Session 3

Task–Condition	L.C.	Controls *M* ± *SD*
Tower of Hanoi		
Most complex problem solved*	6.5	6.2 ± 0.7
Mean planning time (s)	1.7	9.0 ± 5.7
Rule violations	7	1.2 ± 1.2
Word Fluency		
Total words (animals & food)	25	26.3 ± 2.8
Design Fluency		
Free	12	23.4 ± 5.0
Fixed	11	18.4 ± 3.1
Total perseverations	0	2.7 ± 1.1
Working Memory Span*		
Verbal–no interference	3.5	5.0 ± 1.0
Verbal–verbal interference	3.0	3.0 ± 0.7
Verbal–spatial interference	3.5	4.8 ± 1.2
Spatial–no interference	2.5	4.8 ± 1.0
Spatial–spatial interference	0.5	2.8 ± 0.5
Spatial–verbal interference	2.5	4.1 ± 1.0

**Note*. If only one of two items was passed at a level of difficulty, the participant was given a half point credit (e.g., completing one of two items on a seven move problem or a seven item span led to a score of 6.5).

A battery of five speeded information-processing tasks, patterned after those used by Hale (1990), was developed in order to assess the extent of general cognitive slowing. Although L.C. showed left-sided motor difficulties on clinical measures in Sessions 1 and 2, she had no apparent difficulties performing speeded tasks in which the response was to press buttons with her left and right hands. The speeded information-processing battery consisted of simple and choice reaction time tasks, plus three tasks commonly used in experimental research on cognition: letter-matching, visual search, and mental rotation. Stimuli for all five tasks were presented on a video monitor, and stimulus presentation and data collection were under computer control.

For the simple reaction time task, a participant was asked to press a button as soon as an asterisk appeared in a 3-cm box in the center of the monitor screen. The asterisk appeared at random intervals of 1000, 1250, 1500, or 1750 ms after the participant's previous response. The participant completed five practice trials followed by 30 trials with her right hand and 30 trials with her left hand. For the choice reaction time task, the participant was asked to press the left button with her left hand if the stimulus was a left-pointing arrow and the right button with her right hand if the stimulus was a right-pointing arrow. The arrow appeared in a 3-cm box in the center of the monitor screen at random intervals of 1000, 1250, 1500, or 1750 ms after the participant's previous response, and the direction of the arrow alternated randomly. There were 10 practice trials followed by 60 experimental trials.

The visual search task was based on the conjunctive search paradigm (Treisman & Gelade, 1980). The participant was asked to indicate as quickly as possible whether or not a target (a blue triangle) was present among the distracters (red, green, or blue squares and red or green triangles) shown on the monitor by pressing one of two buttons. The right hand was used for target present responses and the left hand was used for target absent responses. The number of items in the display (6, 12, or 18) varied randomly, and the target's location (when present) alternated randomly between the right and left sides of the screen. There were 15 practice trials followed by two blocks of 80 trials for a total of 160 experimental trials, 40 at each display size. In this task (and in the mental rotation and letter matching tasks described next), after the first trial there was always a 1250-ms delay between a response and presentation of the next stimulus.

In the mental rotation task adapted from Cooper and Shepard (1973), the participant indicated whether the stimulus was the letter *F* or a mirror image of the letter *F* by pressing one of two buttons. The right hand was used for the letter *F* and the left hand was used for the mirror image of *F*. The letter or its mirror image was presented randomly at 0°, 60°, 120°, 240°, or 300° from vertical. The conditions with equivalent degrees of rotation (i.e., 60° and 300°, 120° and 240°) were combined to make three levels of rotation. Examples of the stimuli were shown to the participant followed by 10 practice trials. The participant then completed two blocks of 60 trials for a total of 120 experimental trials, 40 at each angle of orientation.

In the letter-matching task adapted from Posner and Mitchell (1967), the participant indicated whether two letters presented simultaneously were the same or different by pressing one of two buttons. The right hand was used for same-letter responses, and the left hand was used for different-letter responses. Upper and lower case letters (*A*/*a*, *B*/*b*, *C*/*c*, & *D*/*d*) were combined to create three conditions: (1) two different letters (e.g., *A*–*d*), (2) two of the same letter in the same case (e.g., *a*–*a*), or (3) two of the same letter, one upper and one lower case (e.g., *A*–*a*). The participant was shown examples of each instance followed by 10 practice trials. The participant then completed two blocks of 40 trials for 80 experimental trials, 40 in which the two letters were different and 40 in which they were the same, of which half had letters of the same case and half had one upper case and one lower case letter.

For all conditions, all of the participants including L.C. were highly accurate, with at least 90% correct responses. For each task, latencies more than 2 standard deviations from a participant's own mean latency for each condition were trimmed to exclude unusual responses. Each participant's mean latency for a condition after trimming was based on at least 15 responses. Response latencies for L.C. and the comparison group on these tasks are shown in Table 3.

Table 3. Response latencies in milliseconds for L.C. and comparison group in Session 3

	L.C.		Controls	
Task–Condition	Left	Right	Left	Right
Simple reaction time	746	670	397	362
Choice reaction time	879	901	623	604
Visual search				
Display-Size 6	1614	1270	1221	982
Display-Size 12	1405	1394	1281	1110
Display-Size 18	1807	1435	1396	1174
Mental rotation				
0°	1676	1659	1296	1376
60°	2849	2809	2214	2187
120°	3774	3514	2840	2780
Letter matching				
Different letters	2045	—	1294	—
Identical letters	—	1464	—	967
Name retrieval	—	2068	—	1266
Category judgment	not given		not given	
Antonym–synonym judgment	not given		not given	
Rhyming judgment	not given		not given	

In order to determine whether L.C. showed general cognitive slowing, her response latencies in each condition were regressed on the corresponding mean latencies of the comparison group. When data are analyzed in this manner, the slope of the regression line indicates the processing speed of the individual (or group) whose latencies contribute the *y*-coordinates of the data points relative to the comparison group whose latencies contribute the *x*-coordinates (Cerella, 1985; Hale, 1990; Hale & Jansen, 1994). Thus, a slope greater than 1.0 would indicate general cognitive slowing, and a slope of 1.5, for example, would indicate cognitive processing 50% slower than the comparison group. A data point that deviates significantly from the prediction of the regression line would indicate an experimental task or condition that involves cognitive processes that are slowed more (if the point is above the line) or less (if the point is below the line) than average for the individual (or group) being assessed.

When L.C.'s latencies were regressed on those of her peers, her performance was well described by a linear function with a slope of 1.22 and an intercept of 156 ms ($r^2 =$ .966). The slope of the regression line was significantly greater than 1.0 indicating that the difference in latencies between L.C. and her peers increased with the cognitive difficulty of the task [$t(17) = 4.02$, $p < .01$]. This pattern of results strongly suggests that, as hypothesized, L.C.'s cognitive processing was slower than that of the comparison group. In addition, the intercept was significantly greater than 0.0 according to a one-tailed test, supporting a hypothesis that L.C.'s cerebellar lesion had also resulted in sensorimotor slowing (i.e., a constant difference in latencies across tasks) [$t(17) = 1.88$, $p < .05$]. The regression lines for the right-hand and left-hand response latencies did not differ significantly in either slope or intercept [both $ts(15) < 1$], indicating no lateralized differences in motor response time for L.C. for the button press response.

The only exception to generalized slowing was the data point (indicated by the black circle in Figure 2) from the condition of the letter-matching task in which the same letter was presented in both upper and lower case, referred to as the name retrieval condition. The term name retrieval is used because letter names must be retrieved in order to decide whether or not the displayed letters are the same. In the physically identical condition of this task (indicated by a black triangle), there are alternative strategies for making a decision (e.g., letters must have the same name if they are physically identical). The name retrieval condition was a

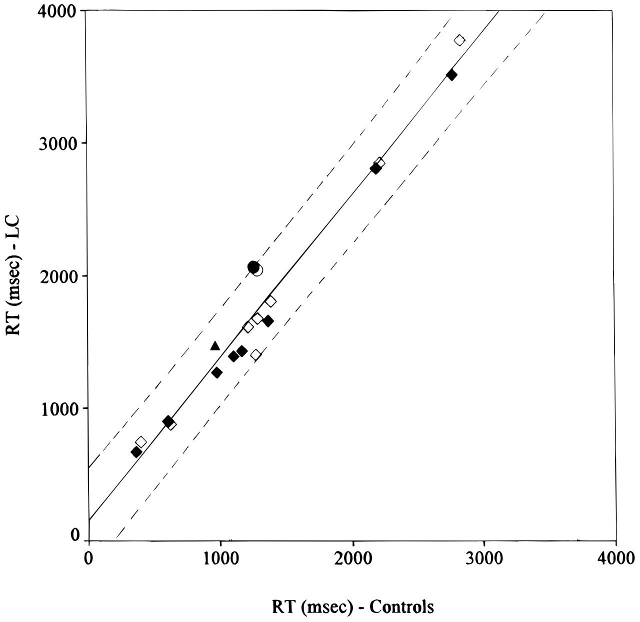

Fig. 2. L.C.'s latencies in Session 3 as a function of those of the control group. Left-hand responses are open and right-hand responses are shaded. Diamonds represent data from simple and choice reaction time, visual search, and mental rotation tasks. The shaded circle represents data from name retrieval condition of the letter-matching task, and the open circle represents data from the different-letter condition. The same-letter condition of the letter-matching task is shown with a shaded triangle. The solid lines represents the best-fitting linear function and the dashed lines the .95 prediction interval.

significant outlier, falling outside the 95% prediction interval for the regression (see Figure 2). The different letter condition of this task, which likely also involves name retrieval (Posner, 1978, pp. 30–31), fell just within the 95% confidence interval. Because L.C.'s mean response latency in the name retrieval condition was much slower than expected, even taking both sensorimotor slowing and general cognitive slowing into account using the predictions of the regression line, it was hypothesized that the retrieval process might be sensitive to some residual aspects of the clinical aphasia that L.C. had experienced post-injury.

Tests of Linguistic and Nonlinguistic Processing Speed: Session 4

In order to better understand the difficulty L.C. showed with name retrieval in Session 3, a battery of speeded information-processing tasks was developed, patterned after those used by Hale and Myerson (1996), in order to focus specifically on the efficiency of linguistic information processing. L.C.'s performance on this computerized battery, relative to her peers, could then be compared with her performance on the battery used in the preceding session which, with one important exception, tapped primarily nonlinguistic processes. In Session 4, in addition to the new linguistic battery and the original battery of speeded information-processing tasks, the reading subtest of the Wide Range Achievement Test (3rd edition; Wilkenson, 1993) was administered to each participant in order to assess general reading ability (see Table 1). The following tasks constituted the linguistic information-processing battery.

In the category judgment task, the participant was asked to indicate whether a word was an animal or not an animal by pressing one of two buttons. The animal and nonanimal words were all nouns matched for word length, word frequency (Kucera & Francis, 1967), and age of acquisition (Carroll & White, 1973; Gilhooly & Logie, 1980). All words had an expected age of acquisition of less than 3.5 years and were within the expected reading vocabulary of second graders (Thorndike & Lorge, 1944). After verbal instructions, the participant was shown examples of animal and nonanimal words and then completed 10 practice trials followed by 40 experimental trials. In this task, as in the other tasks in the linguistic battery, after the first trial there was always a 1250-ms delay between a response and presentation of the next stimulus.

In the antonym–synonym judgment task, the participant indicated whether two words presented simultaneously on the computer screen meant the same thing (e.g., *little–small*) or were opposites (e.g., *little–big*) by pressing one of two buttons. All words were within the expected reading vocabulary of second graders (Thorndike & Lorge, 1944). After verbal instructions, examples of synonym and antonym pairs were shown. The participant then completed 10 practice trials followed by 40 experimental trials.

The rhyming judgment task required the participant to indicate whether pairs of letters presented simultaneously on the monitor screen had the same vowel sounds (e.g., *g–t*) or different sounds (e.g., *g–k*) by pressing one of two buttons. After verbal instructions, the participant was shown examples of rhyming and nonrhyming pairs of letters. The participant then completed 10 practice trials followed by 40 experimental trials.

In general, participants were highly accurate with at least 90% correct responses on all tasks. The only exception was that L.C. had somewhat greater difficulty than the others on the rhyming judgment task, as she required the examples to be repeated several times and achieved 82.5% accuracy on the experimental trials. As with the Session 3 data, for each task any latencies more than 2 standard deviations from a participant's own mean latency were trimmed to exclude unusual responses. Each participant's mean latency after trimming was based on at least 15 responses with each hand (see Table 4). Accuracy rates for L.C. and the comparison groups in Sessions 3 and 4 are presented in Table 5.

L.C.'s performance in relation to the comparison group is shown in Figure 3. The symbols have the same interpretation as in the previous figure except that six new circle symbols have been added to represent the performance for left-hand and right-hand responses for the three new tasks (category judgment, synonym–antonym judgment, and rhyming judgment). The data points for these linguistic tasks, as

Table 4. Response latencies in milliseconds for L.C. and comparison group in Session 4

	L.C.		Controls	
Task–Condition	Left	Right	Left	Right
Simple reaction time	603	499	317	310
Choice reaction time	857	933	573	526
Visual search				
Display-Size 6	1376	1423	1096	908
Display-Size 12	1278	1502	1237	1056
Display-Size 18	1505	1630	1244	1099
Mental rotation				
0°	1828	1678	1634	1222
60°	2917	2735	2303	1954
120°	3025	3321	2546	2425
Letter matching				
Different letters	2145	—	1177	—
Identical letters	—	1543	—	861
Name retrieval	—	2001	—	1171
Category judgment	2422	1838	1085	999
Antonym–synonym judgment	4887	4892	2377	2437
Rhyming judgment	4510	6185	2846	2753

well as the points for the name retrieval conditions of the letter-matching task, all fell just within or outside of the prediction interval for the regression line based on the nonlinguistic conditions of the tasks used in the previous session (see Figure 3). Visual inspection suggested that L.C.'s performance was better represented by two separate regression lines: one for the linguistic data (i.e., that from the category judgment, synonym–antonym judgment, and rhyming judgment tasks, and the name retrieval conditions of the letter-matching task) and one for the nonlinguistic data points (those from the simple reaction time, choice reaction time, conjunctive search, mental rotation, and the physically identical condition of the letter-matching task).

The results of a test for separate regressions (Myerson et al., 1994) strongly supported the hypothesis of greater cognitive slowing on linguistic tasks as demonstrated by a difference in slopes [$t(10) = 4.86$, $p < .01$]. The fit of the two-regression model was very good, explaining 94.9% of the variance in L.C.'s latencies (see Figure 4). This represented an increment of 13.6% over a one-regression model. The slope of the regression of L.C.'s linguistic latencies on those of her peers was 1.96, suggesting that L.C.'s linguistic processing was slower by a factor of approximately 2. The slope for the nonlinguistic latencies was 1.17, replicating the finding that L.C. was slower by a factor of approximately 1.2 on these tasks. However, there was no significant

Table 5. Accuracy rates (percentage correct) for L.C. and comparison groups in Sessions 3 and 4

	Session 3		Session 4	
Task–Condition	L.C.	Controls	L.C.	Controls
Simple reaction time	n.a.	n.a.	n.a.	n.a.
Choice reaction time	100	99	100	100
Visual search				
Display-Size 6	100	99	95	99
Display-Size 12	95	97	98	98
Display-Size 18	95	97	92	96
Mental rotation				
0°	95	98	92	99
60°	92	96	95	97
120°	90	94	90	95
Letter matching				
Different letters	95	97	95	97
Identical letters	100	99	95	96
Name retrieval	95	98	90	96
Category judgment	not given		98	99
Antonym–synonym judgment	not given		90	96
Rhyming judgment	not given		82	94

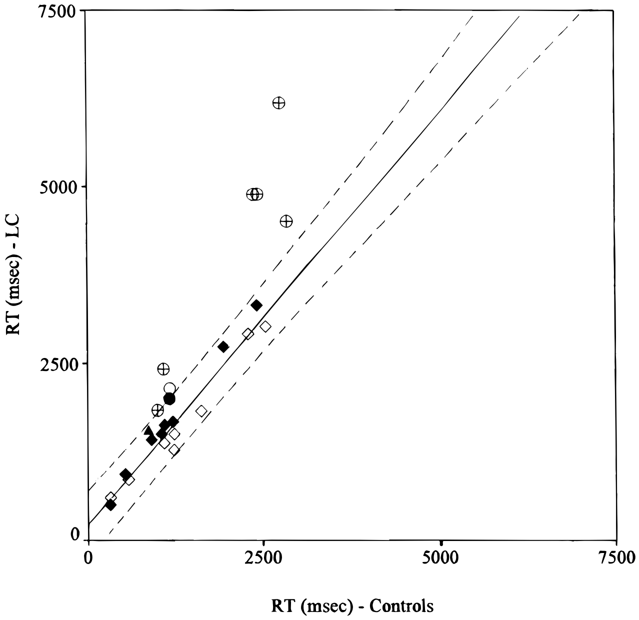

Fig. 3. L.C.'s latencies in Session 4 as a function of those of the control group. As in Figure 2, left-hand responses are open, and right-hand responses are shaded. The diamonds represent data from choice reaction time, visual search, and mental rotation tasks. The shaded circle represents the data from the name retrieval condition of the letter-matching task, and the open circle represents data from the different-letter condition. The same-letter condition of the letter-matching task is shown with a shaded triangle. The circles filled with a cross represent other linguistic tasks: category judgment, antonym–synonym judgment, and rhyming judgment. The solid lines represents the linear function for the nonlinguistic tasks and the dashed lines represent the .95 confidence interval. All of the linguistic conditions lie outside of the interval, with the exception of the name retrieval condition, which lies just within the interval.

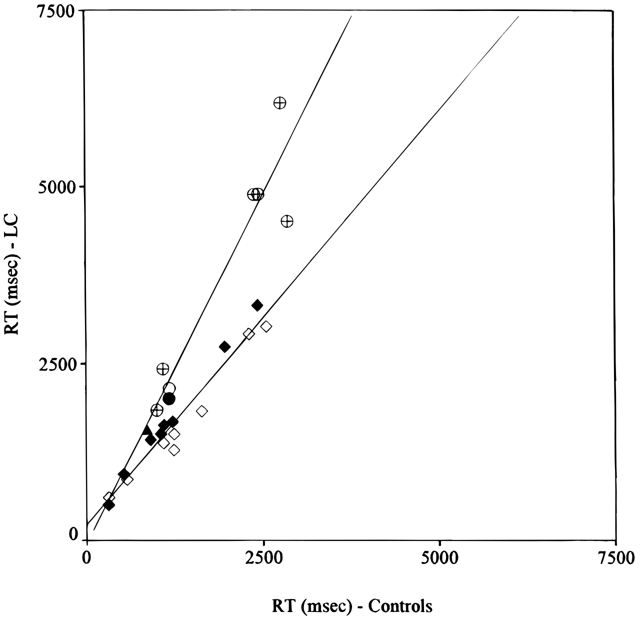

Fig. 4. The data from Figure 3 are shown with the lines of best fit for the nonlinguistic and linguistic data sets. The slope for the linguistic data sets is approximately 2.0, and the slope for the nonlinguistic tasks is approximately 1.2. A slope of 1 would indicate comparable cognitive efficiency for L.C. and the control group.

difference between the intercepts of the linguistic and nonlinguistic regressions [$t(9) = 0.80$]. Visual inspection of individual data for the children in the comparison group revealed that none of the children had a discrepancy between their processing speed for linguistic *versus* nonlinguistic tasks as seen in L.C.'s data.

Finally, it may be noted that, although the number of linguistic and nonlinguistic tasks used in the present study were approximately equal, two of the nonlinguistic tasks had six conditions each, so that the linguistic regression was based on fewer data points. However, similar results were obtained when the number of data points for the linguistic and nonlinguistic regressions were equated. This was done by using only the easiest visual search (Display Size 6) and most difficult mental rotation conditions (120°) along with the choice reaction time task for the nonlinguistic regression and the category, antonym–synonym, and rhyming judgment tasks for the linguistic regression. The specific visual search and mental rotation conditions selected were chosen because they were most comparable in difficulty (based on the reaction times of the control group) to the category and antonym–synonym judgment tasks, respectively. (The letter-matching task was not included because the required decisions could involve either linguistic or nonlinguistic processes or both.) Based on the above six linguistic and six nonlinguistic data points, the slope for the linguistic regression was 1.28, whereas the slope for the nonlinguistic regression was 1.86, values similar to those obtained based on the complete linguistic and nonlinguistic data sets.

DISCUSSION

The present case study examined the cerebellum's role in cognition using a novel approach that measured general processing efficiency over a range of different cognitive tasks. This method is potentially useful because it has been hypothesized that the cerebellum increases efficiency of processing across many types of mental activities (Ito, 1993; Leiner et al., 1989, 1991). There were two primary findings in the present case. First, there was a dissociation between processing speed for linguistic *versus* nonlinguistic information: Following cerebellar injury, L.C. was much slower in the linguistic domain than in the nonlinguistic domain. Second, across all of the tasks within each domain, a consistent degree of slowing was observed: L.C. was approximately 1.2 times slower than her peers at processing nonlinguistic information and approximately 2.0 times slower at processing linguistic information.

There are several factors that need to be considered in the interpretation of these findings. One factor is the characteristics of the experimental tasks, and two others are the lateralization and developmental timing of the cerebellar injury. These issues will be addressed in the following sections.

Task Characteristics

The two sets of measures used to evaluate linguistic and nonlinguistic processing potentially vary in ways other than the linguistic and nonlinguistic content of the task demands. For example, all of the verbal tasks required decisions about the relationship between two stimuli or between a stimulus and a predetermined category. The nonlinguistic tasks were more variable in their task demands and were not directly analogous to the linguistic tasks, although the choice reaction time, visual search, and mental rotation tasks were similar to the category judgment task in matching a stimulus with predetermined categories. The fact that two of the linguistic tasks involved evaluating a relationship between two items, whereas the nonlinguistic tasks were more variable in content, leaves open the possibility that more analogous nonverbal tasks might have led to a different pattern of results.

It should be noted, however, that L.C. showed a far larger deficit on visual search than on category matching, the two most comparable linguistic and nonlinguistic tasks. Category judgment and visual search both involved comparing stimuli with predetermined categories (i.e., animal and blue triangles, respectively), and the reaction times of control subjects on the two tasks were reasonably equivalent. (i.e., for controls, the mean reaction time for both conditions of category judgment was 1042 ms, and the mean reaction time for both conditions of the visual search, Display-Size 6, was 1002 ms). Notably, L.C.'s reaction times were 2.05 times slower than controls on the category judgment task, but only 1.40 times slower on the conditions of the visual search task that were most nearly equivalent in difficulty (i.e., Display-Size 6). In addition, it could be argued that rhyming judgments, when performed silently, involve comparing mental "phonological" images that are at least roughly analogous to the mental visual images that are compared in mental rotation tasks. L.C.'s reaction times were, on average, 2.02 times slower than controls on the rhyming task, but only 1.28 times slower than controls on the most nearly equivalent conditions of the mental rotation task (i.e., 120°). Nevertheless, it must be acknowledged that the comparability of linguistic and nonlinguistic tasks remains a difficult and important methodological issue.

Lateralized Cerebellar Injury and Developmental Timing

In the present case, L.C. suffered an injury to the left cerebellar hemisphere, whereas the right cerebellar hemisphere has been implicated in word generation tasks by some previous PET studies (Petersen et al., 1989; Raichle et al., 1994). The right cerebellar lateralization suggested by these PET studies makes some sense because of the contralateral connectivity between the left cerebrum and the right cerebellum. However, there are two points to consider in addressing this apparent discrepancy with the present findings. The first point is that, although lateralization of activation has been observed with word generation, PET studies have also shown that other linguistic processes (e.g., word reading, silent counting, and the maintenance of verbal information in working memory) activate the cerebellum bilaterally (Decety et al., 1990; Fiez et al., 1996; Petersen et al., 1989). In fact, there is some suggestion that the maintenance of verbal information in working memory activates the left cerebellar hemisphere more than it does the right cerebellar hemisphere (Fiez et al., 1996).

The second point to consider is that lateralized effects of brain injury on linguistic processing may be different in children and adults. A number of studies of brain injury during childhood have reported significant language deficits following right hemisphere damage (Aram et al., 1985; Eisele & Aram, 1993; Feldman et al., 1992; Thal et al., 1991; Vargha-Khadem et al., 1985). These studies suggest that, with the exception of syntax, language deficits in children with right hemisphere injuries occur frequently, and in a number of these studies the reported deficits have been comparable to the deficits found with left hemisphere injuries. This is especially true for deficits on tasks involving lexical comprehension (Eisele & Aram, 1993; Thal et al., 1991). Thus, one possible reason why L.C. may have suffered linguistic deficits following focal damage to her left cerebral hemisphere is because the right cerebral hemisphere appears to be more involved in language functions in children than in adults.

Another possible reason for this deficit is because of the putative nature of the cerebellum's contribution to cognitive processes. That is, it has been proposed that the cerebellum contributes to the formation of associations and the acquisition of cognitive skills (Leiner et al., 1991; Petersen et al., 1989; Raichle et al., 1994) and thus may play an especially important role in children's acquisition of reading and other related language skills at the beginning of the school years. It may be recalled that L.C. suffered her injury in the middle of the first grade, and therefore the fact that her linguistic deficits appear to be greater than her deficits in nonlinguistic functions may be a consequence of the developmental timing of her injury. There are several important aspects to the development of reading comprehension, including the automatization of word identification and improved working memory and self-monitoring (Siegler, 1991). Deficits in any of these specific factors could contribute to less efficient reading comprehension. It is possible, therefore, that the developmental timing of her injury disrupted the acquisition of normal reading comprehension through nonlinguistic processes important for language development. If so, then the developmental timing of cerebellar injury may play an important role in determining the resultant pattern of deficits.

Conclusions

The present finding of marked slowing of cognitive processing and executive dysfunction in L.C. adds to a growing body of evidence indicating a role for the cerebellum in nonmotor cognitive functions. L.C.'s postinjury aphasia and residual inefficiencies in language processing appear to be consistent with Leiner et al.'s (1989, 1991) hypothesis that in humans the cerebellum may be particularly important for language functions. With respect to the nature of the cerebellum's role in cognitive processes, both linguistic and nonlinguistic, it has been hypothesized that the cerebellum enhances the general processing efficiency of cognitive skills (Ito, 1993; Leiner et al., 1989, 1991). The issue of general efficiency is difficult to address using traditional assessment procedures that are designed to identify specific deficits. In contrast, the present regression-based approach seems well suited to evaluating both the degree of difference in processing efficiency between individuals and groups as well as the extent to which such a difference is general in nature. The slope of the regression of a target individual or group's latencies on those of a control group provides a measure of the difference in efficiency (i.e., the degree of slowing). In addition, the proportion of variance accounted for by the regression provides a measure of how general this difference is across multiple tasks (Cerella & Hale, 1994; Myerson et al., 1994).

In the present case study, the hypothesis of a cerebellar contribution to general processing efficiency is supported by the consistency in the degree of slowing observed across tasks within each domain, as evidenced by the high proportions of variance accounted for by the regression models. It should be noted, however, that in addition to its utility in assessing general decreases in processing efficiency the present regression-based approach also provides a technique for identifying specific deficits. Such specific deficits may manifest themselves as significant outliers from the regression, as illustrated in the present case by the results for name retrieval observed in the third testing session. Although a fourth testing session revealed that the name retrieval deficit was likely a specific instance of a more general deficit in linguistic processing efficiency, the identification of a potentially specific deficit that can be followed up in subsequent tests illustrates another application of a regression-based approach.

L.C.'s linguistic deficit might easily have been overlooked for two reasons. First, her scores on standardized tests of verbal abilities were within the normal range; and second, even on the speeded linguistic tasks used to reveal linguistic slowing, her performance was usually highly accurate. Nevertheless, an analysis integrating response latencies from a variety of speeded tasks revealed that L.C. was consistently slower than her peers on all tasks and approximately twice as slow at linguistic processing. Thus, even in the presence of a clear deficit in processing efficiency, it would appear that the cognitive effects of cerebellar injury may be otherwise relatively subtle, and a regression-based approach similar to that in the present study may prove generally useful for evaluating individuals with cerebellar injury.

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