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The cerebellum and English grammatical morphology: Evidence from production, comprehension, and grammaticality judgments

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Abstract

Three neuropsychological experiments on a group of 16 cerebellar patients and 16 age- and education-matched controls investigated the effects of damage to the cerebellum on English grammatical morphology across production, comprehension, and grammaticality judgment tasks. In Experiment 1, participants described a series of pictures previously used in studies of cortical aphasic patients. The cerebellar patients did not differ significantly from the controls in the total number of words produced or in the proportion of closed-class words. They did differ to a marginally significant extent in the production of required articles. In Experiment 2, participants identified the agent in a series of aurally presented sentences in which three agency cues (subject-verb agreement, word order, and noun animacy) were manipulated. The cerebellar patients were less affected than the controls were by the manipulation of subject-verb agreement to a marginally significant extent. In Experiment 3, participants performed a grammaticality judgment task on a series of aurally presented sentences. The cerebellar patients were significantly less able to discriminate grammatical and ungrammatical sentences than the controls were, particularly when the error was of subject-verb agreement as opposed to word order. The results suggest that damage to the cerebellum can result in subtle impairments in the use of grammatical morphology, and are discussed in light of hypothesized roles for the cerebellum in language.

Keywords

cerebellum; cognition; language; grammar; syntax; aphasia; agrammatism; speech; phonology

INTRODUCTION

Contrary to the belief that cerebellar involvement in language is limited to speech production, a variety of neuropsychological and neuroimaging studies in speech perception (Ackermann et al., 1997; Mathiak et al., 2002), verbal working memory (Justus et al., submitted; Desmond et al., 1997), and lexical retrieval (Fiez et al., 1992; Peterson et al., 1989), as well as the developmental dyslexia literature (Nicholson et al., 2001), suggest that the cerebellum makes contributions that are not purely articulatory (for reviews see Silveri & Misciagna, 2000; Mariën et al., 2001). This literature is part of a larger trend in cognitive neuroscience suggesting that the cerebellum makes contributions to cognition more generally, independent of motor demands (for reviews see Desmond, 2001; Justus & Ivry, 2001; Schmahmann, 2001a). One component of language that has been relatively unexplored in patients with cerebellar lesions is grammatical morphology. Here I present the results of three experiments investigating the

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These experiments were presented at the 2003 meeting of the Cognitive Neuroscience Society in New York, NY. This article is based on Chapter 3 of the dissertation of T. Justus (2003).

speech production, comprehension, and grammaticality judgments of a group of sixteen English-speaking cerebellar patients, all with a focus on grammatical morphology.

There were at least three motivations for hypothesizing changes in grammatical morphology following cerebellar damage. The first motivation was provided by the increasing attention that researchers have paid to constraints on grammatical processing that are not based directly in grammar per se, but instead result from limitations in phonological representation, lexical retrieval, and/or verbal working memory (e.g., Kean, 1979; Kilborn, 1991; Just & Carpenter, 1992; Blackwell & Bates, 1995; Kolk, 1995; Haarmann et al., 1997; Caplan & Waters, 1999; Dick et al., 2001). A patient who has a noisy perceptual representation of the speech stream or limited verbal working memory capacity may display an “agrammatic” profile during language comprehension tasks. Agrammatic speech output may also reflect similar processing limitations rather than a loss of discretely-localized grammatical knowledge. Given the links between the cerebellum and speech perception, verbal working memory, and lexical retrieval, damage to the cerebellum may result in the kinds of processing limitations that impact the realization of grammatical knowledge.

A second motivation came from the neuroimaging literature: the cerebellar hemispheres frequently seem to participate along with the contralateral inferior/lateral frontal lobes on a variety of tasks, particularly the left frontal lobe and right cerebellar hemisphere. Most of the cognitive or linguistic tasks that have been shown to involve the cerebellum also implicate these frontal areas, particularly when demands are placed upon working memory, lexical processing, or “executive” processing (e.g., Cabeza & Nyberg, 2000). Neural projections also suggest this functional link; not only does the cerebellum project to the frontal lobe via the dentate nucleus and thalamus, but it also receives input back from it via the pons (e.g., Schmahmann, 2001b). These relationships, along with the traditional description of the left inferior/lateral frontal lobe as critical for grammar, also motivated a search for cerebellar involvement (particularly that of the right cerebellar hemisphere) in grammar.

The third motivation was a small collection of case studies that had directly suggested such deficits in grammatical morphology following damage to the cerebellum. Some samples of speech output from four of these cases are listed in Table 1. The first case study was reported by Silveri et al. (1994), who described an Italian patient who had suffered a right cerebellar infarct. In addition to dysarthric speech and slightly reduced verbal fluency, the patient had a tendency to omit free-standing grammatical morphemes (e.g., auxiliaries) and clitics in his spontaneous speech and often used the infinitive form of a verb rather than conjugating it. Mariën et al. (1996,2000) described a second cerebellar patient with abnormal grammatical morphology. This Dutch-speaking patient had suffered a lesion to the right cerebellar hemisphere, with additional minor damage to the basal ganglia. The speech of this patient was sparse, effortful, and suggestive of word-finding difficulties, and his performance on the letter fluency and category fluency tests represented *z* scores of -1.4 and -2.05 , respectively. With regard to syntactic comprehension, the patient performed poorly on the syntactically loaded sections of the Token Test (6 correct out of 41), whereas performance on the other sections was perfect. In his spontaneous speech he also omitted many morphological markers, such as those marking nouns and verbs. A third agrammatic patient with damage to the right cerebellar hemisphere was reported by Zettin et al. (1997). Like the previous two patients, this Italian-speaking patient often omitted function words and grammatical morphemes in his spontaneous speech. The authors report preservation of grammar on the perceptual side, unlike the previous study. However, the task in this case was a grammaticality judgment, and performance on this task often dissociates from the ability to derive meaning from syntax (Linebarger et al., 1983). Finally, Gasparini et al. (1999) tested a fourth patient with a superior-lateral right cerebellar infarct who also manifested some grammatical difficulties in his Italian speech, along with a slightly reduced verbal immediate recall, slowed speech, and severe word-finding

difficulties. Like the patient described by Mariën et al. (1996,2000), this patient was also impaired on a test of sentence comprehension (8 correct out of 17). While these cases provided the most extensive testing of grammatical morphology, other reports of cerebellar patients focusing on other aspects of language have also mentioned grammatical difficulties (Fabbro et al., 2000; Riva & Giorgi, 2000; Mewasingh et al., 2003).

The goal of the current study was to investigate the morphological aspects of grammar in a group of English-speaking cerebellar patients. Grammatical morphology may be a more likely candidate for a cerebellar impairment in grammar, rather than the comprehension of different syntactic structures (e.g., active versus passive sentences).¹ This rationale was based on work with cortical aphasics demonstrating that the processing of grammatical morphology is more sensitive to brain damage than are the elements of syntax concerned with word sequencing (e.g., Bates et al., 1987a). Further, this dissociation is particularly robust for speakers of English, and less robust in the other Germanic languages, the Romance languages (Bates & MacWhinney, 1989; Bates et al., 2001), as well as Hungarian and Turkish, two non-Indo-European languages (MacWhinney et al., 1991; Slobin, 1991). Bates and MacWhinney (1989) explain this dissociation with a functionalist account known as the Competition Model: English speakers are particularly likely to show the dissociation between grammatical morphology and word order, given that most of the information about who did what to whom in English is carried by word order rather than the grammatical morphemes. In other languages, grammatical morphology is more important to conveying meaning and is thus more resilient following brain damage. Because of these crosslinguistic differences, the grammatical morphology of *English* is perhaps the most likely element of grammar to be disrupted in patients with cerebellar lesions.

In addition, the current study examined English grammatical morphology from the three angles of production, comprehension, and grammaticality judgments. This inclusion of tasks of both the motor (the production task) and the perceptual (the comprehension and grammaticality judgment tasks) sides of language was of interest given the typical association of the cerebellum with dysarthria in speech production and the movement towards more perceptual-cognitive roles of the cerebellum in language (e.g., Ackermann et al., 1997; Mathiak et al., 2002; Justus et al., submitted). A change in the production of grammatical morphemes without any difference in either of the perceptual tasks would not necessarily require a perceptual or cognitive explanation of the impairment. The inclusion of both the comprehension and grammaticality judgment tasks was motivated by the many dissociations observed between these two tasks in cortical aphasic patients (e.g., Linebarger et al., 1983).

Although the literature on the cerebellum and language had suggested that patients with *right* cerebellar damage were the most likely to show disrupted grammatical morphology, the current study examined a variety of cerebellar etiologies: three patients with damage to the right cerebellar hemisphere (R1, R2, R3), three patients with damage to the left cerebellar hemisphere (L1, L2, L4), one with damage to the cerebellar midline (M1), and nine with bilateral degenerative disorders (B1 – B9; see Table 2 and Figure 1). This relatively large group allowed for the potential detection of subtle experimental interactions, which would not have been possible with a single case or smaller group. Further, the inclusion of patients other than those with right-hemisphere lesions provided for the potential observation of new, independent evidence regarding cerebellar laterality.

¹Comprehension of active and passive sentences was tested in a group of seven cerebellar patients with mixed results by Pickett (1998). Whereas control participants made errors on four percent of active sentences and ten percent of passive sentences, cerebellar patients as a group made errors on eleven percent of both active and passive sentences. This was one manipulation within the first of two Tests of Meaning from Syntax (TMS1 and 2) used in this study.

EXPERIMENT 1: SPEECH PRODUCTION

The first experiment of this project was an elicited production, picture description task, designed to test for the use of grammatical morphemes (in particular, closed-class words such as articles) and canonical word order. The task was to describe a series of pictures depicting simple events (see Table 3 for description). On the hypothesis that patients with damage to the cerebellum would demonstrate impairments similar to that of cortical aphasics, they were expected to show a reduction in the use of closed-class words (i.e., function words such as articles, auxiliary verbs, prepositions and pronouns) relative to open-class words (i.e., content words such as nouns, main verbs, adjectives, and adverbs) with respect to controls, while showing retained use of canonical word order. The design of this study and the analyses conducted were based on those of Bates et al. (1987b;1988).

Results

Figure 2 illustrates the total number of words produced, the proportion of closed-class words produced, and the proportion of required articles produced. Comparisons of the patients and controls as a group on these three measures showed a difference that approached significance for article production only (total words: $F(1, 30) = .85, p = .36$; proportion closed-class words: $F(1, 30) = 1.3, p = .27$; proportion required articles produced: $F(1, 30) = 3.4, p = .07$).²

Although as a group, the cerebellar patients did not differ significantly from the controls (with the possible exception of the marginally significant difference in the use of articles), this does not mean that every patient performed within the normal range. Whereas six of the sixteen patients show nearly flawless use of grammatical morphology, four of the patients (B2, B7, L2, and R3) were below the normal range established by the controls in the proportion of closed-class words ($z = -11.0, -3.1, -4.1$, and -2.7 , respectively), and in the production of required articles ($z = -13.7, -5.3, -4.4$, and -5.8 , respectively). These patients also produced the fewest words in general. For example, Patient B2 produced only 18 closed-class words out of 101 total words, and only 10 out of 56 required articles, as suggested by responses such as “*monkey eating banana*”, “*cat on small table*”, and “*cat offering boy a flower*”.

The three output measures of total words, proportion of closed-class words, and proportion of required articles were highly correlated. As the number of words produced increases, both the proportion of closed-class words and the proportion of articles increase (logarithmic fits: $F(14) = 16.1, p < .001$, and $F(14) = 18.8, p < .001$, respectively) with the closed-class proportion leveling off at around 50 to 60 percent. The proportion of closed-class words and article use showed a strong linear relationship with each other ($r = .97, p < .001$; see Figure 5 for a complete set of linear correlations).

Regarding word order, none of the patients produced an AVO sentence (series 3–5) with all three items in anything other than AVO order. This suggests that as expected the use of canonical word order is intact.

One possible concern about the four patients who seemed to show a somewhat agrammatic pattern in their speech is that age and education may have played a role in their performance. As can be seen in Table 2, B2 and B7 were among the oldest patients in the group and B2, L2, and R3 were among the least educated. Both of these variables were related to the use of closed-class words (age: $r = -.37, p = .04$; education: $r = .40, p = .03$) and the use of articles specifically (age: $r = -.42, p = .02$; education: $r = .43, p = .01$).³ Age and education do not seem to explain the language patterns of B2, B7, L2, and R3 completely, however. On

²Probability values given here are based on a more conservative two-tailed test. With a one-tailed test, the difference for the proportion of required articles produced is significant.

inspection, there were two control participants in the same age range as B2 and B7 who did not show a reduction in article use and one control participant with 12 years of education, the same amount as B2 and R3, who produced 100 percent of his required articles. A regression analysis which removed the effects of age and education on article production before testing for the patient effect still suggested that the patients produced fewer required articles than the controls did ($t = 1.73$, $p = .095$, as compared to $p = .074$ when age and education are not taken into account).

A final question concerns the effect of lesion laterality on the production measures. Paired comparisons between the five groups (controls, left, right, midline, and bilateral) for the three production measures revealed a significant difference in the proportion of required articles produced by the bilateral patients ($n = 9$) compared to controls ($F(1, 23) = 4.0$, $p = .058$) and for the left-hemisphere patients ($n = 3$) compared to controls ($F(1, 17) = 4.6$, $p = .046$). None of the other comparisons were significant.

Discussion

The results of Experiment 1 revealed a marginally significant reduction of the use of required articles in the cerebellar patients as compared to the controls. This difference was largely due to a subset of the patients (B2, B7, L2, and R3), whose speech was also characterized by a preponderance of open-class words. These patients were the exceptions, however. By and large, the population of cerebellar patients examined here did not demonstrate a “telegraphic” speech characterized by the omission of articles and other closed-class words, as is the typical case with English-speaking Broca’s aphasics.

The correlations between the total number of words produced, the proportion of closed-class words, and the proportion of required articles are also suggestive of more general relationships between brain damage and the processing of grammatical function words. A reduction in the use of closed-class words in speech does not necessarily mean that brain regions that are specifically involved in the production of closed-class words have been damaged while those involved in the production of open-class words have been spared. Brain damage that limits speech production such that the direct effect is to lower the overall speech output results in a smaller proportion of closed-class words, perhaps because they are the least important in conveying information.

In sum, whereas most of the patients in Experiment 1 did not show a significant change in the use of grammatical morphology in speech production, the data of a small subset did. I shall return to this variability after discussing the results of the other two studies of grammatical morphology: the comprehension and grammaticality judgment experiments.

EXPERIMENT 2: COMPREHENSION

The second experiment consisted of a language comprehension task designed to test for the use of grammatical morphemes (in this case, subject-verb agreement) and canonical word order. The task was to listen to an aurally presented sentence and determine the agent, or “what did the action” (see Table 3 for examples). An animacy manipulation was also included to be fully consistent with the cortical aphasic study on which this was based (Bates et al., 1987a; also see Slobin & Bever, 1982, for the initial use of this task in a developmental study). On the hypothesis that patients with damage to the cerebellum would demonstrate impairments similar to that of cortical aphasics, they were expected to show a reduction in the use of a subject-verb

³Correlations involving age and education are given in the text for the entire group of 32 participants, rather than the group of 16 patients. This is because of the potential concern for effects of these two variables underlying the group differences. All other correlations are given for the patient group alone. This is more conservative for the purposes of identifying relationships between the deficits.

agreement cue relative to controls in making their agency decision, while showing use of word order and animacy cues similar to that of the controls. The design of this study and the analyses conducted were based on Bates et al. (1987a).

Results

Figure 3 presents the results of Experiment 2. A $3 \times 3 \times 3 \times 2$ analysis of variance was conducted with agreement, word order, and animacy as within-subjects factors and group (cerebellar patient or control) as a between-subjects factor. First, the results showed that participants in general were sensitive to the three cues; all three of the within-subjects main effects were significant: Agreement ($F(2, 29) = 9.6, p = .001$), Word Order ($F(2, 29) = 43.7, p < .001$), Animacy ($F(2, 29) = 10.4, p < .001$). Participants were most likely to chose the first noun as the agent when it agreed in number with the verb and the second noun did not (Figure 3A), when NVN word order was used rather than NNV and VNN (Figure 3B), and when only the first noun was animate (Figure 3C).

The two-way interaction between Agreement and Word Order was also significant ($F(4, 27) = 5.3, p = .003$). The effect of the word order manipulation was largest when the agreement cue was neutral (Agree 0). Specifically, when the agreement cue was neutral, participants were nearly as likely to choose the first noun as when the agreement cue indicated the first noun, if the word order was also NVN, but were nearly as likely to chose the second noun as when the agreement cue indicated the second noun, if the word order was NNV or VNN.

Most critical to the hypothesis, the two-way interaction between Agreement and Group approached significance ($F(2, 29) = 2.8, p = .07$; Figure 2A). The effect of the agreement manipulation was smaller for the cerebellar patients compared to the controls. For example, for a sentence such as “*The cow is kissing the goats*,” in which the verb agrees only with the first noun, controls chose the first noun as the agent more often than the patients did, whereas for a sentence such as “*The horse are smelling the zebras*,” in which the verb agrees only with the second noun, controls chose the *second* noun as the agent more often than the patients did. The two-way interaction between Animacy and Group was the only other interaction that approached significance ($F(2, 29) = 2.4, p = .11$; Figure 2C). None of the higher order interactions were significant (all $p > .30$).

As in Experiment 1, correlation analyses were performed to examine how individual variability on the different measures related to one another. As might be expected, sensitivity to the different cues were often negatively related to one another. This is due to the experimental design; as the three cues of subject-verb agreement, word order, and animacy are manipulated orthogonally, they often come into conflict with each other. Use of the order cue, the dominant cue for English speakers, was negatively related to the use of the animacy cue ($r = -.51, p = .04$), and, when control participants are included in the correlation, negatively related to the use of the subject-verb agreement cue ($r = -.42, p = .02$). Age did not predict sensitivity to any of the cues, but education was related to sensitivity to the non-dominant agreement and animacy cues to marginally significant extents ($r = .32$ and $.30, p = .078$ and $.098$, respectively).⁴

An analysis of lesion laterality was also conducted, as in Experiment 1. The four-way ANOVA was repeated comparing the relative sensitivity to the three cues of each of the five groups (controls, right, left, midline, and bilateral). The critical interaction between Agreement and Group was significant for the bilateral patients ($n = 9$) versus the controls ($F(2, 22) = 5.6, p = .01$). This interaction did not approach significance for any of the other comparisons.

⁴For all correlation analyses involving the results of Experiment 2, a cue-sensitivity measure was calculated for each type of cue by subtracting the probability of choosing noun 1 in the Agree 1, NVN, or Animacy 1 condition (those most likely to indicate noun 1) from that of the Agree 2, VNN, or Animacy 2 condition (those most likely to indicate noun 2).

Discussion

The results of Experiment 2 revealed a marginally significant effect for the cerebellar patients to be less influenced by a manipulation of subject-verb agreement than the controls were when making an agency assignment for aurally presented sentences. This is similar to the data of Broca's aphasics tested with this task. While some variability was present, this difference was more consistent across the patient group than were the production effects in Experiment 1. This is particularly intriguing, as the traditional motor conception of the cerebellum would have predicted the reverse: a larger, more consistent impairment in a language production task compared to a language perception task.

EXPERIMENT 3: GRAMMATICALITY JUDGMENTS

The third experiment of this project was a grammaticality judgment task, designed to test for the use of grammatical morphemes (in this case, subject-verb agreement) and canonical word order in making a metalinguistic judgment concerning whether a sentence was or was not properly formed. The task was to listen to an aurally presented sentence and determine whether the sentence was "correct and natural" or "incorrect and unnatural" (see Table 3 for examples). On the hypothesis that patients with damage to the cerebellum would demonstrate impairments similar to that of cortical aphasics, they were expected to show a reduction in the ability to discriminate ungrammatical from grammatical sentences compared to the controls. In particular, they were expected to show this impairment for sentences with subject-verb agreement errors, and to a lesser extent for sentences with word order errors. The design of this study and the analyses conducted were based on Blackwell and Bates (1995; also see Wulfeck & Bates, 1991; Wulfeck et al., 1991).

Results

Figure 4 presents the results of Experiment 3 as A-prime scores for each participant, representing the ability to discriminate ungrammatical and grammatical sentences, for each kind of error tested: agreement and word order. The detection of an error of agreement was more difficult than the detection of an error of word order ($F(1, 30) = 12.9, p = .001$). This was true for the controls ($t(15) = 3.24, p = .006$) and for the patients ($t(15) = 2.65, p = .018$). There was also the main effect that the patients were less able to discriminate successfully in this experiment relative to the controls ($F(1, 30) = 10.4, p = .003$). This was true for both the agreement errors ($t(30) = 2.85, p = .008$) and the word order errors ($t(30) = 3.22, p = .003$). While the group means suggest that the patients were especially impaired for the detection of an agreement error relative to the controls, this interaction did not reach significance ($F(1, 30) = 2.0, p = .17$).

As for Experiments 1 and 2, the variability between participants was examined using correlation analysis. Discrimination of agreement errors and word order errors were significantly correlated with each other ($r = .70, p < .001$) and were each significantly correlated with education (agreement: $r = .52, p = .002$; order: $r = .39, p = .03$). Education does not explain the difference between patients and controls, however. When the effect of education is accounted for in a regression analysis, the cerebellar patients still performed more poorly than the controls in the detection of agreement errors ($t = 2.52, p = .02$, rather than $p = .008$) and in the detection of word order errors ($t = 2.90, p = .007$, rather than $p = .003$).

An analysis of lesion laterality was also conducted, as in Experiments 1 and 2. All three of the left-hemisphere patients had poorer discrimination for the agreement errors compared to the word order errors, creating a significant difference between the two for this group considered alone ($t(2) = 4.59, p = .04$). Although on average the right-hemisphere and bilateral patients

showed a similar trend, it was neither consistent nor significant for these groups. The midline patient, M1, performed well on both kinds of error.

In terms of overall performance on the task, the controls performed better than the bilateral group ($F(1, 23) = 6.4, p = .02$), the left-hemisphere group ($F(1, 17) = 23.2, p < .001$) and the right-hemisphere group ($F(1, 17) = 51.3, p < .001$). The bilateral group also performed better than the left-hemisphere group ($F(1, 10) = 5.2, p = .05$), and the right-hemisphere group ($F(1, 10) = 5.1, p = .05$), who were not significantly different from each other.

The interaction between group and error type, although not significant for the controls versus the patients as a whole, was significant for the left-hemisphere patients versus controls ($F(1, 17) = 18.1, p = .001$), for the right-hemisphere patients versus controls ($F(1, 17) = 4.5, p = .05$), and for the left-hemisphere patients versus the bilateral patients ($F(1, 10) = 5.0, p = .05$).

Discussion

Experiment 3 demonstrated that the cerebellar patients had a reduced ability to discriminate grammatical from ungrammatical sentences, particularly when the source of the ungrammaticality was an error of subject-verb agreement. This deficit is similar to that of Broca's aphasics (Wulfeck & Bates, 1991; Wulfeck et al., 1991). As in Experiments 1 and 2, a great deal of variability was observed across the group of cerebellar patients, with some patients performing nearly flawlessly on the detection of both the word-order errors as well as the more difficult subject-verb agreement errors, and the deficits of other patients creating the group differences.

GENERAL DISCUSSION

Three neuropsychological experiments were conducted on the same group of sixteen cerebellar patients and sixteen controls to investigate whether damage to the cerebellum is associated with alterations in English grammatical morphology in production, comprehension, and grammaticality judgment tasks. In Experiment 1, the participants' verbal descriptions of the picture stimuli suggested that the speech output of only a minority of the patients could be characterized by reductions in grammatical morphology. This reduction was particularly evident on the most sensitive measure: the proportion of required articles produced. In contrast, the patients still produced utterances using canonical word orders, consistent with the dissociation often found between grammatical morphology and word order in cortical aphasic patients. In Experiment 2, the responses of the patients on the agency-assignment comprehension task suggested that the patients were not as strongly affected by a manipulation of subject-verb agreement as the controls were, whereas they were affected by a manipulation of word order to a similar extent as were the controls. In Experiment 3, the responses of the patients on the grammaticality judgment task suggested that the patients were less able to discriminate grammatical from ungrammatical sentences, and this was more the case when the error was one of subject-verb agreement rather than of word order.

To my knowledge, these studies are the first systematic investigations of the grammatical morphology of a large group of cerebellar patients. The patterns of deficit found in these three studies could be described as smaller versions of those found in cortical aphasics, particularly Broca's aphasics (Bates et al., 1987a, 1987b; Wulfeck & Bates, 1991), and compliment the growing literature suggesting roles for the cerebellum in language.

The question remains of what exactly the cerebellar contributions are to the production of grammatical morphemes and their use in auditory comprehension, and how this contribution has been compromised following cerebellar damage. The reduction of grammatical morphology in a subset of the patients on the production task is easiest to reconcile with the

traditional view that the cerebellum is involved in the motor implementation of speech and nothing more. Many cerebellar patients exhibit what is known as ataxic dysarthria, a deficit in coordinating the actions of the speech articulators (Ackermann & Hertrich, 2000). A difficulty in coordinating speech might lead to a sparse, efficient strategy in any task of speech output. This in turn might lead (particularly for English speakers) to a somewhat telegraphic speech with a paucity of closed-class words, as was found to varying degrees in four of the current patients.

The changes associated with cerebellar damage in the perceptual tasks of Experiments 2 and 3 are less easily attributed to secondary consequences of motor speech problems. Unless one tries to remove the distinction between speech perception and production, perhaps by invoking the motor theory of speech perception (e.g., Liberman & Mattingly, 1985), the results suggest that more perceptual roles of the cerebellum in language must be considered. This realization compliments work in speech perception (Ackermann et al., 1997; Mathiak et al., 2002), working memory (Justus et al., submitted; Desmond et al., 1997), lexical retrieval (Fiez et al., 1992; Peterson et al., 1989), and developmental dyslexia (Nicholson et al., 2001), which suggests roles for the cerebellum in speech perception and/or phonological representation.

Relationships Between Performance Across Experiments

In much of the literature on cortical aphasics, dissociations between impairments on different kinds of grammatical tasks have been observed, motivating the abandonment of the concept of a unitary agrammatic syndrome (see Badecker & Caramazza, 1985). Such dissociations were also a motivation for the inclusion of the three tasks in the current experiments. Perhaps the individual variability found among the relatively large group of patients studied here could be put to advantage; perhaps those patients who performed poorly on the production task are not the same patients who performed poorly on the comprehension task or grammaticality judgment task.

To examine this, all possible measures from the three studies were examined in one large correlation analysis. Some additional measures were added to the analysis for the patients for whom they were available. These included the standardized letter fluency and category fluency tasks, in which participants must generate as many items as possible that begin with particular letters or belong to particular categories (e.g., Appollonio et al., 1993). These two scores were available for 15 and 13 of the patients, respectively. Three difference scores from verbal working memory studies previously conducted with these patients (Ivry et al., 2001; Justus et al., submitted) were also included. The difference score representing the word length effect was available for four of the patients in the current study, and the scores representing the phonological similarity effect were available for 9 (auditory condition) and 8 (visual condition) patients of the current study. Finally, two scores from the International Cooperative Ataxia Rating Scale (ICARS, Trouillas et al., 1997) were included for 11 of the patients: the total ataxia score (maximum 100) and the dysarthria score (maximum 8). The total ataxia score indicates the degree of motor impairment, with most of the assessment unrelated to speech. Figure 5 presents a matrix of these correlations.

As a cautionary note, this final analysis should be considered exploratory, given the number of statistical comparisons. By chance alone, six comparisons would meet a significance criterion of $p = .05$, and twelve would meet a significance criteria of $p = .10$. In Figure 5, 15 and 23 comparisons meet these two criteria, respectively; the 23 meeting at least marginal significance are indicated in gray. Only one of these correlations (that between closed-class words and article use) survives correction for multiple comparisons. Nevertheless, the variability observed between patients cannot be overlooked, and Figure 5 may provide a starting point for further research.

The previously discussed correlations within each experiment can be observed in this matrix. However, when measures between the three experiments are correlated, not many of them are significantly related. A few notable exceptions can be observed. First, the extent to which the patients were affected by the word order manipulation in Experiment 2 (i.e., how likely they were to choose the first noun of the sentence with NVN word order versus VNN word order) was related to how sensitive they were to errors of word order in Experiment 3 ($r = .47, p = .07$). Somewhat surprisingly, the patients' total word output in Experiment 1 was related to sensitivity to the animacy manipulation in Experiment 2 ($r = .57, p = .02$). This was the only correlation that was significant between one of the production measures from Experiment 1 and the perception measures of Experiments 2 and 3 within the patient group.

When additional measures from outside of the current experiments are added (in the lower seven rows of the matrix), a few additional correlations emerge. For the four patients who participated in a previous verbal working memory study (reported in Ivry et al., 2001), the size of the word length effect was related to the total number of words they produced to describe the picture stimuli ($r = .95, p = .05$). This adds support to the idea that the word length effect taps into an articulatory rehearsal mechanism that is similar in its underlying brain mechanisms to those of overt speech.

In addition, for the patients who participated in a second verbal working memory study (Justus et al., submitted), the size of the phonological similarity effect was correlated with the auditory manipulations of the current Experiment 2. Specifically, the size of the phonological similarity effect with visual presentation was marginally related to the effect of the subject-verb agreement cue ($r = .66, p = .08$), and the size of the phonological similarity effect with auditory presentation was marginally related to the effect of the word order cue ($r = .60, p = .09$). The phonological similarity effect with auditory presentation was related to performance on the letter fluency task ($r = .71, p = .03$). Although the specific relationships with the modality of presentation may be elusive, these correlations are suggestive of a set of more perceptual resources that are relevant to phonological representation and the extraction of information during speech perception, ones that might be distinct from those involved in articulation.

One might also ask whether the performance on the current experiments related to clinical signs, either the overall ataxia or dysarthria ratings. In general, the answer seems to be no. The dysarthria scores, based on ratings from two observers other than the author, did not correlate with any of the measures in these three studies. The only speech-related correlation involving the dysarthria score that approached significance was that between dysarthria and the size of the phonological similarity effect with auditory presentation ($r = -.67, p = .10$). The total ataxia score was also significantly correlated with performance on the letter fluency task ($r = -.68, p = .03$), and marginally correlated with sensitivity to the use of the animacy cue ($r = .55, p = .08$). Finally, the two scores from the ICARS were significantly related to each other ($r = .65, p = .03$).

Evidence of Cerebellar Lateralization in the Current Experiments

As discussed in the introduction, a variety of evidence suggests that the cerebellar involvement in language is lateralized to the right, in correspondence with a pattern of left cerebral lateralization. However, the current data do not provide any additional support for such a rightward asymmetry. In Experiment 1, the four most impaired patients included two bilateral patients, one left-hemisphere patient, and one right-hemisphere patient. Further, the group effect for the production of fewer required articles was significant for the bilateral and *left*-hemisphere patients but not for the right. In Experiment 2, the critical interaction between group and sensitivity to the agreement cue was significant for the bilateral group, with no clear differences between the left- and right-hemisphere groups. Finally in Experiment 3, both the left- and right-hemisphere patients demonstrated the significant interaction between group and

error type, which was particularly consistent for the *left*-hemisphere group. Given the differences in education between the left- and right-hemisphere patients, and the fact that one person in each group is not right-handed, these trends for a leftward asymmetry should be taken with caution.

CONCLUSION

Just as work with cortical aphasics has moved away from the concept of a singular agrammatic syndrome, the deficits of patients with cerebellar damage on tasks of grammatical morphology are quite variable and seem to dissociate from each other. This first group study of cerebellar grammatical morphology suggests yet another way in which the language system may be impacted upon damage to this subcortical structure. The results call for further exploration of the cerebellum's contributions to language, including whether these deficits can be explained in terms of more basic contributions to speech perception and phonological processing.

METHOD

Participants

Sixteen patients with damage to the cerebellum were tested. This group consisted of three patients with damage to the right cerebellar hemisphere (R1, R2, R3), three patients with damage to the left cerebellar hemisphere (L1, L2, L4), one with damage to the cerebellar midline (M1), and nine with bilateral degenerative disorders (B1 – B9). Sixteen controls of similar age and education also participated. The mean age ($\pm$ sd) of both the patients and controls in this study was 58 ($\pm$ 13) years, and the mean amount of education for both groups was 16 ($\pm$ 3) years. Three of the patients (B1, B4, and B8) and two of the controls were bilingual in Spanish and English (see Table 2 and Figure 1 for details).

Experiment 1 Stimuli, Procedure, and Analysis

The pictures used in this study were originally used by MacWhinney and Bates (1978) and are known as the Given-New Stimuli. They are organized in series of three and are designed to elicit the specific target sentences listed in Table 3. The pictures were presented on a table in front of the participants, beginning with series 1, and followed by a distracter picture, series 2, distracter picture, and so forth. In order to maximize comparability of the performance of individual participants, the pictures were presented in the same order for every patient and control. The participants were given the following instructions: "I will be showing you some pictures. When I point to each picture, I would like to you tell me what you see." In the case of particularly brief descriptions (e.g., one word), other general prompts such as "Could you tell me anything else about it?" were given. The sessions were recorded and the descriptions of the experimental series were transcribed, including all task relevant speech given in response to each picture.

The transcripts were analyzed with regard to the total number of words produced, the proportion of closed-class words, the proportion of required articles produced, and the proportion of canonical word orders produced for the AVO items. For the analysis of closed-class words, the classification of open-class words (i.e., content words such as nouns, main verbs, adjectives, adverbs) and closed-class words (i.e., function words such as articles, auxiliary verbs, prepositions, pronouns) was made based on the British National Corpus (Leech et al., 2001). For the analysis of required articles, the transcript of each participant was examined for the number of places where articles (a, an, the) occurred or should have occurred, for instance a noun phrase using a singular count noun. Exceptions were made for those cases in which the noun phrase was preceded by another word such as a possessive pronoun (e.g., *his*) or a demonstrative adjective (e.g., *this*) that obviated the need for an article. For the analysis of

canonical word order, the proportion of agent-verb-object (AVO) sentences relative to all other sentences in which all three items were given, but in non-canonical orders (OVA, AOV, OAV, VOA, and VAO), was calculated.

Experiment 2 Stimuli, Procedure, and Analysis

The stimuli for this experiment were 54 recorded sentences, each of which contained two nouns, each with the definite article (*the*), and a transitive verb in the present progressive tense (e.g., *is pushing*). The sentences were designed to manipulate three variables orthogonally: subject-verb agreement, word order, and noun animacy (see Bates et al., 1987a; Slobin & Bever, 1982).

Regarding subject-verb agreement, the verb of the sentence could agree in number with both the first and second noun of the sentence (Agree 0), as in “*The pig the cow is pushing*,” with only the first noun of the sentence (Agree 1), as in “*The pig the cows is pushing*,” or with only the second noun of the sentence (Agree 2), as in “*The pig the cows are pushing*.”

Regarding word order, the sentences could be constructed in one of the three possible combinations of two nouns and one verb: noun-noun-verb (NNV), as in “*The pig the cow is pushing*,” noun-verb-noun (NVN), as in “*The pig is pushing the cow*,” or verb-noun-noun (VNN), as in “*Is pushing the pig the cow*.”

Regarding animacy, some sentences presented animals in both noun positions (Animacy 0), as in “*The pig the cow is pushing*,” some of them presented an animal in the first position and an artifact in the second (Animacy 1), as in “*The pig the clock is pushing*,” and some of them presented an artifact in the first position and an animal in the second, as in “*The clock the pig is pushing*.”

These three variables were varied independently in a 3 (agreement) $\times$ 3 (word order) $\times$ 3 (animacy) design, for a total of 27 sentence types. Two experimental sentences were designed for each sentence type, for a total of 54 sentences. The specific nouns used were: pig, cow, horse, chicken, goat, zebra, clock, book, cup. Given the nature of the animacy manipulation, there needed to be twice the number of animate nouns relative to inanimate nouns so that each noun would appear equally often (twelve times) in the experiment. The specific verbs used were: (is/are) pushing, grabbing, biting, smelling, eating, and kissing, and each appeared nine times in the experiment. Each individual noun and verb was also equally likely to occur in each of the agreement conditions, in each of the word order conditions, and in each of the animacy conditions.

The stimuli in both Experiments 2 and 3 were recorded by a monolingual native English speaker, a 36-year-old man from the San Francisco Bay Area.

In each trial, participants listened to a sentence and judged “what did the action” in each sentence, or in other words determined the agent. After hearing the sentence, the two nouns from the sentence appeared on the screen (including plural endings, where appropriate) with the numbers 1 and 2, and the participants made their responses by pressing 1 or 2 on the computer keyboard. For half of the trials, the first noun of the sentence was presented on the left and associated with response button 1, and for the other half, the first noun of the sentence was presented on the right and associated with response button 2. The sentences were presented in random order.

The dependent variable in the study was the proportion of sentences for which the participant chose the first noun as the agent of the sentence, as a function of the three different kinds of cues determining agency: subject-verb number agreement, word order, and noun animacy.

Experiment 3 Stimuli, Procedure, and Analysis

The stimuli for this experiment were 56 recorded sentences, half of which were grammatically correct, and half of which contained one of two kinds of grammatical error. The first type of ungrammaticality was an error of subject-verb agreement, as in “**The women was drinking some wine while talking about the movie.*”⁵ The second type of ungrammaticality was an error of word order between auxiliary and main verb, as in “**Jane’s friends watching were some fireworks while standing on the hill.*” The correct sentences were designed to balance the incorrect sentences for the kinds of grammatical structures present and semantic themes. These stimuli were based on a subset of those used by Blackwell and Bates (1995).

In each trial, participants listened to a sentence and decided whether it sounded “correct and natural,” in which case they pressed the number 1, or “incorrect and unnatural,” in which case they pressed the number 2. The stimuli were presented in random order.

Hits, misses, false alarms, and correct rejections were used for each participant to calculate A-prime scores for each kind of grammatical error. A-prime is a nonparametric variant of D-prime, the more common signal detection statistic, and has frequently been used in other studies using the grammaticality judgment. It is calculated according to the formula:

$$A' = \frac{1}{2} + \frac{(h - f)(1 + h - f)}{4h(1 - f)}$$

where h stands for the probability of a hit (in this case, answering “ungrammatical” when the presented sentence was ungrammatical) and f stands for the probability of a false alarm (answering “ungrammatical” when the presented sentence was grammatical). An A-prime score of 1.0 indicates perfect discrimination, with all hits and no false alarms (Grier, 1971). This formula holds for above-chance performance only, when $h > f$ (Aaronson & Watts, 1987). None of the patients in this study scored below chance.

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⁵This particular example is one of the most difficult errors of subject-verb agreement out of the sample to detect, given the irregular plural of *woman*. I opted to retain this sentence in the pool, rather than trying to bias the stimulus set to include only the more salient regular /s/ plurals. Plural endings in English, as well as the rest of its grammatical morphology, are not very salient; it would be a property of any representative English language stimulus set that these errors are difficult to notice. If anything, these stimuli contain subject-verb agreement that is *more* salient than the norm, given that the past tense is given here as the relatively salient past progressive (e.g., *was drinking* versus *were drinking*).

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Figure 1. Cerebellar Lesions

Damaged areas of the three left-hemisphere and three right-hemisphere patients. For each patient, a column of seven horizontal slices through the pons and cerebellum are shown, with the most superior slice at the top. The approximate corresponding sections in the Schmahmann et al. (2000) atlas are: $z = -9, -17, -25, -33, -41, -49$, and -57 . Within each slice, rostral is toward the top and caudal toward the bottom; left is left and right is right. Gray areas indicate tissue lesions. For further details on these reconstructions, see <http://socrates.berkeley.edu/~ivrylab>.

A

B

C

Figure 2.

(A) *Total Number of Words Produced.* A simple tally of the number of words produced by the participants for the Given-New Stimuli. Cerebellar patients as a group did not produce significantly fewer words than the controls ($p = .36$). (B) *Proportion Closed-Class Words.* As a group, the cerebellar patients did not produce a significantly smaller portion of closed-class words than the controls ($p = .27$). A few individual patients (B2, B7, L2, and R3) stand out as being outside of the range established by the controls. (C) *Use of Articles.* As a group, the cerebellar patients used fewer required articles than the controls ($p = .07$). The same four patients (B2, B7, L2, and R3) again stand out as having used the fewest required articles.

A

B

C

Figure 3.

(A) *Effect of the Subject-Verb Agreement Cue.* Independently of the other two variables, healthy controls were more likely to choose the first noun of the sentence as the agent when it alone agreed in number with the verb (Agree 1 condition) and less likely to do so when the second noun did (Agree 2 condition). This effect is diminished in the patient group ($p = .07$). (B) *Effect of the Word-Order Cue.* Independently of the other two variables, both healthy controls and patients were likely to choose the first noun of the sentence as the agent when the word order was NVN (thus preferring an AVO interpretation to OVA), and likely to choose the second noun when the word order was NNV and VNN (thus preferring OAV and VOA interpretations to AOV and VAO). (C) *Effect of the Animacy Cue.* Independently of the other two variables, both healthy controls and patients were likely to choose the first noun of the sentence as the agent when it alone was animate (Animacy 1 condition) and less likely to do so when the second noun was (Animacy 2 condition).

Figure 4. Grammaticality Judgment Discrimination Scores

A-prime scores for the cerebellar patients and controls indicating the ability to discriminate between ungrammatical and grammatical sentences. Ungrammaticalities were caused either by errors of subject-verb agreement or by errors of word order. Cerebellar patients were significantly less able to perform these discriminations, relative to the controls.

Figure 5. Correlation Matrices of Individual Performance

This plot gives the linear correlations for the measures of Experiments 1–3 for the group of cerebellar patients, including some additional measures taken outside of the current study when available. Correlations with probability values of less than .10 are indicated with gray.

Table 1

Transcripts of Cerebellar Patients with Sparse Grammatical Morphology

 Silveri et al., 1994

Patient's Italian:

Io guardavo televisione. Nel momento dopo, subito dopo, sentire metà non andare. Avere un attacco, non potere parlare. Sopra c'era mia moglie che dormiva perchè era mezzanotte. Io tutto a un tratto alzare, tutto a un tratto andare giù per terra. Non fare niente perchè c'era il tappeto...

Corrected Italian:

Io guardavo la televisione. Nel momento dopo, subito dopo, *ho sentito che* metà *del corpo* non andava. Avevo un attacco, non *potevo* parlare. Sopra c'era mia moglie che dormiva perchè era mezzanotte. Io tutto a un tratto *mi sono* alzato, tutto a un tratto *sono andato* giù per terra. Non *mi sono fatto* niente perchè c'era il tappeto...

Approximate English translation:

I was watching [the] television. One moment after, immediately after, *to feel* one-half not *to go*. *To have* an attack, *to be* unable to speak. Upstairs there was my wife sleeping because it was midnight. I suddenly *to stand up*, suddenly *to fall* down. Not *to do* anything because there was the carpet...

Mariën et al., 1996, 2000

Patient's Dutch:

Zij aardappel aan maken middagmaal.	(from a picture description task)
Deur toe.	(from a repetition task)
Hij komt gevangenis terecht.	(from a reading task)

Corrected Dutch:

Zij is aardappelen aan het klaarmaken voor het middagmaal.
De deur is toe.
Hij komt zeker in de gevangenis terecht.

Approximate English translation:

She [is] potato[es] prepar[ing] [for the] lunch.
[The] door [is] shut.
He will [definitely] end up [in the] jail.

Zettin et al., 1997

Patient's Italian:

Rasoio mano. Prima c'era sapone e pennello. Si passava pennello invece adesso spray. Spuma sulle mani poi palmo crema rasoio mano faccio cosí. Ripeto operazione contropelo. Stessa lametta due volte. Oppure rasoio elettrico. Faccia ben asciutta. Usare prima lozione prebarba. Pile o corrente stessa cosa. Però rasoio elettrico pelle abituata deve essere.

Approximate English translation:

Razor hand. First there was razor and brush. A brush was used now instead spray. Foam on the hands then palm cream razor hand I do like this. I repeat operation against the growth. Same blade twice. Or electric razor. Face well dry. To use before pre-shave lotion. Batteries or current same thing. But electric razor skin used to must be.

Gasparini et al., 1999; Gasparini, personal communication (Italian)

Patient's Italian:

Inizio a... a... a creare la schiuma, a creare la schiuma per, per dopo passarmi il rasoio. Il rasoio si passa dall'alto verso il basso, dall'alto verso il basso... senza... ehm... avendo cura di non tagliarsi e la se... la seconda parte quella, quella che... quella più... quella che dal collo il collo si fa maggior attenzione, perché più delicata.

Corrected Italian:

Inizio col fare la schiuma, per passare poi il rasoio. Il rasoio si passa dall'alto verso il basso, avendo cura di non tagliarsi. La parte del collo richiede maggior attenzione, perché è più delicata.

Approximate English translation:

I begin to... to... to make the lather, to make the lather to, to pass the razor after. The razor has to move downwards, downwards... without... eh... taking care not to cut oneself and the s... the second phase that, the one, the one... that from the neck, the neck you need to be more careful because more delicate.

Table 2

Cerebellar Patients Participating in Experiments 1, 2, and 3

Patient	Hemisphere	Etiology (at age)	Age	Ed. (years)	Handedness	Sex	Language (ⁿ = native)	ICARS Scores		Verbal Fluency	
								Overall	Dysarthria	Letter	Category
L1	left	tumor (47)	58	12	right	M	English ⁿ , Spanish (as child)	19.25	0.5	29	40
L2	left	tumor (34)	57	11	left/mixed	M	English	23.25	5	21	35
L4	left	stroke (48)	54	13	right	M	English	10	1.5	51	48
R1	right	stroke (66)	77	18	right	M	English	--	--	19	48
R2	right	tumor (42)	47	18	left	M	English ⁿ , German (9--)	32.75	3.5	27	50
R3	right	stroke (55)	66	12	right	M	English	4.25	1	61	58
M1	midline	tumor (28)	37	19	right	M	English	--	--	53	62
B1	bilateral	SCA6 (c. 29--)	42	16	right	F	Spanish ⁿ , English (6--)	--	--	21	32
B2	bilateral	degen. (c. 30--)	73	12	right	M	English	45	4.75	25	47
B3	bilateral	degen. (c. 61--)	63	20	right	M	English	17.75	3.25	35	45
B4	bilateral	degen. (c. 20s--)	64	17	right	M	Spanish ⁿ , English (5--)	42.75	5.5	30	47
B5	bilateral	SCA3 (c. 27--)	44	13.5	right	F	English	--	--	16	34
B6	bilateral	SCA3 (c. 38--)	47	18	right	M	English	49.75	3	26	--
B7	bilateral	degen. (c. 70--)	82	16	right	M	English	--	--	17	32
B8	bilateral	degen. (c. 42--)	54	16	right	M	Spanish ⁿ , English (5--)	20.75	3.25	--	--
B9	bilateral	degen. (53--)	56	18	right	F	English ⁿ , German (20--)	29	4.25	49	--

Table 3**Examples of Stimuli Used in Experiments 1, 2, and 3**

Experiment 1: Pictures depicting simple events. 27 pictures organized in 9 sets of 3.
(MacWhinney & Bates, 1978)

Series	Structure	Sentence
1	AV	A (bear, mouse, rabbit) is crying.
2	AV	A boy is (running, swimming, skiing).
3	AVO	A (monkey, squirrel, rabbit) is eating a banana.
4	AVO	A boy is (kissing, hugging, kicking) a dog.
5	AVO	A girl is eating a/n (apple, lollipop, ice cream).
6	AVPL	A dog is (in, on, under) a car.
7	AVPL	A cat is on a (table, bed, chair).
8	AVOD	A woman is giving a (present, truck, mouse) to a girl.
9	AVOD	A cat is giving a flower to a (boy, rabbit, dog).

(A=Agent; V=Verb; O=Object; P=Preposition; L=Location; D=Dative)

Experiment 2: Recorded sentences. 9 shown out of 54.
(based on Slobin & Bever, 1982; Bates et al., 1987a)

Agreement	Order	Animacy	Sentence
Agree 0	NNV	Animacy 0	The cow the chicken is smelling.
Agree 1	NNV	Animacy 0	The horse the goats is grabbing.
Agree 2	NNV	Animacy 0	The pig the zebras are kissing.
Agree 0	NVN	Animacy 0	The pig is grabbing the chicken.
Agree 1	NVN	Animacy 0	The cow is kissing the goats.
Agree 2	NVN	Animacy 0	The horse are smelling the zebras.
Agree 0	VNN	Animacy 0	Is biting the horse the chicken.
Agree 1	VNN	Animacy 0	Is eating the pig the goats.
Agree 2	VNN	Animacy 0	Are pushing the cow the zebras.

(N=Noun; V=Verb)

Experiment 3: Recorded sentences. 9 shown out of 56.
(based on Blackwell & Bates, 1995)

Type of Error	Sentence
Agreement	* The women was drinking some wine while talking about the movie.
	* The vine were growing a few red and yellow flowers.
	* The writer were holding a very big party.
Word order	* Jane's friends watching were some fireworks while standing on the hill.
	* Those girls seeing were some old and famous silent movies.
	* She signing was her newest and biggest story collection.
No error	The girls were eating some fries while waiting for their friends.
	The man was playing both old and modern piano pieces.
	The artists were selling several small but expensive watercolor paintings.