Functional neuroimaging of cerebellar activation during single word reading and verb generation in stuttering and nonstuttering adults

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Abstract

Articulatory discoordinations typically observed in fluent and disfluent speech of stuttering adults suggest an underlying deficiency in the precise timing needed for speech production. Positron emission tomography scans of stuttering adults showed generally higher cerebellar activations pre-treatment compared to nonstuttering control subjects. Intensive fluency treatment resulted in increased cerebellar activation during reading immediately post-treatment and a decrease to near normal levels at the 1 year follow scan. In contrast, verb generation resulted in a gradual but consistent decrease over the three scans. The results suggest that automaticity in motor and cognitive processes during speech production may need to be considered as an important factor in future investigations of stuttering.

Keywords: Neuroimaging; Cerebellar activation; Stuttering; Fluency treatment

The cerebellum has an important role in the control of involuntary and voluntary actions in humans and animals. Over the years, various models have been proposed to explain the role of the cerebellum. For some, the cerebellum acts primarily as a motor controller [7,10], whereas more recently greater attention has been given to a potential additional role of the cerebellum in the regulation of cognitive actions [8,15]. The role of the cerebellum in the control of speech has been well-established based on clinical and experimental findings [3]. Recent neuroimaging studies have suggested that the cerebellum may contribute to the cognitive processes underlying language processes as well [6] although such claims have been challenged by others [1].

The central contributions of the cerebellum to timing and co-ordination of sensorimotor actions are well-established and possibly can be extended to cognition as well. Stuttering often has been characterized as a disorder of temporal co-ordination of the sensorimotor and/or cognitive-linguistic processes involved in speech [4,9]. The question arises, therefore, to what extent differences in cerebellar processes exist between stuttering and nonstuttering speakers. The present investigation was aimed at exploring cerebellar activation in stuttering using positron emission tomography (PET). Thirteen stuttering and ten nonstuttering male adults, ranging in age from 20 to 45 years participated. All subjects used English as their primary language and were screened for a history of relevant neurological or other medical problems and current drug use. The two groups were matched for educational level and for handedness, using the Edinburgh Handedness Inventory [11]. Other than stuttering in the experimental group, none of the participants reported a history of speech, language, or hearing problems. A certified speech-language pathologist diagnosed stuttering in the experimental group and informally screened all the participants for the presence of any additional speech or language problem at the time of initial assessment. None of the stuttering participants had received fluency treatment in the 5 years preceding the present study. As part of the study, each stuttering participant completed a 3 week intensive fluency treatment program followed by a 1 year maintenance phase at the Stuttering Centre in Toronto. This program is an adaptation of the Precision Fluency Shaping Program [16]. Functional PET scans were obtained immediately pre-treatment, immediately post-treatment and after the 1 year follow-up phase. During the scans, participants were asked to perform a baseline and three linguistic tasks.
The non-linguistic baseline task (passive viewing of strings of Xs) served as a reference measure for the three linguistic tasks: two reading tasks (silent and oral reading of single words), and a verb generation task. The order of the reading tasks was counter-balanced across participants. All scans were obtained with the subjects in a supine position and using 1110 Mbq (30 mCi) of the radioisotope $[^{15}\text{O}]\text{H}_2\text{O}$. Individual scans were averaged over a 1 min period. Functional data obtained by subtraction of activation between different conditions were analyzed using Statistical Parametric Mapping [17] at $P < 0.001$.

Stuttering frequency decreased from 7.07 to 1.61% from pre- to post-treatment during spontaneous speech. For reading, stuttering frequency was 6.07 and 1.61%, respectively. Although there was a slight increase at the 1 year follow-up for spontaneous speech (2.8%), fluency during reading continued to improve (0.8%). During the single word reading or verb generation tasks very few stuttering or other disfluencies were observed during the scans in both subject groups.

In order to investigate the extent of cerebellar activation during the three speech tasks, the total volume of activated cerebellar pixels was calculated, and the peak localization of the activation was recorded using the co-ordinate system proposed by Talairach and Tournoux [14]. Stuttering subjects showed an increase in cerebellar activation from pre- to post-treatment and a subsequent reduction in activation at the 1 year follow-up scan during both silent and oral reading (Fig. 1a,b), with higher cerebellar activation during oral than silent reading. The overall cerebellar activation in the stuttering subjects pre-treatment was higher compared to the nonstuttering subjects for both word-reading tasks. The cerebellar volumetric ratio for stuttering/nonstuttering subjects was 5.10 for silent reading and 8.50 for oral reading. The volume of activated voxels during silent reading at the cerebellar level in the stuttering subjects increased from pre- to post-treatment (post/pre ratio = 2.26) and decreased from post-treatment to the 1 year follow-up (1 year/post ratio = 0.13) to a level less than that observed at pre-treatment (1 year/pre ratio = 0.29). A proportionally similar pattern could be observed during the oral reading task, with an increase in cerebellar activation from pre- to post treatment (post/pre ratio = 2.22), and a subsequent decrease from post-treatment to follow-up (1 year/post ratio = 0.13).

In the nonstuttering subjects, the cerebellar activation during silent and oral word reading was localized primarily in left cerebellar cortical regions. The activation pattern for the stuttering subjects was more task-dependent. During silent reading, activation was localized primarily in the medial cerebellum with a very definite right-hemisphere bias. This changed very little from pre- to post-treatment to follow-up. During oral reading, cerebellar activation involved widely distributed cortical, subcortical and medial regions, and increased significantly from pre-treatment to post-treatment scans. At the 1 year follow-up scan, activation was localized primarily in the medial and subcortical regions.

A very different pattern of activation was observed for the verb generation task (Fig. 1c). Both the stuttering and the nonstuttering subjects showed greater cerebellar activation during verb generation compared to silent and oral word reading tasks. Pre-treatment, the ratio of cerebellar activation during verb generation compared to silent reading was 117.60 for nonstuttering and 48.17 for stuttering subjects. For oral reading, the ratios were 12.00 and 2.95, for nonstuttering and stuttering speakers, respectively.

In contrast to the silent and oral reading tasks, no increase in cerebellar activation was observed for the stuttering subjects immediately post-treatment. Instead, cerebellar activation showed a gradual and steady decline from pre-treatment to post-treatment (post/pre ratio: 0.69), and from post-treatment to the 1 year follow-up scan (1 year/post ratio: 0.18).

The word reading and the verb generation task also differed with respect to the level of cerebellar activation at
the 1 year follow-up scan for the stuttering subjects compared to the nonstuttering subjects. For silent and oral reading in the stutterers, cerebellar activation at the 1 year follow-up was still higher than in the nonstuttering control subjects (ratio: 1.50 and 2.44, for silent and oral reading, respectively.) For verb generation, however, the extent of activation observed in the stuttering subjects was lower than that observed in the nonstuttering controls (ratio stuttering/nonstuttering subjects: 0.25).

Both the stuttering and the nonstuttering subjects showed widespread activation in subcortical as well as cortical cerebellar areas during verb generation. For the nonstuttering and the stuttering subjects pre-and post-treatment, this activation was bilateral with a dominance towards the right hemisphere. At the 1 year follow-up scan, the stuttering subjects showed predominately right hemisphere activation in subcortical and medial cerebellum.

Our results provide evidence of increased cerebellar activation in the stuttering speakers pre-and post-treatment, suggesting the presence of increased sensory or motor monitoring of the ongoing or planned movements associated with lower levels of automaticity during the execution of such movements [13], even during silent reading [5]. A related interpretation of the observed increased cerebellar activation in the stuttering speakers could point to a greater demand for attention during speech performance. In a recent study, Allen and Courchesne [2] have provided evidence that activation in the cerebellum can be related to selected attention operations, independent of motor or sensory input. In this respect, it is important to note that most of the stutterers did receive some form of treatment in the past, and all can be expected to employ self-learned techniques to control their speech fluency. As such, it is possible that the increased cerebellar activation in stutterers may reflect their attempts at exerting greater voluntary control over their speech, hence higher attention (effort), greater monitoring and less automatized movement execution.

The hypothesis that the increased cerebellar activation reflects a reduced automaticity during speech seems to be supported by the pattern of change over the three scanning sessions during the silent and oral reading conditions. The increase post-treatment can be accounted for by the increased speech effort and self-monitoring that the subjects were using as a result of the speech therapy all of them had just completed. The speech control skills learned during treatment at this point are not yet automatic and demand constant monitoring and control. At the 1 year follow-up scan, the stuttering subjects have practiced the use of their speech skills intensely in a variety of situations, and for most the use of these skills had become much more automatic requiring far less monitoring and conscious control, resulting in reduced cerebellar involvement.

While the observed pattern of change in the silent and oral reading condition can be accounted for by changes in automaticity during task completion, a very different pattern was observed for the verb generation task. First, it is important to note that the higher levels of cerebellar activation during verb generation compared to reading supports a role of the cerebellum beyond motor control [12,13]. Assuming that the level of articulatory effort during the production of single words for the oral word reading and verb generation task is approximately the same, this increased activation at the cerebellar level has to reflect the added cognitive task demands during verb generation. The stuttering subjects showed a systematic and gradual decline in cerebellar activation over the three scanning sessions. Raichle et al. [13], have reported a similar decline in cerebellar involvement as a result of practice on a verb generation task. As such, our data suggest that the stutterers became increasingly proficient on the verb generation task over the course of the experiment. In our study, however, the stuttering subjects were just as actively using their target behaviors during the verb generation as they were during word reading. Consequently, one could have expected an increase in cerebellar activation immediately post-treatment during verb generation similar to that seen in the silent and oral word reading conditions. Clearly this was not the case. One possible interpretation for this is that the observed cerebellar activation during the verb generation pre-treatment is the summation of increased motor monitoring and attention (as seen in the oral reading condition) and the added cognitive demands inherent to the verb generation task. At the post-treatment and the 1 year follow-up scans, the cognitive demands of the task are reduced because the nouns used during the task are the same as those used pre-treatment, and therefore there may have been greater task familiarity. Therefore, the net decrease in cerebellar activation observed post-treatment may reflect a complex interaction between increased monitoring and attention processes and decreased cognitive demands associated with the verb generation task. Indeed, a volumetric comparison of Fig. 1b,c reveals a similar extent of activation for the oral reading and verb generation tasks at the post-treatment and 1 year follow-up.

In conclusion, the results from this study point to the need to consider cerebellar processes in investigations of the neural bases of stuttering. Further detailed studies of the nature and role of these processes, especially as they related to changes in automaticity during task performance, may promise to yield important new insights into the causes of articulatory disruptions seen in stuttered speech. Further functional imaging studies also should examine the presence of interindividual differences in cerebellar activation using functional magnetic resonance imaging or other appropriate techniques, as well as the relationship of activation extent to stuttering severity.

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[1] Ackermann, H., Wildgruber, D., Daum, I. and Grodd, W., Does the cerebellum contribute to cognitive aspects of


