Editorial

A cognitive affective role for the cerebellum

Traditional neurological teaching suggests that, functionally, the cerebellum is devoted entirely to motor control. Accordingly, the cerebellum is proposed to be primarily concerned with co-ordination in skilled voluntary movement, as well as control of motor tone, posture and gait. In its motor regulatory role, the cerebellum is assumed to function as a comparator that adjusts motor outputs on the basis of afferent signals relating to planned motor action and reafference signals concerning excecuted motor acts. This motor view of cerebellar function has withstood numerous challenges over the past half century (Dow and Moruzzi, 1958).

In the past decade, a growing body of empirical data, largely derived from functional neuroimaging studies, have implicated the cerebellum in diverse higher cognitive functions (Leiner *et al*., 1995). What has been lacking is convincing documentation of cognitive deficits in patients with pathology restricted to the cerebellum. In this edition of *Brain*, Schmahmann and Sherman (1998) provide such neuropsychological and behavioural evidence. Their paper provides detailed clinical descriptions of prominent non-motor deficits in a carefully documented cohort of patients with cerebellar pathology. The authors conclude that the pattern of deficit in these patients is characteristic enough to suggest that it forms a recognizable syndrome, the Cerebellar Cognitive Affective Syndrome. Its defining features are disturbances in executive function, spatial cognition, language and emotional regulation of behaviour. Unlike previous clinical reports, where deficits were mainly those that detailed neuropsychological evaluation, the core deficits were evident enough to be elicited by standard bedside evaluation. Given the complex anatomy of the cerebellum, an obvious question is whether components of the syndrome are associated with pathology of distinct cerebellar regions. Unfortunately, the size of the series and the often diffuse nature of the associated pathology do not allow clear answers to this question. Nevertheless, the authors note a strong tendency for posterior lobe lesions to be associated with the core syndrome, while patients with vermis lesions had pronounced affective disturbance.

A widely accepted principle of neural organization is the interdependence of structure and function. Within this framework, it is instructive to consider whether cognitive deficits in patients with cerebellar pathology can be accounted for in terms of its known anatomy. Two facts about cerebellar anatomy seem pertinent. First, in relation to its intrinsic structure, the cerebellum accounts for over half the brain's population of neurons. More importantly, in terms of its likely cognitive functions, the cerebellum receives inputs from all levels of the CNS. In general terms, these inputs are via vestibulocerebellar (governing bodily equilibrium and eye movements), spinocerebellar (controlling execution of limb movements) and cerebrocerebellar (implicated in the initiation, planning and timing of movements) pathways.

The cerebrocerebellar pathway is an obvious candidate pathway when considering an anatomical basis for cerebellar–cognitive interactions. Its feedforward or afferent projections are derived not only from sensorimotor cortical systems, but also include substantial contributions from dorsolateral and medial prefrontal cortices, frontal language regions, posterior inferior and superior parietal cortices, superior colliculus and superior temporal cortex. Other afferent inputs include those from anterior cingulate cortex and posterior hypothalamus as well as major inputs from neuromodulatory noradrenergic, serotonergic and dopaminergic brainstem nuclei. Feedback circuits, relaying in thalamus, project to the same cortical areas from which the cerebellum receives its afferent inputs. As Schmahmann and Sherman acknowledge, details of pontocerebellar projections remain to be defined, but they point out that cortical association areas are linked to more recently evolved lateral cerebellar hemispheres. Therefore two things are clear from its anatomy. First, the cerebellum has considerable computational resources. Secondly, the cerebellum has bidirectional connections with regions specialized for attentional, visuospatial, mnemonic, executive and emotional regulatory functions. What is striking is the similarity between the defining features of the Cerebellar Cognitive Affective Syndrome and the functional affiliations of target cortical regions with which the cerebellum has reciprocal connections.

Apart from clinical case material, the most powerful data supporting cognitive and affective cerebellar regulatory functions are those derived from functional neuroimaging. These studies have shown activation in tasks involving language, memory, attentional shifting and planning. The interpretation of these functional neuroimaging data has been problematic within the framework of a dominant motoric view of the cerebellum. It has been argued that functional neuroimaging data make an overwhelming case for non-motor cerebellar functions. Nevertheless, alternative interpretations which preserve a motor viewpoint are possible. For example, given that most novel cognitive tasks involve varying degrees of response preparation, it can be argued that what is reflected in cerebellar activation is motor preparation (in relation to likely behavioural responses) rather than anything intrinsically cognitive.

An outstanding question posed by Schmahmann and Sherman's paper, and by functional neuroimaging data, is whether the cerebellum fulfills multiple domain-specific cognitive roles, or whether it performs a more generic function that subsumes its contribution to both cognition and motor function. Influential theories of cerebellar function propose that it links sensory and proprioceptive contexts to motor responses. In this role, its neuronal architecture provides a means of recognizing complex sensory states necessary for the selection and control of action (Houk and Barto, 1992). Therefore, one possibility is that the cerebellum may also provide a means for learning context-specific cognitive responses (Thach, 1996). This predicts that with increasing exposure to a cognitive task, responses become automatized. This hypothesis might account for cognitive deficits seen with cerebellar pathology and the activations seen in functional neuroimaging tasks. In keeping with this suggestion, it should be noted that both cognitive and motor cerebellar activations, recorded with functional neuroimaging, attenuate with practice (Friston *et al*., 1992; Raichle *et al*., 1994).

The importance of Schmahmann and Sherman's study is that the contribution of the cerebellum to cognition and emotion can no longer be ignored. What is now needed is clarification of its precise role. Two immediate issues need to be addressed. First, does the cerebellum perform unitary or multiple cognitive operations? Secondly, what is the relationship between pathology in circumscribed cerebellar regions and specific profiles of cognitive deficit? While answers to these questions will undoubtedly require further neuropsychological study, it is also clear that they will depend upon a greater knowledge of the topography of cerebrocerebellar networks as well as neuroimaging investigations that test specific functional hypotheses.

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