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Cognition, emotion and the cerebellum

The traditional teaching that the cerebellum is purely a motor control device no longer appears valid, if, indeed, ever it was. There is increasing recognition that the cerebellum contributes to cognitive processing and emotional control in addition to its role in motor coordination. Anatomical and physiological studies reveal that there is a primary sensorimotor region of the cerebellum in the anterior lobe, and a secondary sensorimotor region in the medial aspect of the posterior lobe. In contrast, cerebral association areas that subservise higher order behaviour are linked preferentially with the lateral hemispheres of the cerebellar posterior lobe—in feedforward loops via the nuclei of the basis pontis, and in feedback loops from deep cerebellar nuclei via the thalamus. There are also reciprocal connections between the cerebellum and hypothalamus. These pathways facilitate cerebellar incorporation into the distributed neural circuits governing intellect, emotion and autonomic function in addition to sensorimotor control.

The clinical relevance of these observations is found in anecdotal observations of cognitive and psychiatric manifestations of cerebellar lesions, and in the description of the cerebellar cognitive affective syndrome (CCAS) in patients

with lesions confined to the cerebellum (Schmahmann and Sherman, 1998). The CCAS has subsequently been observed in adults and children with stroke, tumour, cerebellar degeneration, superficial siderosis, cerebellar hypoplasia and agenesis, and children born very preterm who have disproportionately small cerebella. These neurobehavioural deficits may occur in the absence of the cerebellar motor syndrome. They are characterized by impairments in executive function (planning, set shifting, verbal fluency, abstract reasoning, working memory), spatial cognition (visual spatial organization and memory) and linguistic processing (agrammatism and dysprosodia) when the lesions involve the hemispheric regions of the cerebellar posterior lobes. Patients with the CCAS experience dysregulation of affect when their lesions encroach upon the vermis.

Cerebellar activation by language tasks in functional imaging experiments was initially regarded as surprising, but subsequent PET and functional MRI studies show that multiple cognitive domains are associated with cerebellar activation. Further, these studies are in agreement with anatomical and clinical observations. Sensorimotor tasks activate primary (anterior lobe) and secondary sensorimotor regions. Cognitive paradigms preferentially activate different and, sometimes, discretely localized regions of the cerebellar posterior lobes.

The recognition that the cerebellum is involved in multiple domains of cognitive function raises many questions. Two of the most pressing issues are first, precisely with which functions is the cerebellum involved? Second, are these cognitive functions in some way related to the role of the cerebellum in motor control?

The paper by Susan Ravizza and co-workers in this issue of *Brain* addresses both these questions by evaluating verbal working memory (VWM)—the ability to maintain information in the mind for the purpose of manipulation—in patients with cerebellar damage. VWM stands at the crossroads of cognition and motor function. Looking in one direction, it is critically involved in many cognitive functions (Goldman-Rakic, 1996); looking in the other, VWM relies on subvocal rehearsal which, in turn, requires normal articulatory abilities (Waters *et al.*, 1992). Thus, a disturbance of motor function affecting articulation could potentially affect many cognitive functions by disrupting subvocal rehearsal and thereby reducing VWM capacity. The study by Ravizza *et al.* investigates the first link in this chain, by looking at the question of whether cerebellar patients have VWM disorders and whether those disorders are secondary to limitations on rehearsal.

Three studies were conducted. First, the authors found that 15 patients with unilateral cerebellar lesions had reduced verbal forwards and backwards digit spans on the WAIS, but did not differ from controls on a spatial working memory span test. They conclude that cerebellar patients have selective VMW limitations. Second, Ravizza *et al.* found that nine cerebellar patients were impaired on a verbal visual span-matching task, in which subjects responded with a key-press. Third, they found that eight cerebellar patients showed the same effects of word length and concurrent articulation on recall of lists of words and non-words as controls. Experiments 2 and 3 are taken as evidence that rehearsal problems do not account for the VWM deficits in these patients, since experiment 2 did not require an overt verbal response, and normal effects of word length and concurrent articulation are standard tests for the integrity of rehearsal. The implication is that cerebellar patients have VMW disorders that are not due to rehearsal limitations, a potentially important part of an argument that their cognitive disorders are independent of any motor impairments.

Some aspects of this study limit the enthusiasm for its conclusions. The reliability of the span measurements in experiment 1 can be questioned as only 2 trials at each span length were presented. In experiment 2, subjects were able to rehearse items before responding and, therefore, the possibility that the patients' lower spans were due to rehearsal disturbances is not entirely eliminated. In experiment 3, while the patients and controls performed similarly,

neither showed the pattern of performance indicative of intact rehearsal—an interaction of length and the presence or absence of concurrent articulation. It is puzzling that the VMW deficit in experiment 1 was correlated with lesions in lobules VIII–X, whereas in experiment 2 performance on the verbal span-matching task correlated with location of lesions in lobules I–V and VI–VII. The finding of a correlation between VWM and overall cerebellar motor signs in experiment 2 does not appear to be entirely consistent with the conclusion that VWM is unrelated to dysarthria. Information is not presented regarding the interval between stroke/surgery and inclusion in the study, possible involvement of cerebellar nuclei in deeper lesions is not discussed, and whereas lobule VI is in the superior aspect of the cerebellum, lobules VI and VII should rightly be considered part of the posterior lobe.

The CCAS was originally defined on the basis of clinical and neuropsychological data, and tools derived from experimental psychology are needed to explore the nature of the deficits seen after cerebellar lesions in greater detail. Ravizza and co-workers have, therefore, investigated a potentially critical issue: whether the VWM impairment in cerebellar patients can be accounted for on the basis of deficient motor programming that results in disrupted covert articulatory rehearsal. The study shows that efforts to characterize the nature and mechanisms of these cerebellar functions can be advanced by the methods of contemporary cognitive neuroscience and that this is a demanding task.

Further studies of the cerebellar role in cognition and emotion that are carefully designed and performed will have clinical relevance for cerebellar patients with impairments in mental flexibility, multitasking, visual-spatial organization, linguistic processing and mood. A hypothesis that may serve to organize observations is that the cerebellar role is constant in all domains—sensorimotor and otherwise—as its histological uniformity would imply. Is there indeed a 'universal cerebellar transform' (perhaps automatization, cerebellum as an oscillation damper optimizing performance according to context) applied to a number of behaviours by different cerebellar areas interconnected via highly arranged anatomic pathways with brain regions that subserve different functions (the dysmetria of thought hypothesis, Schmahmann, 2004)?

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