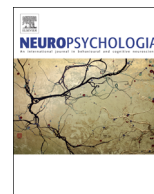




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# Modulation of linguistic prediction by TDCS of the right lateral cerebellum



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## ABSTRACT

It has been postulated recently that the cerebellum contributes the same prediction and learning functions to linguistic processing as it does towards motor control. For example, repetitive TMS over posterior-lateral cerebellum caused a significant loss in predictive language processing, as assessed by the latency of saccades to target items of spoken sentences, using the Visual World task. We aimed to assess the polarity-specific effects of cerebellar TDCS, hypothesising that cathodal TDCS should impair linguistic prediction, and anodal TDCS facilitate it. Our design also tested whether TDCS modulated associative learning in this task. A between groups (sham, anodal, cathodal) design was used, with concurrent stimulation during performance of a manual variation of the Visual World paradigm, and with assessment of latency reduction over repeated presentations of the spoken sentences. Mixed model ANOVA was used to analyse change in response latency. Cathodal TDCS decreased participants' response time advantage for the predictable sentence items without change for non-predictable items, consistent with the previous TMS results. Furthermore, anodal stimulation enhanced the response time advantage for the predictable items, again without change in latencies for non-predictive items. We found a clear practice-based effect over 4 blocks. However, this difference was not significantly modulated by either anodal or cathodal stimulation. Our results therefore support the hypothesis that cerebellum contributes to predictive language processing, mirroring its predictive role in motor control, but we do not yet have evidence that the learning process was affected by cerebellar TDCS.

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## 1. Introduction

The common view that the cerebellum has a function restricted to motor control has recently shifted to accommodate evidence suggesting it also contributes to cognition. From an evolutionary perspective, the lateral cerebellum evolved following other cerebellar regions, and concurrent to the cerebral association cortex (Leiner et al., 1991). As these neocortical and neocerebellar regions evolved, neuronal connections between them also developed (Finlay and Darlington, 1995; Leiner et al., 1991). This increased cerebellar computational capacity, connecting with areas of the cerebral cortex not associated with sensorimotor processing, suggests the lateral cerebellum receives information sent from the associative and cognitive cerebral regions, and might output to the same, non-motor regions (Balsters et al., 2010; Ito, 2008; Ramnani, 2011). Evidence from functional imaging studies suggests substantial overlap in prefrontal and parietal connectivity with the

posterior-lateral cerebellum, Crus II (O'Reilly et al., 2010). Thus, the more recently evolved cerebro-cerebellar pathway may function as an important - potentially bidirectional - link between the posterior and frontal lobes involved in cognitive function (Balsters et al., 2010), including language processing and inferring a cerebellar contribution to language. Consistent with this, growing evidence implicates the right lateral cerebellum in non-motor processing (Fiez, 1996; Stoodley and Schmahmann, 2009; Strick et al., 2009; Thach, 1998).

Findings from functional neuroimaging research also support the notion of right cerebellar involvement in language tasks (Desmond and Fiez, 1998; Moberget et al., 2014; Stoodley, 2011). For example, Frings et al., (2006) found greater right posterior cerebellar activity in a verb-generation task requiring participants to produce a semantically related verb in response to a noun, relative to word reading tasks, and independent of motor activity due to speech. Clinical studies on populations with right cerebellar abnormalities compliment these findings. Indeed some clinical populations showing developmental language impairments demonstrate right cerebellar irregularities; examples include cerebellar cognitive affective syndrome (Schmahmann and Sherman,

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1998), smaller right cerebellar volume in language impaired individuals with autism (Hodge et al., 2010), and cerebellar structural differences in dyslexia (Eckert et al., 2003). However, clinical studies can lack specificity, because affected individuals may exhibit heterogeneous effects as well as having diverse contributing symptoms, such as working memory or attentional deficiencies.

There has been recent speculation that the cerebellar contribution to cognitive processing may have generalised from its contribution to motor control (Ramnani, 2006; Salinas et al., 2008). This is based on the uniformity of the cerebellar cortical structure, with the same internal neural circuits receiving from and targeting diverse cortical regions (Bloedel, 1992). Function may be similar across the cerebellar cortex; different cerebellar regions may equivalently manipulate signals from different cerebral regions. There is considerable evidence that the motor regions of the cerebellum form “forward models” to predict the sensory consequences of a motor response (Miall et al., 1993). These predictive estimates are learnt with experience, used to better control actions, and to anticipate sensory signals arising from action (Wolpert and Miall, 2002). The advantage of forward modelling in language processes is also recognised (Pickering et al., 2014), but evidence linking linguistic prediction to the cerebellum is still quite limited (Argyropoulos et al., 2011; Moberget et al., 2014).

Recently Lesage et al. (2012) used the Visual World Paradigm to monitor language processing through eye movements (Huettig et al., 2011) and tested the effects of cerebellar disruption with repetitive TMS. They found that low frequency rTMS over the right cerebellum increased the latency of saccades towards target images but only in conditions where a spoken verb predicted a specific target, consistent with disruption of linguistic prediction.

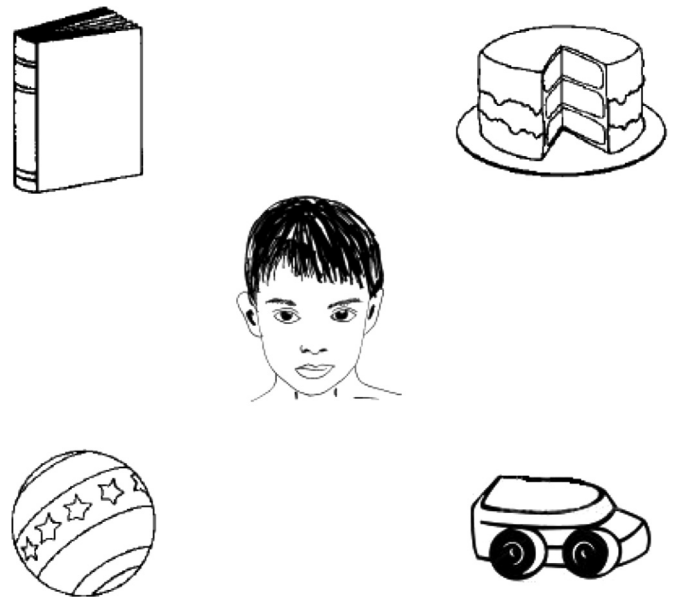
To our knowledge no study has yet tested both excitatory and inhibitory stimulation to enhance and disrupt cerebellar involvement in a language task. This could consolidate the argument that the cerebellum's role in language processing parallels its role in motor control. There are polarity specific effects of direct current stimulation on cerebellar excitability (Galea et al., 2009). We hypothesised, therefore, that anodal stimulation over the right cerebellum should enhance Visual World performance through exciting cerebellar activity, whilst cathodal stimulation, like low frequency rTMS, should disrupt it. In both cases, we predict that the changes would be confined to the predictive trials and not affect general performance.

There is also evidence associating cerebellar activity with practice-dependent associative learning in a verb generation task (Petersen et al., 1998) and in spoken or written word learning (Davis et al., 2009; Lesage et al., n.d.). In the motor domain, anodal cerebellar tDCS has been shown to enhance adaptation in visuo-motor tasks (Galea et al., 2011), dynamic tasks (Herzfeld et al., 2014) and in sequence learning (Stagg et al., 2011), whereas cathodal stimulation or low frequency TMS worsens learning (Herzfeld et al., 2014; Jenkinson and Miall, 2010; Stagg et al., 2011). Note, however, other reports suggest less clear-cut polarity specific effects on learning (Jacobson et al., 2011; Stagg et al., 2011). Evidence also suggests the cerebellum may contribute only indirectly to learning in cognitive tasks (Pope et al., 2015). So we also hypothesised that there would be a modulation of learning over repeated blocks of the Visual World task, but we were agnostic about whether anodal or cathodal stimulation would facilitate or impair learning, compared to sham.

## 2. Methods

### 2.1. Design and participants

Seventy three healthy native English-speaking students from



**Fig. 1.** An example of a visual display in the Visual World Paradigm. In the specific condition, this static display would be presented concurrent with the spoken sentence “the boy will eat the cake”. The only plausible answer according to the specific verb “eat” is the “cake” image. In the general condition, the display might be presented along with the spoken sentence “the boy will move the cake”, or any other object (book, ball or car). Hence each of the 4 images in the display is consistent with the general verb “move”. The display screen was  $25 \times 25$  cm,  $820 \times 820$  pixels, and viewed at normal reading distance of approx. 50 cm.

the University of Birmingham were sought for participation, in exchange for course credit or cash (56 were females; mean age = 19.8; SD = 2.7, range 18–54). All participants were screened for possible exclusion criteria for brain stimulation, including familial epilepsy, neurological medications, and recent drug, caffeine and sleep levels. The University of Birmingham ethical panel approved all procedures, and all participants gave signed, informed consent. Handedness was self-reported for 35 participants; the remainder also completed the Edinburgh Handedness scale. In total, six participants were left-handed; all participants were allowed to use the computer mouse with their preferred hand.

### 2.2. Visual world paradigm

In order to measure the speed of language processing, a manual version of the VWP was developed and run using Psychtoolbox v3 under MATLAB R2007B. On each trial the participant viewed a static visual display with one high contrast black and white line drawing image presented in each corner (Fig. 1). After 3 s a line-drawn image of a person (the agent) appeared in the screen centre to signal that the trial could begin. The participant was required to move the visible cursor onto this agent and to click the computer mouse to initiate the trial. The agent image then became low contrast, and after 500 ms a sentence spoken by either a male or female computer generated voice was delivered through headphones. The participant was required to then move the computer mouse as soon as possible towards the corner target visual image that was referenced at the end of the sentence (see legend, Fig. 1). In half the trials per block, the verb in the spoken sentence predicted one specific target image. In the other half the verb did not predict any specific target, and could be applied to all four images.

These two sentence types (specific and general) were presented pseudo-randomly. The time participants took to move the computer mouse towards the target image was measured from sentence onset, with a threshold of 200 pixels of cursor motion or about 1.5 cm of mouse movement. Short high or low beeps were

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