Neuropsychologia 169 (2022) 108206

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Cerebellar tDCS does not modulate language processing performance in healthy individuals

Fleur L.P. Bongaerts, Dennis J.L.G. Schutter, Jana Klaus *

Utrecht University, Helmholtz Institute, the Netherlands

ARTICLE INFO

Keywords:
Cerebellum
Lexical decision
Sentence processing
Transcranial direct current stimulation
Verbal fluency

ABSTRACT

Clinical and neuroscientific studies have established that the cerebellum contributes to language processing. Yet most evidence is correlational and the exact role of the cerebellum remains unclear. The aim of this study was to investigate the role of the right cerebellum in language comprehension and production using non-invasive brain stimulation. In this double-blind, sham-controlled experiment, thirty-six healthy participants received anodal or sham transcranial direct current (tDCS) stimulation to the right cerebellum while performing a lexical decision, sentence comprehension, verbal fluency and a non-language control task. Active tDCS did not modulate performance in any of the tasks. Additional exploratory analyses suggest difficulty-specific performance modulation in the sentence comprehension and lexical decision task, with tDCS improving performance in easy trials of the sentence comprehension task and difficult trials in the lexical decision task. Overall, our findings provide no evidence for the involvement of the right posterior cerebellum in language processing. Further research is needed to dissociate the influence of task difficulty of the underlying cognitive processes.

1. Introduction

Language ability is considered a uniquely human feature, as no other species shows syntactic recursion, nor the same degree of creativity, flexibility and innovativeness in their use of communication (Barón Birchenall, 2016). Effective communication through language requires the capacity for both language comprehension and speech production. These abilities are thought to mostly recruit cortical regions of the left frontotemporal language network, with language production being focused in the left inferior frontal (i.e., Broca's area) and language comprehension in the superior temporal gyrus (i.e., Wernicke's area; Hertrich et al., 2020). Over the last few decades, however, research has shown that the distinction between language production and comprehension is not as clear-cut as initially thought. To what extent language production and comprehension recruit shared regions of this network has been a primary focus of neuroimaging studies (e.g., Humphreys and Gennari, 2014; Menenti et al., 2011; Segaert et al., 2012; Silbert et al., 2014). As a result, contributions by regions outside of this network remain understudied (Tremblay and Dick, 2016). However, recent evidence suggests that other brain regions may play an important role in the processes of language production and comprehension as well. One such area is the cerebellum, long viewed as an area mainly responsible for motor functions. It has since been shown to contribute to cognitive processes as well (Buckner, 2013; King et al., 2019; Stoodley and Schmahmann, 2009), including language (Hertrich et al., 2020; Mariën, 2017; Mariën et al., 2014; Murdoch, 2010; Pleger and Timmann, 2018). Specifically, researchers have suggested that the cerebellum may contribute to predictive aspects of language processing (Argyropoulos, 2016; Lesage et al., 2017; Miall et al., 2016; Skipper and Lametti, 2021), assuming that the cerebellum holds a domain-general supervisory function in adaptive prediction (Hull, 2020; Schmahmann, 1996; Sokolov et al., 2017). Furthermore, there is evidence of functionally distinct cerebellar involvement in language and other cognitive functions which do not specifically tap into prediction (E et al., 2014; Guell et al., 2018; King et al., 2019; Stoodley and Schmahmann, 2009), challenging the idea that the cerebellum is responsible for a single universal computation (Diedrichsen et al., 2019).

Next to neuroimaging and behavioral studies, non-invasive brain stimulation is used to further shed light on the role of the cerebellum in different linguistic processes. Transcranial direct current stimulation (tDCS) is becoming a routinely used approach to examine cerebellar contributions to non-motor functions (Grimaldi et al., 2014, 2016; Ponce et al., 2021) and recovery following stroke (Ferrucci et al., 2016; Sebastian et al., 2017). During tDCS, a constant weak electric current

* Corresponding author. Utrecht University, Department of Experimental Psychology, Heidelberglaan 1, 3584 CS, Utrecht, the Netherlands.
E-mail address: j.klaus@uu.nl (J. Klaus).

https://doi.org/10.1016/j.neuropsychologia.2022.108206
Received 19 November 2021; Received in revised form 3 March 2022; Accepted 3 March 2022
Available online 9 March 2022

(usually 1–2 mA) is applied to the brain through two or more electrodes placed on the scalp. Even though the majority of the electric field is shunted by the scalp, a small yet significant portion of the field can reach the superficial layers of the cortex (Berryhill and Martin, 2018; Nitsche et al., 2008). In the motor cortex, anodal tDCS is thought to increase spontaneous neural firing, leading to performance improvement, whereas cathodal tDCS decreases cortical excitability, causing a performance decrement (Fernandes Medeiros et al., 2012; Nitsche et al., 2008). However, work focusing on brain areas outside of the motor cortex has suggested that this dichotomy may be less straight-forward for non-motor cortical regions (Brückner and Kammer, 2017; Klaus and Hartwigsen, 2020; Klaus and Schutter, 2018b) including the cerebellum (Oldrati and Schutter, 2018).

Within the domain of language, numerous studies have applied tDCS over cerebral language regions to investigate language processing (for meta-analyses, see Klaus and Schutter, 2018b; A. R. Price et al., 2015; Westwood and Romani, 2017). Studies targeting the cerebellum are less common and so far have provided inconsistent results. Anodal tDCS to the right cerebellum has been shown to modulate sensorimotor learning and auditory feedback control in speech production (Lametti et al., 2018; Peng et al., 2021). Furthermore, anodal tDCS of the right cerebellar hemisphere has been reported to modulate performance and task-related functional activation in linguistic prediction tasks (D'Mello et al., 2017; Miall et al., 2016; Rice et al., 2021) and phonemic fluency (Turkeltaub et al., 2016). Some studies also reported task- and difficulty-specific performance modulations induced by cerebellar tDCS. In a verbal working memory task, cerebellar tDCS decreased performance at medium (Macher et al., 2014) and high difficulty (Maldonado and Bernard, 2021). Moreover, by contrasting performance changes in a verb and noun reading with a more challenging verb generation task, Pope and Miall (2012) reported a facilitatory effect of cathodal cerebellar tDCS only in the verb generation task (cf. Spielmann et al., 2017).

Notably, the majority of these studies focused on only one specific linguistic capacity and tested the effects of tDCS between participants. The goal of the current study was therefore to synthesize findings from previous work by administering both anodal and sham tDCS and three different language tasks within the same healthy volunteers. Specifically, we examined the potential involvement of the right cerebellum in a picture-mediated sentence comprehension, a lexical decision, and a verbal fluency task. Studies in both healthy participants and patients with cerebellar damage have demonstrated cerebellar involvement in lexical decision (Carreiras et al., 2007) and access (Fabbro et al., 2000), verbal fluency (Molinari and Leggio, 2016), and sentence comprehension (Geva et al., 2021; Stowe et al., 2004). By administering tasks that require both language comprehension and production, we here examined potential domain-specific differences in cerebellar involvement. If language comprehension and production indeed recruit the right cerebellum alongside the frontotemporal language network, we expected for anodal tDCS to evoke performance differences compared to sham tDCS. If, by contrast, the cerebellum is not implicated in these abilities, no tDCS-induced effects were expected. Given the unclear influence of anodal cerebellar tDCS on performance (Oldrati and Schutter, 2018), we had no specific expectations with respect to the polarity of a potential effect (i.e., facilitation or inhibition). For tDCS applied to the cerebellum, a clear anodal-facilitation/cathodal-inhibition distinction has not been established (Oldrati and Schutter, 2018), and interindividual differences in the response to tDCS are likely to contribute to the variability of observed effects. To assess within-participant consistency, we therefore additionally examined the correlation between individual responses to tDCS per task. Following previous work (Klaus and Schutter, 2018a) investigating the effect of cathodal tDCS over the left dorsolateral prefrontal cortex on language processing tasks, we anticipated a positive correlation between performance differences between the active and sham tDCS condition for the language tasks. This would imply that despite the potential heterogeneity of the response to tDCS between participants, within-participant modulation would consistently yield either facilitation or inhibition for the language tasks.

2. Methods

2.1. Preregistration and data availability

The study protocol was preregistered on the Open Science Framework prior to data collection (https://osf.io/6dqy9). Data and analysis scripts can be found at https://osf.io/65yev/.

2.2. Participants

Thirty-six healthy volunteers (22 female; mean age: 23.65 years, *SD* = 3.31, range: 18–36) participated in the study. Sample size was determined based on a medium effect size of $d = 0.5$ at an alpha-level of 0.05, yielding a minimum sample size of 33 participants. Counterbalancing of the three language tasks used in this experiment required a number of participants that was a multiple of 12, resulting in a total number of 36 participants.

All participants were native Dutch speakers, right-handed and had normal or corrected-to-normal vision. None of them reported current neurological or psychiatric illnesses, current pregnancy, drug or alcohol addiction, skin diseases or allergies, metallic objects in their heads or any type of stimulator in their body, or family history of epilepsy. All participants gave written informed consent prior to the study, which was approved by the faculty ethics assessment committee of Utrecht University (protocol number 19–235). Participants received 16 euros compensation or course credit for their participation upon completion of the experiment. Due to technical issues, one participant was replaced.

2.3. Tasks

The experiment consisted of four tasks (Fig. 1), each lasting between 3 and 5 min. All tasks were programmed in jsPsych (de Leeuw, 2015) and displayed in full screen mode in Google Chrome on a 24 inch monitor (Dell Ultrasharp, U2417H). Manual responses were recorded via a wired keyboard (Dell Multimedia Keyboard, KB216), and spoken responses with an Olympus WS-852 digital voice recorder.

2.3.1. Verbal fluency task

In this task, participants were prompted to say out loud as many words as possible starting with the letter shown on the screen within 1 min. They were asked to avoid brand names, first names, and conjugations of words they had already used. To avoid training effects, participants were presented with three different letters in each session (K, O, and M, or P, G, and R, respectively), the order of which was counterbalanced across sessions and stimulation conditions. These stimuli have been shown to be of comparable difficulty for native Dutch speakers (Schmand et al., 2008).

2.3.2. Sentence comprehension

In this task, 112 sentence-picture pairs were presented. In half of the trials, the sentence described the picture accurately, and in the other half of the trials, the sentence did not match the action shown in the picture. Participants had to indicate whether a pairing was correct or not by pressing the F (for correct trials) or G key (for incorrect trials) on the keyboard placed in front of them. Participants were instructed to use only their left middle and ring finger for this task.

Images for this task were taken from Segaert et al. (2011). All images were scaled to a height of 600 pixels and displayed in the middle of the screen with the sentence directly under it. Pictures were depictions of different transitive actions illustrating a subject performing an action on a direct object (e.g. "De vrouw bedient de man." [the woman serves the man] or "De vrouw bezorgt de pakketjes." [the woman delivers the packages]), or a subject performing a basic action (e.g. "De man lacht." [the man laughs]). Two different experimental lists were compiled and

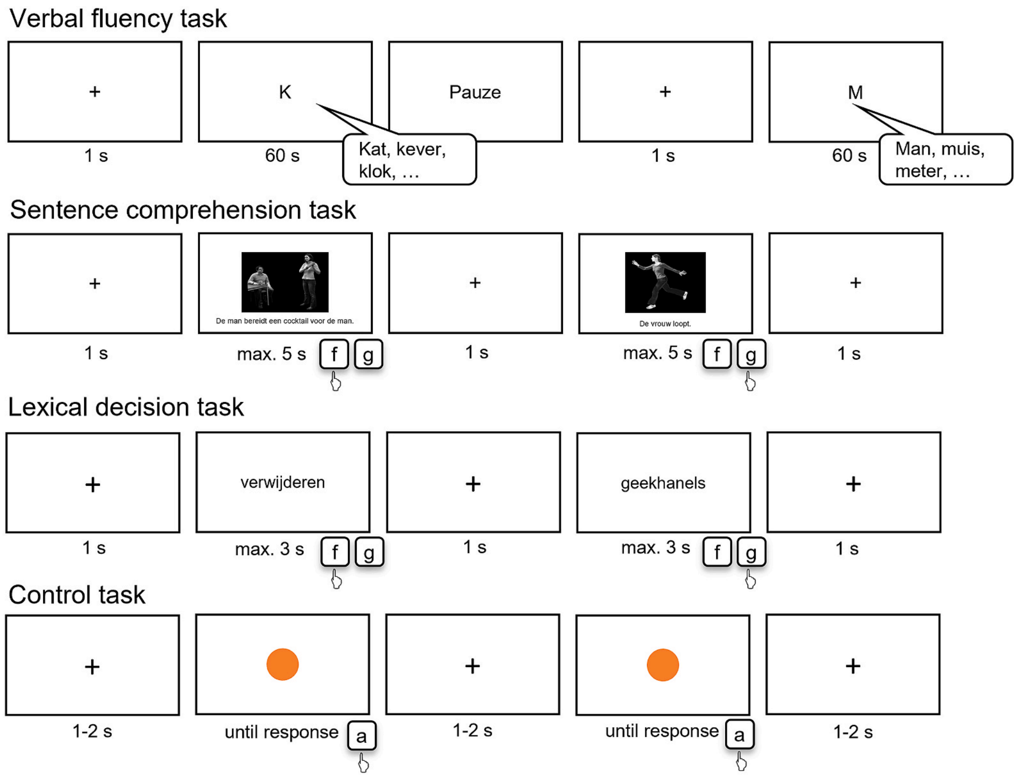

Fig. 1. Two exemplary trials for each of the four tasks administered during the experiment.

presented to participants in different sessions in a counterbalanced order to prevent training effects. Sets contained the same ratios of sentence types and right/wrong presentations.

During an experimental trial, a fixation cross was shown for 1000 ms, followed by the presentation of the picture-sentence pair. As soon as the participant had responded, or after a maximum of 5000 ms, the next trial was initiated.

2.3.3. Lexical decision

The lexical decision task consisted of 200 word stimuli of which 100 were existing words in Dutch (e.g., “verwijderen” [to remove]) and the other 100 were phonotactically legal pseudowords (e.g. “geekhanels”). Stimuli were taken from Ernestus and Cutler (2015). Participants were instructed to indicate as fast and accurately as possible whether the word shown in the middle of the screen existed in Dutch or not by pressing the F key (if the word existed) or the G key (if the word did not exist) on the keyboard in front of them. Like for the sentence comprehension task, participants were instructed to use only their left middle and ring finger for this task.

In an experimental trial, a fixation cross was shown for 1000 ms, followed by the presentation of the word stimulus. The stimulus remained visible until the participant gave a response, or until a maximum of 3000 ms had elapsed. Then the next trial was initiated automatically. To avoid training effects, different stimuli were presented in the two sessions.

2.3.4. Control task

A control task was included in this study to examine unspecific cerebellar tDCS effects not related to linguistic processing. In this task, participants were asked to press the A key on the keyboard in front of them as soon as an orange circle appeared on the screen. Circle images were scaled to a height of 300 pixels and presented in the middle of the screen. Participants were instructed to respond as quickly as possible and to only use their left little finger in this task. A fixation cross appeared on the screen between trials with a jitter between 1000 and 2000 ms, followed by the presentation of the target stimulus, which disappeared as soon as a response had been recorded. The task consisted of 100 trials.

2.4. *Transcranial direct current stimulation*

Anodal tDCS was delivered in a randomized double-blind manner by a battery-driven stimulator via two electrode sponges covered in conductive gel (3 × 3 cm each; NeuroConn GmbH, Ilmenau, Germany). Electrode sponges were kept in place by an EEG cap. The anode was placed approximately 2 cm below the location corresponding to the electrode position I2 in the international 10–20 system and the cathode was placed approximately 2 cm below EEG position PO10. This montage was chosen as it has been shown to induce a more focal electric field in the right posterolateral cerebellum than previously used montages placing the reference electrode over the contralateral supraorbital region or the ipsilateral buccinator muscle (Klaus and Schutter, 2021). Previous tDCS studies (e.g., D'Mello et al., 2017; Pope and Miall, 2012; Rice et al., 2021; Turkeltaub et al., 2016) placed the anode more superior to the current position (e.g., 1 cm below and 4 cm to the right of the inion) and the return electrode over extracephalic locations (e.g., the right deltoid muscle or clavicle). Furthermore, these studies used substantially larger electrodes (25 or 35 cm^2 instead of 9 cm^2), decreasing the current density. Together, such montages are deemed less optimal for targeting the right posterior cerebellum, as a larger distance between the two electrodes reduces the focality of the electric field (Klaus and Schutter, 2021; Moliadze et al., 2010) and elicits electric fields outside of the cerebellum (Klaus and Schutter, 2021).

After a 30 s ramp-up, stimulation was delivered at an intensity of 2 mA (current density: 0.22 mA/cm^2). Stimulation continued while participants performed the previously described tasks. Impedance of the electrodes was kept below 15 kΩ. Real and sham stimulation was distributed evenly across the two sessions, with half of the participants receiving real tDCS in the first session and sham tDCS in the second session. Experimenter blinding was achieved using a pre-assigned code entered into the DC stimulator at the beginning of each session.

2.5. Procedure

Participants were tested in two separate sessions of approximately 45 min each. Each session was separated by at least seven days to minimize carry-over effects and took place at the same time of the day. The day before the first session, participants received information about the study in writing and were asked to fill in the screening forms, which were then reviewed by the experimenter. At the start of the first session, participants were also informed verbally. Participants then received the opportunity to ask further questions, after which they were asked to fill in the consent form.

Afterward, an EEG cap was fitted to the participant's head and centered over the vertex. Then, tDCS was administered. During stimulation, participants performed the experimental tasks. Prior to the start of each task, instructions were presented on the screen and participants were provided with the opportunity to ask questions. The order of language tasks was counterbalanced across participants and each session ended with the motor control task. After completion of the final task, participants filled in a sensation questionnaire to provide information about their perception of the stimulation (i.e., physical sensations and influence on performance on a scale from 1 [not at all] to 5 [very strongly] as well as perceived duration on a scale from 0 [only at the beginning] to 2 [until the end]). At the end of the second session, participants were debriefed about the purpose of the study and asked to guess which of the two sessions had been the active session, allowing us to check whether blinding had been maintained.

2.6. Data preprocessing

For the tasks requiring manual responses (i.e., sentence comprehension, lexical decision, and control task), trials in which a wrong or no button press was given were coded as errors and discarded from the reaction time analyses. Then, reaction times deviating from a participant's individual mean (computed separately for the two stimulation conditions) by more than 3 *SD*s were marked as outliers and excluded from the datasets. Four participants had unusually high error rates in the sentence comprehension task, the lexical decision task, or both. At the end of an experimental session they indicated that they had confused the meaning of the appropriate keys and erroneously used the F key for wrong responses and the G key for correct responses. After recoding these records, their error rates fell within the normal range, so to avoid data loss we decided to keep these participants in the dataset.

For the fluency task, the number of correctly generated words for each letter was counted by the experimenter immediately after transcription of the data. In case of uncertainty, an independent rater was consulted to assess the eligibility of specific utterances. Words that did not start with the letter shown on the screen, had already been uttered by the participant, were a conjugation or plural form of a previously uttered word and words that did not exist were coded as incorrect responses and did not count towards the total.

2.7. Analysis

2.7.1. Preregistered analyses

Statistical analyses were computed in R (version 4.0.3, R Core Team, 2020). For the verbal fluency task, the number of words produced per participant per session was summed and analyzed with a one-sample *t*-test due to the low number of trials (three per stimulation condition). For all other tasks, we initially ran one-sample *t*-tests on stimulation condition-aggregated reaction times and error rates to explore the differences between anodal and sham tDCS. Additionally, we calculated generalized linear mixed models including the sum-coded within-participant fixed effect tDCS (anodal vs. sham) and by-participant intercepts as well as by-participant slopes for tDCS. For reaction times, a Gamma distribution with an identity link was fitted, accounting for the right skew of the distribution. For error rates, a binomial distribution was fitted. Finally, we explored whether there was within-participant consistency of the tDCS effect across tasks. To this end, we correlated the individual tDCS effect (mean of dependent measure under anodal tDCS – mean of dependent measure under sham tDCS) across all three language tasks. All statistical tests were two-tailed. For the *t*-tests and the mixed model analyses, the α-level was set to 0.05. To account for multiple comparisons in the correlational analyses, the α-level for these analyses was set to 0.017.

2.7.2. Exploratory analyses

Following previous reports of cerebellar tDCS effects as a function of task-specific difficulty (Macher et al., 2014; Maldonado and Bernard, 2021; Pope and Miall, 2012), we conducted two additional, non-preregistered analyses for the sentence comprehension and lexical decision task, respectively, including the fixed effect difficulty (low vs. high). This distinction was possible due to the differences in stimuli inherent in the two stimulus sets, which were, however, not completely controlled a priori. For the sentence comprehension task, low difficulty was defined as those stimuli depicting a simple transitive action performed by an agent (e.g., "het meisje lacht" [the girl is laughing]), whereas high difficulty referred to stimuli in which an agent exerted an action on a patient (e.g., "het meisje bewaakt de schatkist" [the girl is guarding the treasure chest]). For the lexical decision task, real and pseudowords were divided into low and high difficulty, respectively, according to their morphological complexity (Ernestus and Cutler, 2015). Low difficulty referred to one-stem words with one or two affixes (e.g. "kreupelheid" [lameness] or "beklaagde" [accused]), while high difficulty referred to two-stem words (i.e., compounds) with or without suffix (e.g., "haarfijn" [very fine] or "dasspelden" [tie pins]). For both analyses, we included the sum-coded fixed effect difficulty as a main effect and its interaction with tDCS. We started out with the interaction of difficulty and tDCS as a by-participant intercept. For the sentence comprehension task, a model using this complex random structure did not converge, so we simplified the model by including by-participant slopes for the main effects of difficulty and tDCS.

3. Results

3.1. Preregistered analyses

Table 1 reports descriptive statistics for the respective dependent variables for all four experimental tasks, broken down by stimulation condition (active vs. sham tDCS).

3.1.1. Verbal fluency

There were no significant differences in the number of words produced between real and sham tDCS ($t_{35} = 0.12$, $p = .906$).

3.1.2. Sentence comprehension

572 erroneous responses (7.6%) and 95 trials marked as outliers (1.3%) were removed from the reaction time analysis. There were no

Table 1
Descriptive statistics (mean and SD) for the four experimental tasks.

	Verbal fluency	Sentence comprehension		Lexical decision		Control task
	Number correct words	RT in ms	Error rate in %	RT in ms	Error rate in %	RT in ms
active tDCS	47 (12)	1595 (306)	7.1 (3.9)	851 (145)	10.7 (5.1)	256 (30)
sham tDCS	47 (11)	1607 (327)	8.2 (5.2)	861 (157)	10.1 (5.2)	254 (23)

significant effects of tDCS in the *t*-tests (RTs: $t_{35} = -0.28$, $p = .782$; error rates: $t_{35} = -1.09$, $p = .285$) or linear mixed models (RTs: $\beta = -7.61$, $SE = 5.36$, $t = -1.42$, $p = .156$; error rates: $\beta = -0.06$, $SE = 0.07$, $z = -0.92$, $p = .355$).

3.1.3. Lexical decision

899 erroneous responses (10.4%) and 157 trials marked as outliers (1.8%) were removed from the reaction time analysis. For reaction times, a *t*-test did not reveal a significant difference between the tDCS conditions ($t_{35} = -0.47$, $p = .640$). The mixed model analysis indicated marginally significantly faster responses for the active compared to the sham condition ($\beta = -6.32$, $SE = 3.48$, $t = -1.82$, $p = .067$). There were no significant differences in the error rates (*t*-test: $t_{35} = 1.20$, $p = .236$; mixed model: $\beta = 0.03$, $SE = 0.04$, $z = 0.82$, $p = .410$).

3.1.4. Control task

99 trials (2.8%) were marked as outliers and removed from the analysis. Reaction times in the motor task were almost identical and revealed no differences between active and sham tDCS (*t*-test: $t_{35} = 0.65$, $p = .522$; mixed model: $\beta = 0.61$, $SE = 0.94$, $z = 0.65$, $p = .517$).

3.1.5. Individual effects of tDCS across tasks

Stimulation effects ($\text{performance}_{\text{active}}$ — $\text{performance}_{\text{sham}}$) in the language tasks were significantly correlated between the lexical decision and sentence comprehension task ($r_{34} = 0.595$, $p < .001$, $R^2 = 35.4\%$), but not between the lexical decision and verbal fluency task ($r_{34} = -0.187$, $p = .275$, $R^2 = 3.5\%$) nor between the verbal fluency and sentence comprehension task ($r_{34} = -0.254$, $p = .135$, $R^2 = 6.5\%$; Fig. 2).

3.2. Exploratory analyses

For the sentence comprehension task, the analysis including the fixed effect difficulty (low vs. high) revealed a main effect of tDCS ($\beta = -12.21$, $SE = 3.38$, $t = -3.62$, $p < .001$), a main effect of difficulty ($\beta = 233.25$, $SE = 5.26$, $t = -44.38$, $p < .001$), and, crucially, an interaction of the two ($\beta = 7.35$, $SE = 3.19$, $t = 2.30$, $p = .021$). Follow-up contrasts showed that active tDCS facilitated reaction times in the low difficulty condition relative to sham ($\beta = -39.12$, $SE = 8.94$, $z = -4.38$, $p < .001$), but had no effect in the high difficulty condition ($\beta = -9.73$, $SE = 9.63$, $t = -1.01$, $p = .313$; Fig. 3A).

For the lexical decision task, the same analysis revealed a main effect of difficulty ($\beta = 27.34$, $SE = 3.03$, $t = 9.04$, $p < .001$) and an interaction of tDCS and difficulty ($\beta = -9.70$, $SE = 3.40$, $t = -2.86$, $p = .004$). Contrary to the sentence comprehension task, this reflected a marginally significant, facilitatory effect of tDCS in the high difficulty condition ($\beta = -30.90$, $SE = 16.8$, $z = -1.84$, $p = .066$), but no effect in the low difficulty condition ($\beta = 7.90$, $SE = 16.70$, $z = 0.47$, $p = .637$; Fig. 3B).

3.3. Blinding

At the end of the second session, 25 participants guessed correctly which stimulation condition they had received in which session, while the other 11 participants guessed incorrectly or were not sure ($X^2_1 = 4.01$, $p = .045$). In the sensation questionnaires administered at the end of each experimental session, participants reported a stronger sensation of warmth under the electrodes under active ($M = 0.68$, $SD = 0.84$) than sham tDCS ($M = 0.35$, $SD = 0.69$, $t_{33} = 2.24$, $p = .032$). Note that for this sensation, two participants failed to indicate any sensation in the questionnaire in one of the two sessions, so this analysis is based on 34 participants. Participants indicated a stronger influence of anodal tDCS ($t_{34} = 2.75$, $p = .009$; $M = 0.4$, $SD = 0.65$) than sham tDCS ($M = 0.09$, $SD = 0.28$), with one participant failing to indicate a response on this question. None of the other sensations significantly differed between stimulation conditions (*ps* $> .162$). However, there was a significant difference between the perceived duration of the stimulation ($t_{35} = 6.29$, $p < .001$), with anodal tDCS being perceived longer ($M = 1.08$, $SD = 0.84$) than sham tDCS ($M = 0.17$, $SD = 0.51$). Because this sensation could be indicated on a three-point scale (range: 0–2), this means that on average participants perceived anodal tDCS until about the middle of the stimulation duration.

To examine whether awareness of the real stimulation condition may have increased general alertness resulting in unspecific facilitation, we analyzed the performance in the motor control task in a subsample of the 25 participants who guessed their stimulation sequence correctly. However, as for the full sample, we found no effect of tDCS in this analysis ($\beta = 1.4$, $SE = 3.0$, $t = 0.46$, $p = .644$). Therefore, it is less likely that the compromised blinding systematically affected participants' performance.

4. General discussion

The aim of the current study was to investigate the possible contribution of the right cerebellum in different language processing tasks. While previous studies reporting modulation of task performance as a result of cerebellar tDCS focused on predictive aspects of language processing (e.g., D'Mello et al., 2017; Miall et al., 2016; Rice et al., 2021), the current study examined effects on language processing tasks that cannot specifically be framed within a predictive processing account. Our preregistered analyses provided no significant main effects of tDCS. Exploratory analyses revealed a dissociation between task difficulty for the lexical decision and sentence comprehension task, respectively, with anodal tDCS selectively decreasing reaction times in the low-load condition in the sentence comprehension task and in the high-load condition in the lexical decision task. Overall, these results provide no evidence for language-specific involvement of the cerebellum, supporting theories that the cerebellum plays a domain-general role in language processing (Skipper and Lametti, 2021). However, our

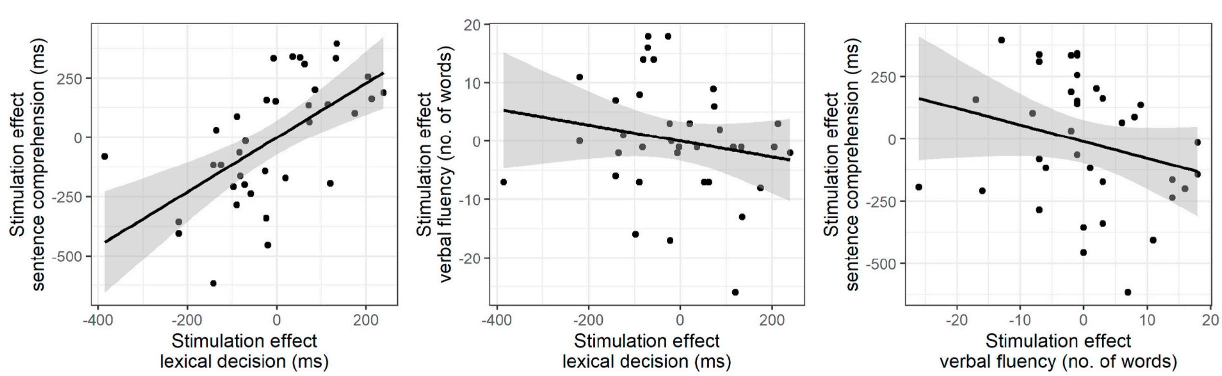

Fig. 2. Correlation between individual tDCS effects ($RT_{active} - RT_{sham}$) for the three linguistic tasks. Positive values indicate inhibition and negative values facilitation from active tDCS relative to sham.

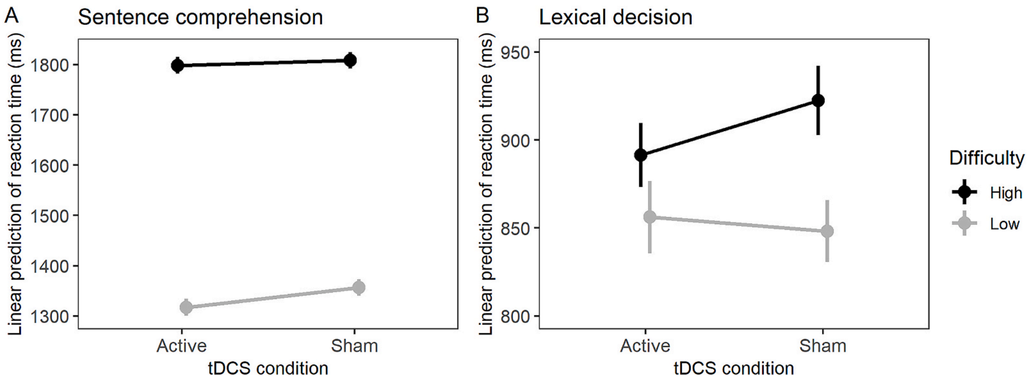

Fig. 3. Results from exploratory analyses including difficulty (high vs. low) in the RT analysis of the sentence comprehension task (A) and the lexical decision task (B).

findings do tentatively suggest task- and difficulty-specific involvement of the right cerebellum, particularly the right posterolateral cerebellum, during language processing.

The lexical decision task, which required a manual response and evoked comparably low reaction times, showed a marginally significant facilitation effect from anodal tDCS. Mariën et al. (2009) reported a case study of a patient with a right cerebellar-pontine infarction who, despite operational letter processing, presented with severely impaired visual lexical decision performance, particularly an overclassification of non-words as real words. This suggests that lesions in the right posterior cerebellum negatively affect processes associated with lexical decision. In our study, healthy volunteers showed a small benefit from tDCS to the right posterolateral cerebellum with respect to overall processing speed. However, an interesting pattern emerged in our exploratory analysis, in which we added task difficulty, defined by the morphological complexity of the stimuli, as an additional factor. Results from this analysis suggest that the marginal facilitatory tDCS effect in the lexical decision task was driven by responses to the morphologically complex items, with low-difficulty items showing no differences between the tDCS conditions. Speculatively, this could imply a role of the right cerebellum in more challenging lexical decision trials, potentially associated with the release of additional resources from the contralateral prefrontal cortex (Maldonado and Bernard, 2021; Pope and Miall, 2012). However, because the significance of the effect of tDCS in the high-difficulty condition was above the a priori determined α-level of 0.05 (two-tailed), we refrain from drawing conclusions for this particular contrast. Future studies should systematically test whether lexical decision effects of stimulation of the right posterolateral cerebellum differ as a function of task difficulty. This could be done by introducing a response deadline or manipulating the lexical frequency and/or phonological neighborhood density of the real words.

For the sentence comprehension task, the overall effect of tDCS was also not statistically significant. Importantly, due to the increased overall complexity of this task relative to the lexical decision task, average reaction times were about twice as long as for the lexical decision task, and inter- and intra-participant variability was substantially higher. It is therefore possible that for such a complex linguistic task, right cerebellar involvement plays a less crucial role, or may have been compensated by cerebral language regions. Results from the exploratory analysis including task difficulty, which was defined by the syntactic complexity of the to-be-evaluated sentences and images, showed a difficulty-specific pattern. While there was no tDCS-induced effect in the high-difficulty condition, the low-difficulty condition displayed a facilitatory effect of anodal tDCS relative to sham. Speculatively, this pattern may be reconciled with a prediction-based account of cerebellar involvement in language comprehension. The easy condition required the matching of a short subject-verb sentence to the presented picture. In such a case, a prediction error can be detected relatively quickly, because the mismatch can only occur on two possible locations (i.e., the agent or the action). In other words, stimuli in the easy condition are relatively more predictable compared to the difficult condition. In the latter, both the agent and the direct object needed to be selected from two possible alternatives, rendering a correct matching of the sentence with the picture less predictable. In a study using the visual world paradigm, Lesage et al. (2012) found that participants were slower to fixate highly predictable images after inhibitory cerebellar repetitive transcranial magnetic stimulation (rTMS), while eye movements in an unpredictable control condition were unaffected. Similarly, Miall et al. (2016) reported shorter response times following anodal and cathodal tDCS compared to sham for predictable items. Moreover, rTMS to the right cerebellum has been shown to impair decisions on semantically probable (e.g., “red apple”) compared to incorrect (e.g., “lucky milk”) adjective-noun pairs (Gatti et al., 2020). Here, we report performance improvement from arguably facilitatory cerebellar tDCS in trials with relatively higher predictable contents. The findings from this exploratory analysis are in agreement with forward models of cerebellar prediction, which assume that the cerebellum detects prediction violations and uses continuously updated internal models to optimize performance (Sokolov et al., 2017). Importantly, we would like to stress that the exploratory analyses were conceived entirely post-hoc, so the stimulus sets were not perfectly designed to capture potential difficulty-related differences. Follow-up studies are needed to test hypotheses generated from these results.

Performance in the verbal fluency task, which required a vocal response, was also not modulated by cerebellar stimulation. To our knowledge, so far only two studies have measured changes in (phonemic) fluency in combination with cerebellar tDCS. Turkeltaub et al. (2016) reported improved performance following anodal tDCS in healthy individuals, while DeMarco et al. (2021) found no effects from five sessions of anodal tDCS combined with speech therapy in individuals with chronic stroke aphasia. It should however be noted that both of these studies compared fluency before and immediately after tDCS and between participants, whereas we measured performance *during* the application of active or sham tDCS within the same participants. It is currently unknown to what extent, or if at all, mechanisms related to online effects of cerebellar tDCS differ from those of prolonged aftereffects (Grimaldi et al., 2016). One could therefore speculate that successful modulation of verbal fluency performance, at least in healthy individuals, depends on slowly unfolding changes in cerebellar neurotransmitters (Grimaldi et al., 2016), which have not yet been completed during the application of tDCS. Additionally, a recent study examining language dysfunction in four patients with lesions in the right posterior medial cerebellum reported unimpaired phonemic and semantic fluency (Geva et al., 2021), suggesting that this region may not be crucial for fluency performance. Finally, it should be noted that like the majority of studies assessing verbal fluency, our single dependent variable was the total number of words produced. This does not exclude the possibility that cerebellar tDCS affected more specific processes associated with this task, like strategies related to lexical clustering or the time course of retrieval (Luo et al., 2010; Shao et al., 2014).

The finding that individual tDCS effects on the lexical decision task and sentence comprehension task were positively correlated, showing that the (descriptive) directionality of the tDCS-induced performance modulation in the these tasks was consistent within individuals. It should be noted, however, that these analyses are based on non-significant main effects of tDCS. Interestingly though, the same pattern was found by Klaus and Schutter (2018a), where the effect of tDCS on the left dorsolateral prefrontal cortex on three different tasks (i.e., picture naming, sentence comprehension, Flanker task) was tested. Both findings suggest that there are differences in the magnitude of the tDCS effect between individuals, adding to the existing literature on between-participant variability in response to tDCS (Cheeran et al., 2017; López-Alonso et al., 2015; Wiethoff et al., 2014). This variability is potentially augmented in stimulation studies targeting the cerebellum, owing to its highly folded structure which may cause substantial differences in polarization (Rahman et al., 2013). Future research is needed to further improve stimulation protocols to minimize between-participant variability, particularly in light of clinical applications.

Finally, an important limitation of the study should be addressed. Our analyses showed that complete blinding was not maintained, as participants were disproportionately more likely to guess the correct stimulation condition. Interestingly, however, differences in how participants rated the stimulation sensations were small and only presented in the extent to which participants perceived warmth under the electrodes. To our knowledge, the current study is the first to adopt a montage placing both 9 cm^2 electrodes in relatively close proximity to each other, which is based on electric field modelling in a sample of 20 individuals (Klaus and Schutter, 2021). Therefore, it still needs to be determined whether perceptual differences are isolated occurrences or indeed specific to the electrode setup. However, in the current study, all participants were naïve to tDCS. Furthermore, restricting the analysis of performance in the motor task to those participants who guessed the stimulation sequence correctly did not affect the results. Therefore, we do not consider it very likely that the correct guessing of the stimulation sequence introduced a systematic bias in performance. For future studies, it would nonetheless be useful to deliberately interview participants about their expectations at the end of the experiment, to further dissociate potential differences of the induced tDCS effects. Furthermore, applying a topical anesthetic to the area beneath the electrodes to reduce discomfort in the active condition (McFadden et al., 2011) and improve the likelihood of successful participant blinding may diminish effects of expectations.

In conclusion, the current study provides no evidence for the involvement of the right posterior cerebellum in language processing. Exploratory analyses indicate a role for the right cerebellum in task- and difficulty-specific aspects of comprehension-based language processing (i.e., sentence comprehension and lexical decision), putatively extending previous findings on the cerebellar role in language prediction.

Credit author statement

Fleur L.P. Bongaerts: Conceptualization, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Dennis J.L.G. Schutter**: Writing – original draft, Writing – review & editing, Funding acquisition. **Jana Klaus**: Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization.

Declaration of competing interest

The authors have no competing interests to declare.

Acknowledgments

This work was supported by the Dutch Research Council(NWO, VI. C.181.005).

References

Argyropoulos, G.P.D., 2016. The cerebellum, internal models and prediction in 'non-motor' aspects of language: a critical review. Brain Lang. 161, 4–17. https://doi.org/10.1016/j.bandl.2015.08.003.

E, K.-H., Chen, S.-H.A., Ho, M.-H.R., Desmond, J.E., 2014. A meta-analysis of cerebellar contributions to higher cognition from PET and fMRI studies. Hum. Brain Mapp. 35, 593–615. https://doi.org/10.1002/hbm.22194.

Barón Birchenall, L., 2016. Animal communication and human language: an overview. Int. J. Comp. Psychol. 29 (1) https://doi.org/10.5070/P4291028000.

Berryhill, M.E., Martin, D., 2018. Cognitive effects of transcranial direct current stimulation in healthy and clinical populations: an overview. J. ECT 34 (3), e25. https://doi.org/10.1097/YCT.0000000000000534.

Brückner, S., Kammer, T., 2017. Both anodal and cathodal transcranial direct current stimulation improves semantic processing. Neuroscience 343, 269–275. https://doi.org/10.1016/j.neuroscience.2016.12.015.

Buckner, R.L., 2013. The cerebellum and cognitive function: 25 Years of insight from anatomy and neuroimaging. Neuron 80 (3), 807–815. https://doi.org/10.1016/j.neuron.2013.10.044.

Carreiras, M., Mechelli, A., Estévez, A., Price, C.J., 2007. Brain activation for lexical decision and reading aloud: two sides of the same coin? J. Cognit. Neurosci. 19 (3), 433–444. https://doi.org/10.1162/jocn.2007.19.3.433.

Cheeran, B., Lopez-Alonso, V., Del-Olmo, M.F., 2017. Variability in response to non-invasive brain stimulation: basic physiology. Brain Stimulation 10 (2), 379–381. https://doi.org/10.1016/j.brs.2017.01.125.

de Leeuw, J.R., 2015. jsPsych: a JavaScript library for creating behavioral experiments in a Web browser. Behav. Res. Methods 47 (1), 1–12. https://doi.org/10.3758/s13428-014-0458-y.

DeMarco, A.T., Dvorak, E., Lacey, E., Stoodley, C.J., Turkeltaub, P.E., 2021. An exploratory study of cerebellar transcranial direct current stimulation in individuals with chronic stroke aphasia. Cognit. Behav. Neurol. 34 (2), 96–106. https://doi.org/10.1097/WNN.0000000000000270.

Diedrichsen, J., King, M., Hernandez-Castillo, C., Sereno, M., Ivry, R.B., 2019. Universal transform or multiple functionality? Understanding the contribution of the human cerebellum across task domains. Neuron 102 (5), 918–928. https://doi.org/10.1016/j.neuron.2019.04.021.

D'Mello, A.M., Turkeltaub, P.E., Stoodley, C.J., 2017. Cerebellar tDCS modulates neural circuits during semantic prediction: a combined tDCS-fMRI study. J. Neurosci. 37 (6), 1604–1613. https://doi.org/10.1523/JNEUROSCI.2818-16.2017.

Ernestus, M., Cutler, A., 2015. BALDEY: a database of auditory lexical decisions. Q. J. Exp. Psychol. 68 (8), 1469–1488. https://doi.org/10.1080/17470218.2014.984730.

Fabbro, F., Moretti, R., Bava, A., 2000. Language impairments in patients with cerebellar lesions. J. Neurolinguistics 13 (2), 173–188. https://doi.org/10.1016/S0911-6044(00)00010-5.

Fernandes Medeiros, L., de Souza, I.C., Pinto Vidor, L., de Souza, A., Deitos, A., Volz, M. S., Fregni, F., Caumo, W., Torres, I.L., 2012. Neurobiological effects of transcranial direct current stimulation: a review. Front. Psychiatr. 28 https://doi.org/10.3389/fpsyt.2012.00110.

Ferrucci, R., Bocci, T., Cortese, F., Ruggiero, F., Priori, A., 2016. Cerebellar transcranial direct current stimulation in neurological disease. Cerebellum Ataxias 3 (1), 16. https://doi.org/10.1186/s40673-016-0054-2.

Gatti, D., Van Vugt, F., Vecchi, T., 2020. A causal role for the cerebellum in semantic integration: a transcranial magnetic stimulation study. Sci. Rep. 10 (1), 18139. https://doi.org/10.1038/s41598-020-75287-z.

Geva, S., Schneider, L.M., Roberts, S., Green, D.W., Price, C.J., 2021. The effect of focal damage to the right medial posterior cerebellum on word and sentence comprehension and production. Front. Hum. Neurosci. 15, 239. https://doi.org/10.3389/fnhum.2021.664650.

Grimaldi, G., Argyropoulos, G.P., Boehringer, A., Celnik, P., Edwards, M.J., Ferrucci, R., Galea, J.M., Groiss, S.J., Hiraoka, K., Kassavetis, P., Lesage, E., Manto, M., Miall, R. C., Priori, A., Sadnicka, A., Ugawa, Y., Ziemann, U., 2014. Non-invasive cerebellar stimulation—a consensus paper. Cerebellum 13 (1), 121–138. https://doi.org/10.1007/s12311-013-0514-7.

Grimaldi, G., Argyropoulos, G.P., Bastian, A., Cortes, M., Davis, N.J., Edwards, D.J., Ferrucci, R., Fregni, F., Galea, J.M., Hamada, M., Manto, M., Miall, R.C., Morales-Quezada, L., Pope, P.A., Priori, A., Rothwell, J., Tomlinson, S.P., Celnik, P., 2016. Cerebellar transcranial direct current stimulation (ctDCS): a novel approach to understanding cerebellar function in health and disease. Neuroscientist 22 (1), 83–97. https://doi.org/10.1177/1073858414559409.

Guell, X., Gabrieli, J.D.E., Schmahmann, J.D., 2018. Triple representation of language, working memory, social and emotion processing in the cerebellum: convergent evidence from task and seed-based resting-state fMRI analyses in a single large cohort. Neuroimage 172, 437–449. https://doi.org/10.1016/j.neuroimage.2018.01.082.

Hertrich, I., Dietrich, S., Ackermann, H., 2020. The margins of the language network in the brain. Front. Commun. https://doi.org/10.3389/fcomm.2020.519955.

Hull, C., 2020. Prediction signals in the cerebellum: beyond supervised motor learning. Elife 9, e54073. https://doi.org/10.7554/eLife.54073.

Humphreys, G.F., Gennari, S.P., 2014. Competitive mechanisms in sentence processing: common and distinct production and reading comprehension networks linked to the prefrontal cortex. Neuroimage 84, 354–366. https://doi.org/10.1016/j.neuroimage.2013.08.059.

King, M., Hernandez-Castillo, C.R., Poldrack, R.A., Ivry, R.B., Diedrichsen, J., 2019. Functional boundaries in the human cerebellum revealed by a multi-domain task battery. Nat. Neurosci. 22 (8), 1371–1378. https://doi.org/10.1038/s41593-019-0436-x.

Klaus, J., Hartwigsen, G., 2020. Failure to improve verbal fluency with transcranial direct current stimulation. Neuroscience 449, 123–133. https://doi.org/10.1016/j.neuroscience.2020.09.003.

Klaus, J., Schutter, D.J.L.G., 2018a. The role of left dorsolateral prefrontal cortex in language processing. Neuroscience 377, 197–205. https://doi.org/10.1016/j.neuroscience.2018.03.002.

Klaus, J., Schutter, D.J.L.G., 2018b. Non-invasive brain stimulation to investigate language production in healthy speakers: a meta-analysis. Brain Cognit. 123, 10–22. https://doi.org/10.1016/j.bandc.2018.02.007.

Klaus, J., Schutter, D.J.L.G., 2021. Electrode montage-dependent intracranial variability in electric fields induced by cerebellar transcranial direct current stimulation. Sci. Rep. 11 (1), 1–11. https://doi.org/10.1038/s41598-021-01755-9.

Lametti, D.R., Smith, H.J., Freidin, P.F., Watkins, K.E., 2018. Cortico-cerebellar networks drive sensorimotor learning in speech. J. Cognit. Neurosci. 30 (4), 540–551. https://doi.org/10.1162/jocn_a_01216.

Lesage, E., Hansen, P.C., Miall, R.C., 2017. Right lateral cerebellum represents linguistic predictability. J. Neurosci.: Offic. J. Soc. Neurosci. 37 (26), 6231–6241. https://doi.org/10.1523/JNEUROSCI.3203-16.2017.

Lesage, E., Morgan, B.E., Olson, A.C., Meyer, A.S., Miall, C.C., 2012. Cerebellar rTMS disrupts predictive language processing. Curr. Biol. 22 (18), R794–R795. https://doi.org/10.1016/j.cub.2012.07.006.

López-Alonso, V., Fernández-Del-Olmo, M., Costantini, A., Gonzalez-Henriquez, J.J., Cheeran, B., 2015. Intra-individual variability in the response to anodal transcranial direct current stimulation. Clin. Neurophysiol. 126 (12), 2342–2347. https://doi.org/10.1016/j.clinph.2015.03.022.

Luo, L., Luk, G., Bialystok, E., 2010. Effect of language proficiency and executive control on verbal fluency performance in bilinguals. Cognition 114 (1), 29–41. https://doi.org/10.1016/j.cognition.2009.08.014.

Macher, K., Böhringer, A., Villringer, A., Pleger, B., 2014. Cerebellar-parietal connections underpin phonological storage. J. Neurosci. 34 (14), 5029–5037. https://doi.org/10.1523/JNEUROSCI.0106-14.2014.

Maldonado, T., Bernard, J.A., 2021. The Polarity-specific Nature of Single-Session High-Definition Transcranial Direct Current Stimulation to the Cerebellum and Prefrontal Cortex on Motor and Non-motor Task Performance. Cerebellum, London, England. https://doi.org/10.1007/s12311-021-01235-w.

Mariën, P., 2017. A role for the cerebellum in language and related cognitive and affective functions. In: Mody, M. (Ed.), Neural Mechanisms of Language. Springer US, pp. 175–198. https://doi.org/10.1007/978-1-4939-7325-5_9.

Mariën, P., Baillieux, H., De Smet, H.J., Engelborghs, S., Wilssens, I., Paquier, P., De Deyn, P.P., 2009. Cognitive, linguistic and affective disturbances following a right superior cerebellar artery infarction: a case study. Cortex 45 (4), 527–536. https://doi.org/10.1016/j.cortex.2007.12.010.

Mariën, P., Ackermann, H., Adamaszek, M., Barwood, C.H.S., Beaton, A., Desmond, J., De Witte, E., Fawcett, A.J., Hertrich, I., Küper, M., Leggio, M., Marvel, C., Molinari, M., Murdoch, B.E., Nicolson, R.I., Schmahmann, J.D., Stoodley, C.J., Thürling, M., Timmann, D., Ziegler, W., 2014. Consensus paper: language and the cerebellum: an ongoing enigma. Cerebellum 13 (3), 386–410. https://doi.org/10.1007/s12311-013-0540-5.

McFadden, J.L., Borckardt, J.J., George, M.S., Beam, W., 2011. Reducing procedural pain and discomfort associated with transcranial direct current stimulation. Brain Stimulation 4 (1), 38–42. https://doi.org/10.1016/j.brs.2010.05.002.

Menenti, L., Gierhan, S.M.E., Segaert, K., Hagoort, P., 2011. Shared language: overlap and segregation of the neuronal infrastructure for speaking and listening revealed by functional MRI. Psychol. Sci. 22 (9), 1173–1182. https://doi.org/10.1177/0956797611418347.

Miall, R.C., Antony, J., Goldsmith-Sumner, A., Harding, S.R., McGovern, C., Winter, J.L., 2016. Modulation of linguistic prediction by tDCS of the right lateral cerebellum. Neuropsychologia 86, 103–109. https://doi.org/10.1016/j.neuropsychologia.2016.04.022.

Moliadze, V., Antal, A., Paulus, W., 2010. Electrode-distance dependent after-effects of transcranial direct and random noise stimulation with extracephalic reference electrodes. Clin. Neurophysiol. 121 (12), 2165–2171. https://doi.org/10.1016/j.clinph.2010.04.033.

Molinari, M., Leggio, M., 2016. Cerebellum and verbal fluency (phonological and semantic). In: Mariën, P., Manto, M. (Eds.), The Linguistic Cerebellum. Academic Press, pp. 63–80. https://doi.org/10.1016/B978-0-12-801608-4.00004-9.

Murdoch, B.E., 2010. The cerebellum and language: historical perspective and review. Cortex 46 (7), 858–868. https://doi.org/10.1016/j.cortex.2009.07.018.

Nitsche, M.A., Cohen, L.G., Wassermann, E.M., Priori, A., Lang, N., Antal, A., Paulus, W., Hummel, F., Boggio, P.S., Fregni, F., Pascual-Leone, A., 2008. Transcranial direct current stimulation: state of the art 2008. Brain Stimulation 1 (3), 206–223. https://doi.org/10.1016/j.brs.2008.06.004.

Oldrati, V., Schutter, D.J.L.G., 2018. Targeting the human cerebellum with transcranial direct current stimulation to modulate behavior: a meta-analysis. Cerebellum 17 (2), 228–236. https://doi.org/10.1007/s12311-017-0877-2.

Peng, D., Lin, Q., Chang, Y., Jones, J.A., Jia, G., Chen, X., Liu, P., Liu, H., 2021. A Causal Role of the Cerebellum in Auditory Feedback Control of Vocal Production. Cerebellum, London, England. https://doi.org/10.1007/s12311-021-01230-1.

Pleger, B., Timmann, D., 2018. The role of the human cerebellum in linguistic prediction, word generation and verbal working memory: evidence from brain imaging, non-invasive cerebellar stimulation and lesion studies. Neuropsychologia 115, 204–210. https://doi.org/10.1016/j.neuropsychologia.2018.03.012.

Ponce, G.V., Klaus, J., Schutter, D.J.L.G., 2021. A brief history of cerebellar neurostimulation. Cerebellum. https://doi.org/10.1007/s12311-021-01310-2.

Pope, P.A., Miall, R.C., 2012. Task-specific facilitation of cognition by cathodal transcranial direct current stimulation of the cerebellum. Brain Stimulation 5 (2), 84–94. https://doi.org/10.1016/j.brs.2012.03.006.

Price, A.R., McAdams, H., Grossman, M., Hamilton, R.H., 2015. A meta-analysis of transcranial direct current stimulation studies examining the reliability of effects on language measures. Brain Stimulation 8 (6), 1093–1100. https://doi.org/10.1016/j.brs.2015.06.013.

R Core Team, 2020. R: the R Project for Statistical Computing. R Foundation for Statistical Computing. https://www.R-project.org/.

Rahman, A., Reato, D., Arlotti, M., Gasca, F., Datta, A., Parra, L.C., Bikson, M., 2013. Cellular effects of acute direct current stimulation: somatic and synaptic terminal effects. J. Physiol. 591 (10), 2563–2578. https://doi.org/10.1113/jphysiol.2012.247171.

Rice, L.C., D'Mello, A.M., Stoodley, C.J., 2021. Differential behavioral and neural effects of regional cerebellar tDCS. Neuroscience 462, 288–302. https://doi.org/10.1016/j.neuroscience.2021.03.008.

Schmahmann, J.D., 1996. From movement to thought: anatomic substrates of the cerebellar contribution to cognitive processing. Hum. Brain Mapp. 4 (3), 174–198. https://doi.org/10.1002/(SICI)1097-0193(1996)4:3<174::AID-HBM3>3.0.CO;2-0.

Schmand, B., Groenink, S.C., den Dungen, M., 2008. Letterfluency: psychometrische eigenschappen en Nederlandse normen. Tijdschr Gerontol. Geriatr. 39 (2), 64–74. https://doi.org/10.1007/BF03078128.

Sebastian, R., Saxena, S., Tsapkini, K., Faria, A.V., Long, C., Wright, A., Davis, C., Tippett, D.C., Mourdoukoutas, A.P., Bikson, M., Celnik, P., Hillis, A.E., 2017. Cerebellar tDCS: a novel approach to augment language treatment post-stroke. Front. Hum. Neurosci. 10, 695. https://doi.org/10.3389/fnhum.2016.00695.

Segaert, K., Menenti, L., Weber, K., Hagoort, P., 2011. A paradox of syntactic priming: why response tendencies show priming for passives, and response latencies show priming for actives. PLoS One 6 (10), e24209. https://doi.org/10.1371/journal.pone.0024209.

Segaert, K., Menenti, L., Weber, K., Petersson, K.M., Hagoort, P., 2012. Shared syntax in language production and language comprehension—an fMRI study. Cerebr. Cortex 22 (7), 1662–1670. https://doi.org/10.1093/cercor/bhr249.

Shao, Z., Janse, E., Visser, K., Meyer, A.S., 2014. What do verbal fluency tasks measure? Predictors of verbal fluency performance in older adults. Front. Psychol. 5, 772. https://doi.org/10.3389/fpsyg.2014.00772.

Silbert, L.J., Honey, C.J., Simony, E., Poeppel, D., Hasson, U., 2014. Coupled neural systems underlie the production and comprehension of naturalistic narrative speech. Proc. Natl. Acad. Sci. Unit. States Am. 111 (43), E4687–E4696. https://doi.org/10.1073/pnas.1323812111.

Skipper, J.I., Lametti, D.R., 2021. Speech perception under the tent: a domain-general predictive role for the cerebellum. J. Cognit. Neurosci. 33 (8), 1517–1534. https://doi.org/10.1162/jocn_a_01729.

Sokolov, A.A., Miall, R.C., Ivry, R.B., 2017. The cerebellum: adaptive prediction for movement and cognition. Trends Cognit. Sci. 21 (5), 313–332. https://doi.org/10.1016/j.tics.2017.02.005.

Spielmann, K., van der Vliet, R., van de Sandt-Koenderman, W.M.E., Frens, M.A., Ribbers, G.M., Selles, R.W., van Vugt, S., van der Geest, J.N., Holland, P., 2017. Cerebellar cathodal transcranial direct stimulation and performance on a verb generation task: a replication study. Neural Plast. 2017, e1254615 https://doi.org/10.1155/2017/1254615.

Stoodley, C.J., Schmahmann, J.D., 2009. Functional topography in the human cerebellum: a meta-analysis of neuroimaging studies. Neuroimage 44 (2), 489–501. https://doi.org/10.1016/j.neuroimage.2008.08.039.

Stowe, L.A., Paans, A.M.J., Wijers, A.A., Zwarts, F., 2004. Activations of "motor" and other non-language structures during sentence comprehension. Brain Lang. 89 (2), 290–299. https://doi.org/10.1016/S0093-934X(03)00359-6.

Tremblay, P., Dick, A.S., 2016. Broca and Wernicke are dead, or moving past the classic model of language neurobiology. Brain Lang. 162, 60–71. https://doi.org/10.1016/j.bandl.2016.08.004.

Turkeltaub, P.E., Swears, M.K., D'Mello, A.M., Stoodley, C.J., 2016. Cerebellar tDCS as a novel treatment for aphasia? Evidence from behavioral and resting-state functional connectivity data in healthy adults. Restor. Neurol. Neurosci. 34 (4), 491–505. https://doi.org/10.3233/RNN-150633. Scopus.

Westwood, S.J., Romani, C., 2017. Transcranial direct current stimulation (tDCS) modulation of picture naming and word reading: a meta-analysis of single session tDCS applied to healthy participants. Neuropsychologia 104, 234–249. https://doi.org/10.1016/j.neuropsychologia.2017.07.031.

Wiethoff, S., Hamada, M., Rothwell, J.C., 2014. Variability in response to transcranial direct current stimulation of the motor cortex. Brain Stimulation 7 (3), 468–475. https://doi.org/10.1016/J.BRS.2014.02.003.